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REPORT OF THE  
INTERNATIONAL TECHNICAL AND SCIENTIFIC COMMITTEE OF FLORENCE 2016  
ON THE PROTECTION OF FLORENCE FROM FLOODING

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**2016** Progetto Firenze

*L'alluvione  
Le alluvioni*





# **Saving a World Treasure: Protecting Florence from Flooding**

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The people of Florence, alone, were beginning the work of salvage. They went about their task in silence, each doing what they had to do, as if they were all members of one army, commanded by one invisible but omnipresent general. Inspired by their love for Florence, they labored on-and the most divided and contentious population in the world found unity and brotherhood in service of the stricken city... To me, as I watched and participated in the work, it was a moving and inspiring experience, and I shall always thank Providence for the privilege of having lived through it. It was only late on the following morning, as I sloshed through the mud at Santa Croce and the Via dei Benci in the wake of an imposing presidential tour of inspection, that I heard from certain stricken houses the heart-chilling shouts for "Bread!" and "Water!" This was the first time since the disaster that I had heard anyone speak these words. For forty-eight hours the people of Florence had not thought about themselves; hunger and thirst were as nothing compared with the anguish and heart-ache they endured as they beheld the suffering of their beloved city.

Enrico Mattei, *How the people of Florence fought back* (1967)



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# Preface

The Firenze 2016 Committee was established in 2013 on the impetus of the Rector of the University of Florence Alberto Tesi, who suggested that Florence Council, the Tuscan Region and scientific and cultural institutions collaborate in the preparation of the fiftieth anniversary of the 1966 Florence Flood.

All main Institutions both political and cultural have participated in the Committee, as well as very numerous national and international Public and Private Associations. A complete list of the over 100 participants of the Committee can be found on the Project's website <[www.firenze2016.it](http://www.firenze2016.it)>.

In the period 2013-2014, the Committee was presided over by Mario Primicerio, former mayor of the Florence Municipality and from 2014 by the Mayor of Florence, Dario Nardella. As from 2015, the President of the Tuscan Region, Enrico Rossi, has taken on the charge of co-President.

The Committee Secretary is prof. Giorgio Valentino Federici of the University of Florence.

Since the foundation of the Committee, we have established an International Technical and Scientific Committee (ITSC) for an independent evaluation of what had been and what could still be done to reduce the flood risk for Florence. I wish to emphasize the importance and the innovative character of this initiative for our Country where the practice of accountability, common in the Anglo-Saxon world, seems to be considerably less present. It is indeed the case that, to help solve Venice's problems, an international scientific committee was set up. This, however, operated under the aegis of the Consortium of companies responsible for the planning and realisation of the works, and therefore followed procedures which cannot be seen as an example of 'accountability'. It is also important to observe that, with regard to Venice's problem, the Italian Government adopted, even amongst a thousand difficulties, quite a different strategy from that adopted for Florence. The special law for Venice has allowed the city of Venice to enjoy enormous funding for its defence and the safeguarding of the lagoon, funding of an order of magnitude higher than that allocated to the defence of the city of Florence.

How was such a different treatment possible? The flood risk "has been removed", as we say in Florence. Many people believe that the risk still remains.

For this reason, about three years ago, together with Mario Primicerio, former Mayor of Florence, we decided to set up the institution of an International Scientific

Committee (ITSC). We were aware that a Fellow of the Accademia dei Lincei, prof. Giovanni Seminara, was an expert of water engineering very much involved in the scientific problems related to the safeguard of Venice and its lagoon. He had never been professionally involved in the management of the Arno flood risk but, together with his high qualifications, he was the ideal candidate for the ITSC. So we asked him to extend the efforts he had devoted to protecting Venice to supporting the equally important aim of protecting Florence from the flooding of the Arno River. With his help, we then identified a possible composition of the Committee, inspired by the strict principle of independence that had guided us from the beginning. The choice of Gerry Galloway as Chair of the ITSC is also in line with the objective of seeking a guide of great authority and, at the same time, of total independence.

And so the ITSC experience began. We wish to extend many thanks, also on behalf of the co -chairs of the Firenze 2016 Committee, Dario Nardella the Mayor of Florence and Enrico Rossi President of the Tuscany Region, to the members of the ITSC, and in particular to Gerry Galloway and to Giovanni Seminara, for their generous and hard-working commitment. Note that the principle of accountability was also applied to ITSC. Indeed, the final Report was sent for review to two anonymous referees, who wished their identities to be disclosed, namely Prof. Murugesu Sivapalan (University of Illinois at Urbana-Champaign) and Prof. Demetris Koutsoyiannis (Technical University of Athens). The manuscript was also submitted for comments to the three former Secretaries of the Arno Basin Authorities, Prof. Angelo Nardi, Prof. Giovanni Menduni and Dr. Gaia Checcucci.

Finally, let us thank the Rector of the University of Florence, Luigi Dei, for supporting the publication of this report printed by the FUP – Firenze University Press.

The Secretary of the Firenze 2016 Committee  
Giorgio Valentino Federici



# Executive Summary

Florence, Italy, is recognized as one of the world's great treasures in art, culture, and Renaissance history. It is a UNESCO heritage site and an internationally visited tourist attraction. The importance of its legacy cannot be understated and its preservation is important to the citizens of Florence, Italy, and the world population. The tragic flooding of Florence in 1966 caused 38 deaths, severe damage to many of its most precious art works and threatened the economic and social viability of the city and its residents. In the aftermath of this event, people from around the world gathered to help the city recover and restore damaged works and the strength of the city. Governmental bodies argued that such flood tragedies should not be repeated. In the 50 years since the flood, the cultural and societal relevance of Florence has grown further world-wide and has produced a marked increase in the economic value of tourism.

In January 2014, Progetto Firenze 2016, a regional body convened by the University of Florence and now chaired by the mayor of Florence and the president of the Tuscany Region, invited six engineers and scientists from Europe and the United States to form an International Technical Scientific Committee (ITSC) to examine the current status of flood protection for Florence and to identify steps that might be taken to reduce any identified risks facing the city. The ITSC met as a body in June 2014, October 2015, and in October 2016 and was in communication throughout the period. In October 2016, the ITSC presented its report to Progetto Firenze 2016 for further transmission to the governments of Florence, Tuscany and Italy. The ITSC concluded that Florence remains at risk to significant flooding and this risk grows each day. It is not a question of whether a flood of the magnitude of 1966 or greater will occur, but when. In fact, the level of protection that exists in Florence now does not yet provide the risk reduction needed for the city and is not on a level appropriate to the citizens and treasures that rest within the city. If, under current conditions, a 1966-like flood occurred, the consequences to human lives, treasures, other properties and community infrastructure could be much more catastrophic than they were in 1966.

Since 1966, some actions have been taken to reduce the risk to flooding, however, these actions have not been sufficient to provide the standards that one would expect for a city like Florence. Because of the changes that have occurred throughout the

river basin, there are still threats to human lives and property. In 1996, an Arno River Basin Plan was issued by the Arno River Basin authority and described the actions deemed necessary to deal with the flooding as it was perceived at the time of the plan. Unfortunately, resources to support implementation of the plan have been slow in coming and thus most of the proposed projects have not been resourced and actions initiated. Some actions that are proceeding are underfunded. In fact, several of the measures that have been planned in 1996 were proposed again in the Hydro-Geological Plan (PAI) issued in 2005 and are again proposed by the Management Plan of Flood Risk (PGRA) that was approved in 2016 by the Arno River Basin Authority in compliance with the European Flood Directive.

At the current pace of activity, ongoing flood risk reduction efforts will not ensure the safety of the city and its patrimony for many decades to come.

The ITSC believes that, while the citizens of Florence and Tuscany may be aware of some potential flooding from the Arno River, it does not believe that they have adequate understanding of the magnitude and significance of this flooding. It is critical that national, regional, and local governments work together to communicate these risks to the public and develop an integrated plan to deal with the hydrologic risks they face.

The protection of Florence is a problem of national and international relevance. The ITSC suggests that the Italian Government should urge the appropriate Institutions (Florence, Municipality, Tuscany Region, Arno River Basin Authority and National Civil Protection), to prepare, on an accelerated time-schedule, and submit to its attention a comprehensive plan, which integrates structural and non-structural measures for protection of Florence. The plan should be structured to maximize the coordination among mitigation measures being employed therefore resolving the current fragmentation among responsible bodies. It should be detailed enough to define what further interventions are needed, with their feasibility based on a cost benefit analysis and a realistic time scale for their implementation. The plan should also include a comprehensive assessment of the socio-economic impact of a flood similar to the 1966 event on Florence and its cultural heritage. The ITSC suggests that the Italian Government should appoint an independent international committee (including no member of the ITSC) to serve as an advisory body in the preparation of the comprehensive plan.

Florence (Italy), December 2016

# Acknowledgements

We wish to acknowledge the help of various institutions and individuals who, in various ways, have supported our work.

Alberto Tesi, Past Rector and Luigi Dei, present Rector of the University of Florence, have given the ITSC their full support. Our colleagues of the University of Florence, Enrica Caporali, Fabio Castelli, Enio Paris and Massimo Rinaldi have generously shared some of their work. Leonardo Rossi and Gianluca Pompei of Pubblacqua S.p.A. have provided much appreciated hospitality at our first meeting and our visit to the Bilancino reservoir. Alessandro Leoncini, of ENEL S.p.A. has kindly guided our visit to Levane dam. Mauro Grassi (Italia Sicura), Giovanni Massini (Tuscany Region), Alessandro Mazzei (Tuscany Water Authority), Marcello Brugioni (Arno Basin Authority) and Bernardo Mazzanti (Arno Basin Authority) have joined our technical discussions. Giulia Mugnai (Major of Figline e Incisa Valdarno), Lorenzo Tilli (Assessore at Figline e Incisa Valdarno), David Settesoldi (West Systems s.r.l.) and Oreste Tavanti (Commissioner for the construction of the Pizziconi, Restone – Valdarno flood retention areas) are thanked for hosting us and guiding our visit of the works in progress.

We are also grateful to Prof. Murugesu Sivapalan (University of Illinois at Urbana-Champaign) and Prof. Demetris Koutsoyiannis (Technical University of Athens) for their valuable review comments.

Finally, special thanks are due to Professor Giorgio Valentino Federici, University of Florence, who served as the principal representative of Firenze 2016 with the Committee and who provided invaluable assistance to the ITSC throughout its efforts, and to Gabriella Montagnani (Firenze 2016) for her continuous, warm and effective administrative support.



## Chapter One

# Reducing the Flood Risk to Florence and Its Treasures

### 1.1 The flood risk to Florence

Florence, Italy, is recognized as one of the world's great treasures in art, culture, and Renaissance history. It is a UNESCO heritage site and an internationally visited tourist attraction. The importance of its legacy cannot be understated and its preservation is important to the citizens of Florence, Italy, and the world population. Tragic flooding in 1966 caused 38 deaths in Florence and its province, severe damage to many of its most precious art works and threatened the economic and social viability of the city and its residents.

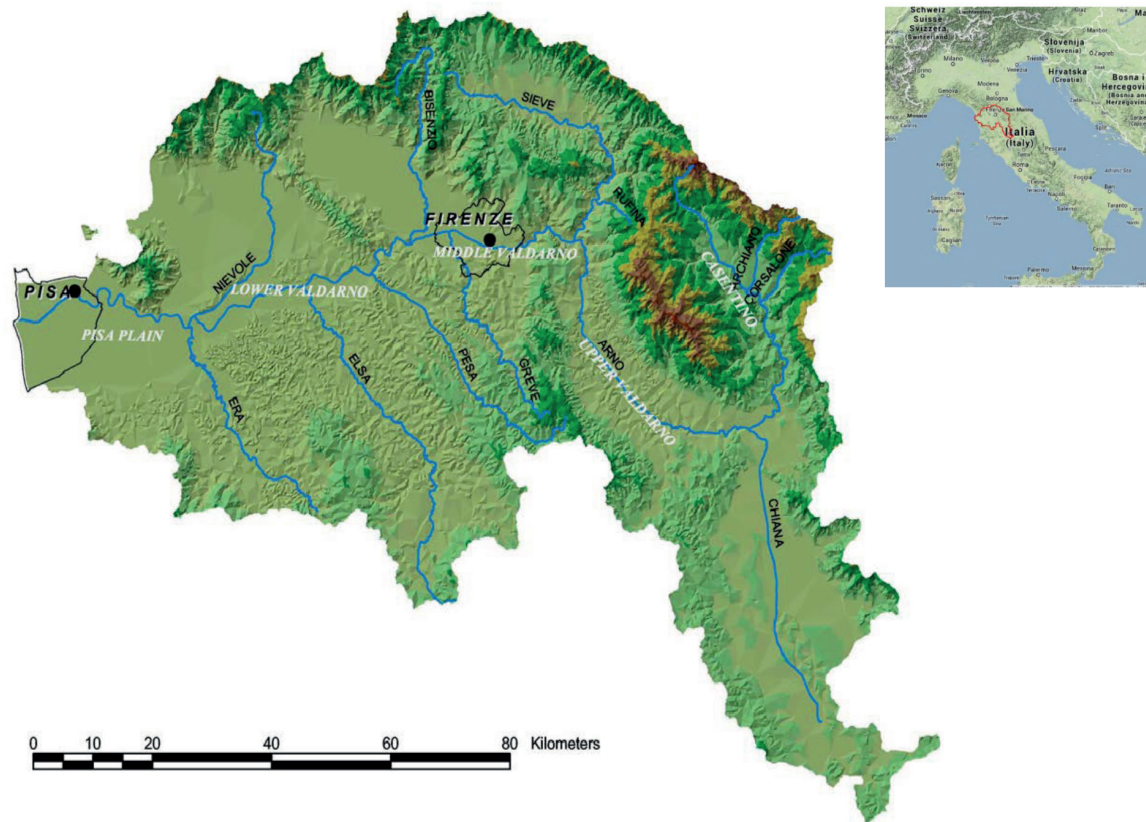
In January 2014, Progetto Firenze 2016, a regional body convened by the University of Florence and currently chaired by the mayor of Florence and the president of the Tuscany Region, invited six engineers and scientists from Europe and the United States to form an International Technical Scientific Committee (ITSC) to examine the current status of flood protection for Florence and to identify steps that might be taken to reduce any identified risks facing the city. The ITSC met as a body in June 2014, October 2015, and in October 2016 and was in communication throughout the period. *This report represents the ITSC response to Progetto Firenze 2016's charge to the committee and is being provided for further transmission to the governments of Florence, Tuscany and Italy. (Throughout this report, text in bold italics represents important comments of the ITSC)*

### 1.2 The drainage network of the Arno River

The Arno River Basin is mostly confined within the region of Tuscany in Central Italy. The length of the river is approximately 241 km. The catchment area is about 8 238 km<sup>2</sup> and its mean elevation is 353 m a.s.l.

The Arno River Basin (Fig. 1-1) is composed of four major reaches: starting from upstream the *Casentino*, the *Valdarno superiore* (upper Arno valley), the *Valdarno medio* (middle Arno valley) with the Florence plain, and the *Valdarno inferiore* (lower Arno valley) with the Pisa plain. The Casentino drains the valley bounded by the Alpe di Catenaia (east), the Falterona mountains (north) and the Pratomagno mountains (west). In this reach it receives the waters of the Corsalone tributary. The river





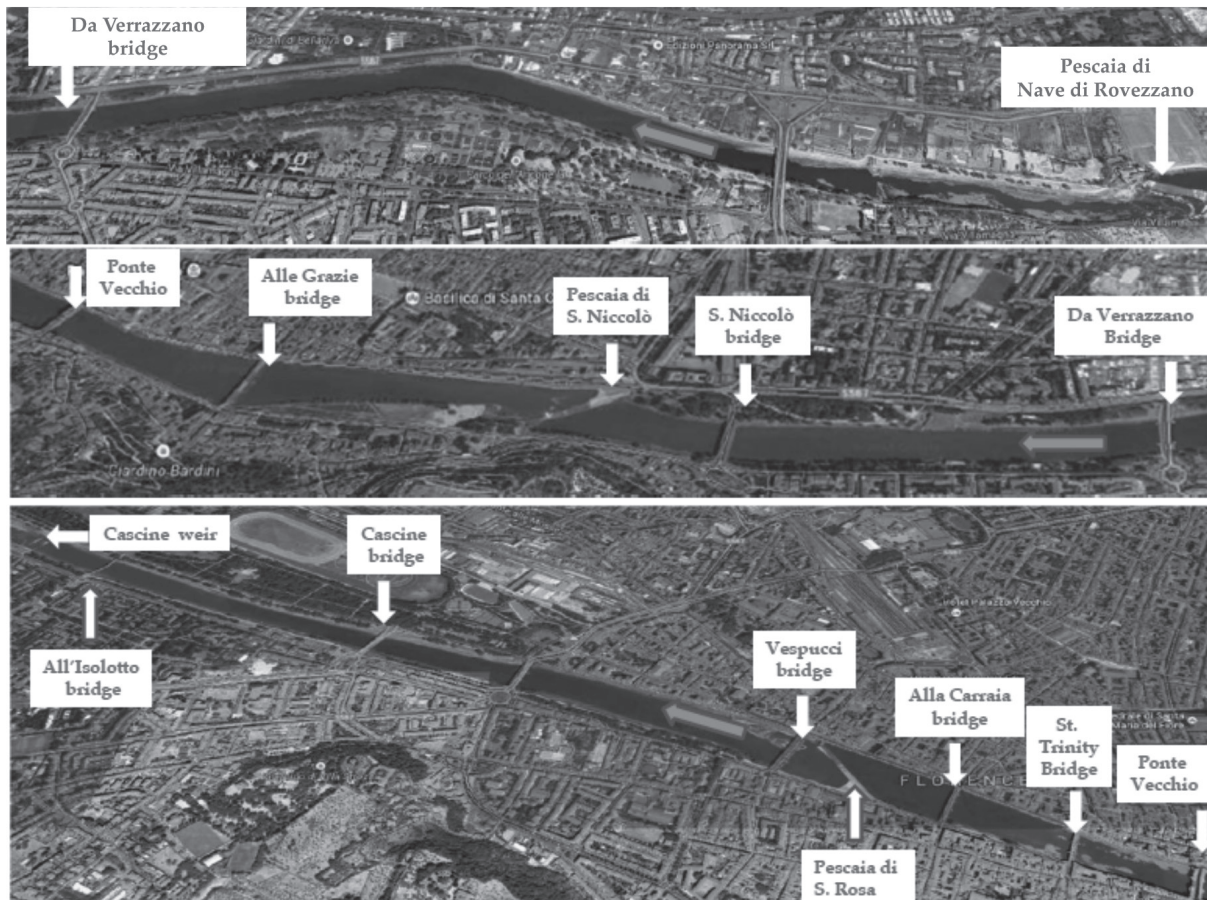
**Fig. 1-1.** The Arno basin with its main tributaries, and location map (Reproduced from Caporali et al., 2005; location map from Mazzanti, I meeting ITSC, 2014).

then turns northward, receives the waters drained by the Valdichiana near the city of Arezzo, and flows into the upper Arno Valley, bounded westward by the Chianti mountains. After receiving the waters of a major tributary, the Sieve, the Arno turns westward, crosses the Florence plain and flows into the middle Arno Valley.

The middle Valdarno drains the Tosco Emiliano Appennine northward, the Chianti and the Albano mountains southwest and the secondary chain adjacent to the Valdinievole westward. In this reach, the Arno receives the waters of various tributaries, notably the Ombrone and the Bisenzio from the north and the Greve from the south. It then enters the Gonfolina canyon to flow into the lower Valdarno where it receives the waters of several tributaries, the Pesa, the Elsa and the Era on the left and the Nievole on the right. In its final reach, the Arno crosses the Pisa plain to debouch into the Tyrrhenian Sea.

### 1.3 The Arno River through Florence

Understanding the characteristics of the Arno River as it passes through Florence from a historical perspective is crucial to understanding hydraulic complexity created by some of its distinct features, most notably bridges and weirs (*pescaie*) which, over time, have significantly affected both the hydrodynamics and the morphodynamics of the fluvial stream. The sequence of weirs and bridges which control the river in the



Florence reach are indicated in the Fig. 1-2 and briefly described below. A detailed discussion of these structures is found in Appendix C.

**Fig. 1-2.** Florentine reach of the Arno River with location of bridges and weirs (pescaie).

#### *Weirs/Pescaie*

While the word 'Pescaie' can literally be translated into 'fishing ponds', the functions of pescaie were much wider than the latter expression would suggest. Pescaie were originally used to prevent bank and bottom erosion and allow for the storage of water to be employed as a natural supply for the city and to produce the energy required by the great number of water driven plants located along the river. Various further uses motivated the construction of pescaie as a source of water for irrigation and for the defense of Florence from possible attacks of its enemies sailing along the Arno River.

Four weirs are located in the urban area of Florence:

- the *Pescaia di Nave di Rovezzano* at the upstream end of the urban area;
- the *Pescaia di San Niccolò*, situated in the vicinity of the Porta di San Niccolò (gate);
- the *Pescaia of Santa Rosa* located downstream of the city center, near the Parco delle Cascine;
- the *Traversa dell'Isolotto* (or *delle Cascine*) located at the downstream end of the urban area.



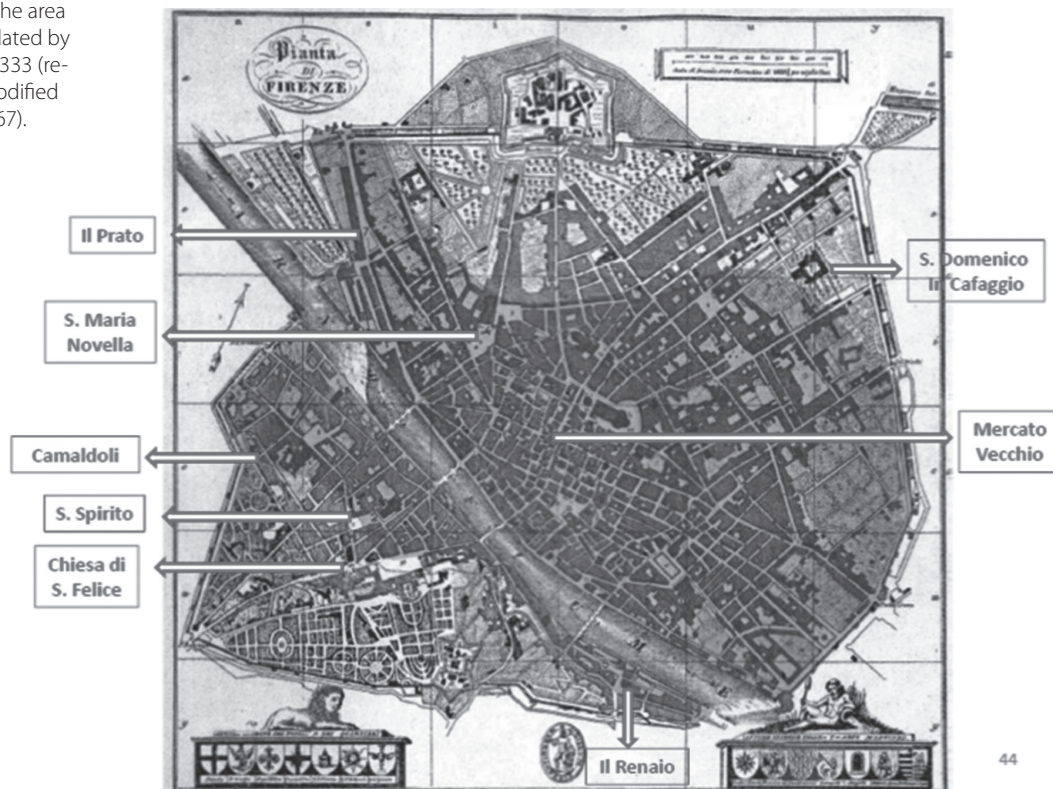
### *Bridges*

Eight bridges connect the right bank of Florence, where the historical city was located, to the left bank, a more popular area until, in the 16th century, Cosimo I (the second Duke of Florence from 1537 to 1569 and first Grand Duke of Tuscany since 1569) moved his residence there. Since all the bridges except the Ponte Vecchio, which dates back to the 13<sup>th</sup> Century, were destroyed by the Germans as they retreated north, the present heritage of the bridges varies with some rebuilding taking advantage of the original designs, rich history, and surviving structural elements and others representing entirely new structures. Six of the bridges are supported by piers of varying number and span length. The bridge piers have always been a factor to be considered in examining the morphology of the river and sediment deposition and scour near pescaie add to the complexity.

## 1.4 The Flood of 1966

Floods have been part of the Arno River history and have been recorded back to the 12<sup>th</sup> Century. According to the Hydraulic Risk Plan of 1996, Florence has suffered from the effects of urban floods that have occurred 56 times since 1177, the most catastrophic ones being those in 1333, 1547, 1557, 1589, 1740, 1758, 1844 and 1966. Figure 1-3 illustrates the extent of the flood of 1333.

**Fig. 1-3.** Map of the area of Florence inundated by the big flood of 1333 (reproduced and modified from Losacco, 1967).



In October 1966, intense precipitation events were recorded everywhere in Italy and several exceptional storms hit several regions. During November 3<sup>rd</sup> and 4<sup>th</sup>, several rain gauges located in the Arno River basin recorded more than 200 mm of rainfall in 48 hours (Malguzzi et al., 2006). Cumulative precipitations occurred between November 3 1966, 9 a.m. and November 5<sup>th</sup> 1966, 9 a.m. and have been plotted by Gazzolo (1969). These exceptional cumulative values did not arise from intense storms (no significant flood occurred in October), but rather from persistent precipitations lasting longer than 10 days with high but not exceptional daily cumulative values.

The storm event started on November 3 in the early morning and, in Tuscany lasted about 26-28 hours. Cumulative daily precipitations on November 4, exceeded 300 mm only at Badia Agnano in the Arno basin (338.7 mm). The peak of the event occurred in the afternoon and in the evening of November 3. It then decayed in the night and increased its intensity again the next morning with peaks lower than those experienced the previous day, with one important exception: the Sieve basin was hit by the strongest storm on November 4.

Florence was flooded in the morning of November 4. The stream overtopped the bank protections initially upstream and then next along the Lungarni, where the banks failed at various sites (Figures 1-4 and 1-5).

Following three weeks of chaos, the figures indicating the extent of the disaster were finally assessed (Alexander, 1980; Italian National Research Council, Research Institute for Geo-hydrological Protection, 2017):



**Fig. 1-4.** The Arno overtops the banks at the level of Piazza Cavallotti, opposite the Biblioteca Nazionale (National Library) on November 4, 1966 (Photo Banchi, reproduced from Principe and Sica, 1967).



**Fig. 1-5.** Lines of equal elevation (above mean sea level) reached by the waters flooded on November 4, 1966 (reproduced and modified from Principe and Sica, 1967).



- *47 deaths in Tuscany (38 in the city of Florence and its province);*
- 800 municipalities affected (including major ones, like Florence and Grosseto);
- 12 000 farms and homes damaged, 50 000 farm animals dead or slaughtered, 16 000 pieces of agricultural machinery damaged or ruined;
- closure of many factories;
- *destruction of works of art, early literature and archaeological exhibits, which will never be forgotten and will stand as a cornerstone event in the history of Florence.*

The exceptional character of the flood experienced in the Arno basin in 1966 was due to three concurrent factors:

- First, the effects of the October event had not vanished yet, so the water levels in the Arno were significantly higher than normal;
- Second, the degree of saturation of the soil subject to the persistent precipitations of the previous month was quite high;
- Third, as discussed above, the intensity of precipitations was exceptionally high.

*The flood that occurred on 4 November, 1966 is the most catastrophic one that has occurred in the city of Florence in terms of damages to cultural heritage and economic activities.* Its emotional impact on the city, Italy and the international community was extremely great (Nencini, 1966).



### **1.5 The review of the International Technical and Scientific Committee (ITSC) of Florence 2016**

#### *ITSC Activity*

Since its initial organization in May 2014, the ITSC has closely examined existing literature on the historic and current flooding situation in Florence, the plans that have been developed to deal with the flood challenge, and the actual progress made in moving ahead in reducing the current risk to Florence. The committee has been aided in this effort by the close cooperation of public officials at all levels in providing reports and summary information and the generous assistance of Italian universities in ensuring open access to library. The ITSC first met in Florence in June 2014 and received briefings from the relevant officials from Florence, Tuscany and the federal government. It was also able to conduct inspections of flood related infrastructure in Florence and the Arno basin above Florence. The ITSC made an initial report to the governments at the end of its first meeting.

During the period between June 2014 and October 2015, the date of the second meeting of the ITSC, reviews were conducted by ITSC members of areas of interest identified during the first meeting. Communication among the members was made possible using the internet and other communications measures. Committee members located in Italy were able to work with their colleagues in their universities and in federal, regional, and local agencies to examine specific issues.

The ITSC met again in person in October 2015 and focused on reviewing the results of the ongoing literature searches and the individual research efforts by committee members. The ITSC was also able to continue its inspection of infrastructure in Florence and to visit the upstream detention areas in Figline and the Bilancino Dam and Reservoir. The ITSC provided a second interim report to the governments of Florence, Tuscany and Italy in December 2015.

Between December 2015 and the submission of this report, the ITSC continued its review of current plans, analyzed models that have been used in plan development, corresponded with members of the relevant agencies on new proposals for flood flow reduction and addressed questions that had been raised within the committee, and in meetings with the agencies. In May 2016, the ITSC began preparation of this report and verification of information that had been previously provided to the ITSC. The pre-publication version of the report was presented to officials from the national and local governments at an International Conference, Florence 1966-2016: Resilience of Art Cities to Natural Catastrophes: The Role of Academies, sponsored by Accademia Nazionale Dei Lincei in Rome from 11-13 October 2016. It was also presented to Florence municipal officials and international mayors at the Conference, Unity in Diversity, sponsored by the City of Florence in Florence on 2-3 November 2016.



## Chapter Two

# Reducing Flood Risk: The Legal Basis

### 2.1 Introduction

Immediately following the 1966 Florence flood, the government of Italy established an Interministerial Committee for the Study of Watercourse Management, the De Marchi Commission, named for its chair, Professor Giulio De Marchi. The Commission's three-year work, which addressed both the Arno and the nation as a whole, introduced a national program of interventions for land protection and led to the enactment in 1989 of the landmark Law 183, which moved Italy towards a more integrated approach to soil and water management and the establishment of river basin authorities.

In order to appreciate the development of planning efforts concerning the Arno Basin since 1966, it is important to understand how legislation concerning flood protection has changed in Italy over the last century. This section provides a synthesis of the principal developments that have affected the flood management of the Arno in Florence.

### 2.2 The Law prior to 1989

A convenient starting step for the synthesis is the fundamental Italian Law on Public Works issued in 1865 (Law n. 2248 of 20 March 1865). This law regulated 'Waters subject to public administration', thus covering hydraulic protection works, works needed for water exploitation (e.g. navigation, water supply, irrigation, etc.) and rules regulating the matter of issuing permits or forbidding interventions on public waters. The matter of 'waters' was treated as a unitary subject.

This important feature was lost in subsequent legislative developments, which, through several distinct laws, complicated and fragmented the previously unitary administrative framework. Various 'categories' of public works concerning waters were introduced (1904), the real estate registry of water uses established (1933), and separate regulation of distinct water uses put into force (e.g. internal navigation, 1913, forests and mountain regions, 1923, sanitation, 1934, dams, 1959, water supply, 1963).

Fragmentation of regulations brought with it the break-up of the associated jurisdiction among *central bodies* (Ministries for Public Works, Environment and Industry), *peripheral Offices* (Water Magistrates and Public Works Offices, namely 'Genio Civile and Provveditorati alle Opere Pubbliche) and *Regions* (since 1970).

### 2.3 The Law n. 183 (1989) and later developments

The enactment of Law n. 183 in 1989 reordered the legislation governing the management and functions of soil protection (*Norme per il riassetto organizzativo e funzionale della difesa del suolo*). This law was a major breakthrough in the Italian legislation concerning public waters. For the first time, the parliament adopted a holistic approach to regulate the whole matter of planning and carrying out interventions connected with protection from natural catastrophes, water utilization and control of water quality. As noted above, a major novel feature of Law 183 (a 'framework law') was the choice of *water basins* as the territorial divisions for all the actions related to soil protection. The entire national territory was sub-divided into hydrographic basins of national, inter-regional and regional relevance. Moreover, this framework law established, for each of the seven water basins of national relevance, a *Water Basin Authority*. The basin authorities are supported by Institutional Committees, Technical Committees and General Secretariats. The *Institutional Committees* were designed to involve in the management of the water basins all the important administrative Institutions (Ministry for Public Works and Infrastructures, Ministry for the Environment, Ministry of Agriculture, Ministry of Cultural Inheritance, and Regions falling in the Water Basin). The *Technical Committees* were established to bring together the scientific community as well as professional expertise in such management. The Authority is 'formally' chaired by the Minister for the Environment.

However, as noted by Urbani (2014), in spite of its declared (and appropriate) goals, this reform was not seen as successful in providing a clear and simplified regulation of the jurisdictions of State and Regions in the management of public waters.

An attempt to overcome these deficiencies in Law 183 was pursued through enactment of Laws 59/1997 and 112/1998, which essentially transferred power from the center to the periphery (Regions, Provinces and Drainage Consortia) leaving, however, the 'planning responsibility' in the hands of Basin Authorities. Essentially, Regions (and further local administrative institutions) were given major tasks:

- Regions are required to transform planned actions into actual interventions, a process that implies revisiting preliminary designs or design ideas, managing the executive design process, obtaining the required authorizations from a number of institutions and, finally, managing the calls for competitive bids.
- Regions and local bodies are given the responsibility to manage existing hydraulic structures.
- Responsibility for controlling and authorizing any intervention that might affect the regime of fluvial waters is also entrusted to Regions.

In 2000 the European Community added its guidance on water management, issuing the *Water Framework Directive* (2000/60/CE), followed in 2007 by a Floods

Directive concerning specifically the assessment and management of flood risks (2007/60/CE). The former directive introduced Water District Authorities, larger scale Authorities that incorporate the Basin Authorities established by Italian Law 183. The Water Framework Directive (WFD) was adopted in Italian legislation in 2006 (DL 152/2006), though the implementation process is yet incomplete (Water Districts have not yet been fully established). Some concepts that were included in the WFD, such as the requirement of issuing regional Master Plans for Water Resources Management, were earlier adopted in Italy through the DL 152/1999. The Floods Directive was adopted in 2010 through the DL 49/2010.

Recognizing that the fragmentation of administrative responsibilities hinders the rapid implementation of actions aimed at flood risk mitigation, and that attempting to reorder the whole organizational structure would be difficult, the Italian Government established a hydrologic disaster oversight element in the Prime Minister's Office (*Struttura di missione contro il dissesto idrogeologico, art.10 law 116/2014*). This element was given the task to cooperate with all the involved institutions to speed up planning, preparation and funding of interventions needed to overcome most critical disaster-related situations, notably in metropolitan areas.

Finally, beginning in 2015, *Program Agreements* between Regions and the Minister of Environment are expected (art.7 Law 164/2014) to be used to co-fund extraordinary, integrated interventions related to risk mitigation, biodiversity recovery and relocation of buildings located in risky areas.

## 2.4 Fragmentation and inefficiency

The above survey of Italian legislation identifies the *fragmentation* of administrative responsibilities and *lack of coordination mechanisms* among institutions pursuing those actions needed to manage flood risk and soil protection. According to P. Urbani (2014), a recognized authority in the field of Italian Administrative Law, there appears to be an absence of recognized leadership in the process of planning and realization of interventions and the actual role of Water Basin Authorities (now Districts) is residual. Basin Plans encounter strong difficulties in the approval stage, the planning of works is most often superficial and proves irrelevant to the actual design of interventions, which no longer involve Water Basin Authorities. Urbani (2014) points the need to reorder the organizational structure to remove fragmentation and lack of coordination and the persistent approach of allocating funds on an emergency basis rather than as a result of reasoned planning. *The ITSC concurs in this opinion*



## Chapter Three

# The 1996 Hydraulic Risk Plan of the Arno River Basin Authority

### 3.1 Introduction

Between 1966 and 1996, little action was taken to reduce the flood risk on the Arno and local flood protection efforts were not part of a comprehensive plan. The establishment of the Arno River Basin Authority under Law 183 led to the development, in 1996, of a Hydraulic Risk Plan (HRP) for the Arno Basin containing the measures required to reduce the vulnerability of the basin to flooding from the Arno River. The ITSC reviewed this plan to determine how its implementation would affect flood risk reduction in the Florence region.

### 3.2 Hydraulic risks in the Arno Basin and Florence

In its introduction to the 1996 Plan, the River Basin Authority expressed major concerns about the hydraulic risks facing the city of Florence. [This is the only official document found by the ITSC that identifies these risks]. The plan states that:

- Florence has suffered from the effects of urban floods that have occurred 56 times since 1177, the most catastrophic ones being those in 1333, 1547, 1557, 1589, 1740, 1758, 1844 and 1966.
- The river is unable to contain floods characterized by recurrence intervals ranging, at different locations, from a few years to 200-years.
- In 1966 at the Florence gage station, the estimated discharge exceeded 4 000 m<sup>3</sup>/s with a conveyance capacity in the urban reach slightly larger than 2 500 m<sup>3</sup>/s, although the flood wave had already undergone significant attenuation due to extensive flooding in the upstream reach (especially Casentino and Valdarno), amounting to a few tens of Mm<sup>3</sup>.
- The post-1966 lowering of the aprons at Ponte Vecchio and Santa Trinita Bridge along with heightening of the bank walls allow (in 1996) for a discharge of 3 100 m<sup>3</sup>/s to be safely contained within the banks (and up to 3 400 m<sup>3</sup>/s with no safety allowance).
- *Under the 1996 plan, Florence would still be at risk to a 1966 flood.* Also at risk are the upstream reaches of the river (Casentino and upper Valdarno) as well as the downstream reach (middle-lower Valdarno) and the city of Pisa,

even taking into account the Pontedera floodway which was designed to relieve pressure on Pisa.

The Plan identified the principal causes of this situation:

- Inadequate hydraulic protection works and total absence of storage works.
- Urbanization of areas formerly employed for agricultural purposes, a process that developed primarily after 1967 and was continuing in 1996.
- Abandonment or replacement of forestry-agricultural activities carried on in hilly regions.
- Insufficient maintenance of hydraulic works and of river channels.

### 3.3 Floods in the Arno Basin: historical analysis

The plan describes in some details various historical floods that have occurred in the Arno Basin. They also are described in Appendix C of this report. The plan also refers to some notable historical facts concerning actions taken to protect basin cities from flooding of the Arno River or to exploit it for a variety of purposes. In particular:

- Starting from the 14th century, controlled flooding of the Arno was induced through diversions, ‘trabocchi’, to protect the city of Pisa. One of these (trabocco di Fornacette) was still functioning in 1745 and diverted Arno waters into a swampland (Padule di Stagno) through a canal (canale Arnaccio). (Later, the grand duke preferred to fill the swampland in order to widen the cultivated area, thus showing an attitude towards hydraulic risk comparable to modern times!)
- In 1606, to protect the city of Pisa from flooding and the Arno outlet from silting up, the outlet was moved northward through the so called “taglio Ferdinando” (from the name of Ferdinando II de’ Medici).
- Starting from the 14th century, the Arno River and some of its tributaries were channelized, thus reducing significantly their widths (in some cases from 1-2 km to few tens of meters such as in the Montelupo – Empoli – Fucecchio area where, originally, the river was clearly braided). Other fluvial reaches were straightened by means of various artificial meander cutoffs. The aim was to increase channel conveyance but also allow for navigation and transport of floating material, most notably wood coming from the forests of Casentino and Valdarno (a practice that lasted until 1863). Channel modifications did lead to increased flooding, which, however, was compensated by the fact that, at that time, the floodplain, especially in the lower Valdarno, was used for agricultural purposes.
- The river was often subdivided into two or three channels (called *bisarni*) upstream to cities such to distribute the flood discharge among various channels which did re-join downstream.
- The flood discharge of the Arno River increased further (by 350-650 m<sup>3</sup>/s) as the Medici family decided to reclaim the Chiana valley. Eventually, the Chiana waters, formerly debouching into the Tiber River, were diverted into the Arno River.



The Plan concluded that, because of the inundation of the floodplain along the Arno River, the flood peak was progressively reduced; otherwise it might have theoretically reached 7 000 m<sup>3</sup>/s at Pisa. *Moreover, the plan clearly stated that, protection from a catastrophic event might need to store in the Arno Basin a water volume as large as 350-400 Mm<sup>3</sup>, with 200 Mm<sup>3</sup> needed upstream of Florence. The Plan then stated that meeting those objectives, would require use of a portfolio of measures.*

### 3.4 Previous solutions proposed to mitigate the hydraulic risk in the Arno River

The 1996 Plan provided a discussion of previous solutions proposed to mitigate the hydraulic risk in the Arno River and summarized the few structural works completed before 1996, only two of which mitigate the risk of flooding in Florence:

- Lowering of the aprons of Ponte Vecchio and S. Trinita Bridge. Here, the Plan states that, according to official data, the conveyance capacity of the Arno River in the urban reach has increased from 2 500 m<sup>3</sup>/s (in 1966) to 3 100 m<sup>3</sup>/s (3 400 m<sup>3</sup>/s with no safety allowance) (Sect. 3, p. 26). *However, calculations reported in elsewhere in the Plan (see Sect. 5.2) suggest that the maximum discharge safely contained within the banks does not exceed 2 800 m<sup>3</sup>/s.*
- Construction of the Bilancino dam on the Sieve River (close to completion in 1996). Storage in Bilancino is to be used mainly for water supply to the city of Florence and to provide for a minimum flow during the dry season.

The plan indicated that other works were constructed along the reach below Florence:

- Pontedera floodway (Fig. 3-1), designed and initiated before 1966: maximum discharge 1 400 m<sup>3</sup>/s, actual discharge (in 1996) 1 000 m<sup>3</sup>/s due to silting and lack of maintenance.
- A bypass canal on the Elsa River at Castelfiorentino.
- Bed stabilization in the Montelupo – Pontedera reach, pursued by the construction of four weirs

**Fig. 3-1.** The Pontedera floodway delivers up to 1 400 m<sup>3</sup>/s directly to the Tyrrhenian sea, thus mitigating the risk that the Arno may flood the city of Pisa.



### 3.5 Goals and strategy of the HRP

The stated goals of the HRP are quite generic:

- Reducing the hydraulic risk, i.e. the frequency and intensity of flooding, and
- Reducing the resultant damage to people, environment and local.

*It should be noted that cultural heritage does not receive any specific attention in the goals of the HRP. The target events in the HRP for risk mitigation were the 1992 event and the much more severe 1966 event, but these events were not associated with specific recurrence intervals.*

The goals were to be achieved through a strategy calling for a series of measures which would be completed within 15 years:

- Increasing the storage capacity for flood waters in the basin.
- Increasing the conveyance capacity of the river.
- Strengthening the levee system.
- Improving control of and response to flood events.

Periodic updates of the HRP were to be prepared 'at least every three years'.

### 3.6 Supporting data collection and modeling

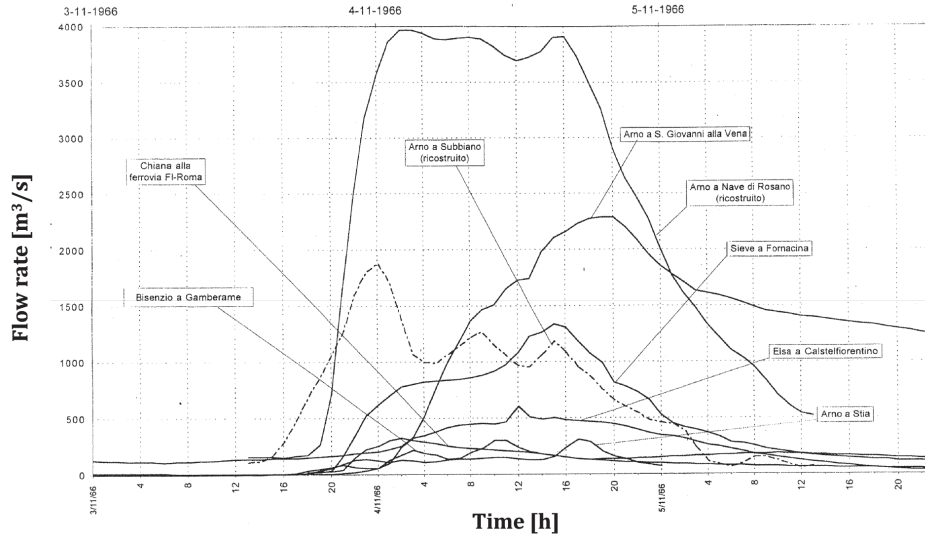
#### *Data*

Data collected to support plan development included:

- *Hydrometric data.* Data were recorded on major flood events at 14 stations, six of them on the Arno River (Figure 3-2). *Data had two main shortcomings: monitoring stations did not work continuously, whence prolonged gaps were present in the records; moreover, reliable rating curves were not available for the stations.*

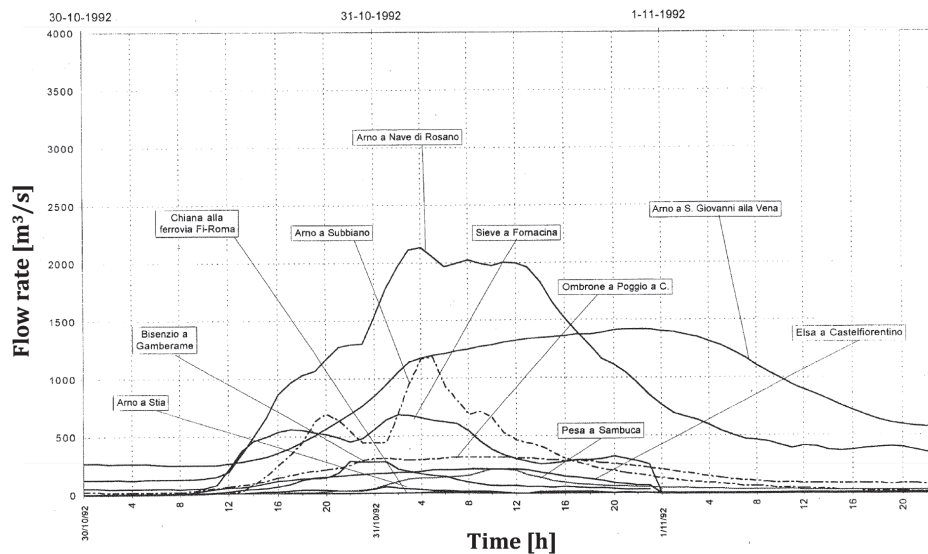
**Fig. 3-2.** Sites of the six hydrometric stations located on the Arno River.





**Fig. 3-3.** Hydrographs of the 1966 event at different stations along the Arno River and some of its major tributaries (from 1996 Hydraulic Risk Plan).

Figures 3-3 and 3-4 provide two examples of hydrographs recorded (and partly reconstructed) for the two events taken as reference events for the Arno Basin. Note that, in the 1966 event the peak of the Sieve tributary lagged behind the peak in the Arno, whilst it was nearly in phase in 1992.



**Fig. 3-4.** Hydrographs of the 1992 event at different stations along the Arno River and some of its major tributaries (from 1996 Hydraulic Risk Plan).

- *Geometry of cross sections.* 1000 cross sections were surveyed between the Levane dam and the sea at different times, 620 surveyed for the Plan in the reach upstream of Levane Dam.
- *Daily precipitation data.* Data were collected for the annual peak flow event in the period 1943-1993, for all the rain gauges working in the Arno River Basin at the time each event occurred. The data were collected by the National Hydrographic



service and a relevant effort was made to make sure that all the existing observations had been stored. Mean areal precipitation was computed for each event using regression techniques. The plan reports that a digital elevation model in raster form with a 400x400 meters grid cell was used to compute the areal precipitation, but it does not report any more specific detail. For the two events that occurred in November 1966 and October 1992 an effort was made to collect rainfall data at 10 min time resolution. *Historical maps of flooded areas*. Maps were collected for several past events for which information was available in the literature (see Appendix C of this report).

- The Plan reports that comparison between surveys performed in the previous 40 years suggested that the bed had experienced a general degradation, though this observation was not supported by any quantitative plot. The process turned out to be weak between the Levane dam and Figline but increased downstream, reaching local peaks of several meters. Overall, the increase in channel volume was roughly 12 Mm<sup>3</sup>.

### *Modeling*

The Plan did not give many details of the characteristics of the hydrologic and hydraulic models employed to simulate flood formation and propagation in the Arno Basin. However, from the information provided, one may infer that:

- The rainfall-runoff transformation was modeled through a semi-distributed hydrological model, by dividing the catchment in 30 sub-basins, corresponding to the main tributaries. A raster model with resolution 400x400 meters was applied to each sub-basin, therefore matching the resolution of the DEM. At each DEM cell, they applied (1) an infiltration model to compute the net rainfall, (2) a linear reservoir model to compute the local contribution to the runoff production, and (3) a kinematic model to transfer the runoff along the hillslopes and the river network towards the closure of the considered sub-basin. The model ran at hourly time step through the following operation scheme:
  - a) Local rainfall was computed for each considered event according to the above described regression technique.
  - b) Net rainfall was computed through the infiltration model.
  - c) Local contribution to runoff was computed.
  - d) The kinematic model was applied to transfer the local runoff to the outlet.
  - e) The transferred contributions were summed up to obtain the river flow at the basin outlet.

### *Calibration and simulation of the 1992 and 1966 events*

Calibration was performed by matching observed and simulated river flows. The hydraulic model was 1-D and unsteady but was able to account for the exchanges between the channel and the adjacent areas, treated as static storage. Moreover, tributaries were included through their calculated or recorded hydrographs at confluences. The downstream boundary condition consisted of an assumed rating curve.

To calibrate the model, simulated hydrographs for the two reference events were compared with recorded hydrographs at the Levane and La Penna dams, as well as at the hydrometric stations.

*The plan reports that the model parameters were expected to attain physically meaningful values, but this expectation is unrealistic and parameter values are not provided in the plan. The plan states that accepted relative errors for discharges and free surface elevations were 5%. It is not clear whether this level of reliability was attained. Also, the plan does not provide any other performance measure. Moreover, it is not clear whether validation was performed (it seems not). No measure of uncertainty was provided [in the 1990s, uncertainty assessment techniques were not well developed]. It is clear that, based on similar experiences, the uncertainty in simulation may be very significant, with relative errors of the order of magnitude of 20-40% for the peak flows.*

*In addition, it should be noted that:*

- *The cross sections employed in the simulations differed from those existing at the time of the 1966 and 1992 flood events.*
- *Calibration did not lead to estimated values of the calibrated parameters independent of the specific event. In other words, the Plan uses an event-based calibration technique.*

The HRP points out that by 1996, downstream of the Levane and La Penna dams, part of the floodplain naturally inundated by floods was no longer available for this purpose, as, at the time the Plan was completed, the floodplain was protected by levees.

*This loss of temporary storage has increased the vulnerability of the downstream reach to intense events. As a result, under the HRP, the lower Valdarno and the Florentine plain (including Florence) play the role of expansion areas for flood propagation.*

*The flow of the Arno River in the urban reach*

A steady state fixed bed simulation of the flow in the urban reach of the Arno River was performed in order to ascertain the conveyance capacity of the river, accounting for the morphological variations that had taken place since 1966, as shown by the most recent surveys available at that time. Simulations covered the reach between the Rovezzano weir and the Cascine weirs, of length 8.5 km. In this reach, a comparison between surveys performed in the period 1966-1978 and those performed in 1990 showed *bed degradation*, with an average of two meters in the reach Rovezzano – S. Niccolò and four meters between S. Niccolò and Ponte alle Grazie; *weak degradation and even aggradation* between Ponte alle Grazie and Ponte alla Carraia; again, *degradation* between Ponte alla Carraia and Cascine weirs with an eight meter peak downstream of Santa Rosa weir.

No detail was given about the software employed in the simulation. The HRP provided no information about how energy losses experienced by the flow at the historical bridges were estimated nor about the modeling assumptions applied in analysis of oblique weirs. The simulations indicated that:

- The maximum safe discharge in the urban reach (with 1 m safety allowance) should not exceed 2 800 m<sup>3</sup>/s.
- The maximum discharge contained between the banks of the river in the urban reach (with no safety allowance) should not exceed 3 200 m<sup>3</sup>/s.

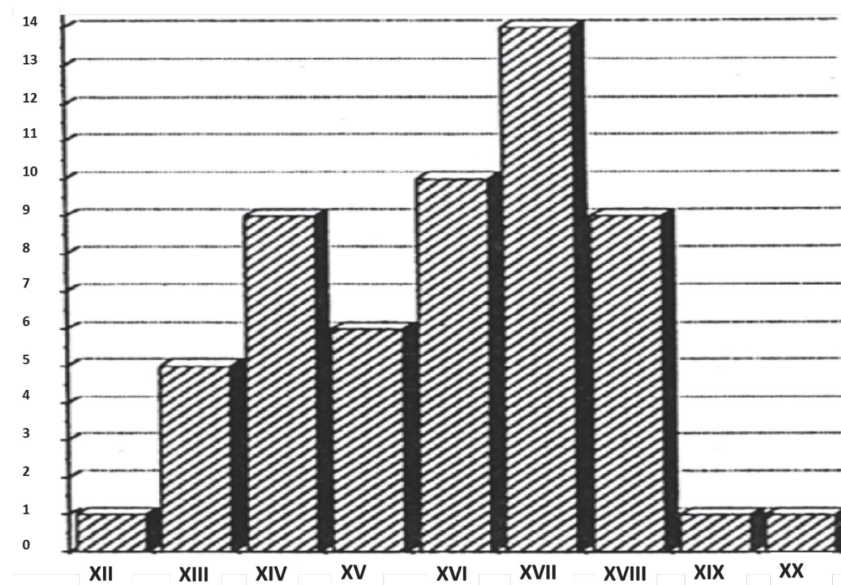
### 3.7 Analysis of the upper part of the watershed

The HRP also analyzed briefly the extensive modifications undergone by the upper portion of the watershed throughout the centuries. In particular:

- The Plan suggests a correlation (previously hypothesized by Targioni Tonzetti) between deforestation pursued since the 16th century and the increased frequency of floods experienced by the basin in those centuries (Figure 3-5). While deforestation may have undoubtedly played a role, climatic reasons also must have contributed to enhancing flood frequency, as deforestation did continue in the 19th century which experienced only one major flood.
- Deforestation was mainly associated with the transformation of forested areas into lands used for agricultural purposes as well as pastoralism. An extensive restoration activity was pursued in the upper watershed at the beginning of the 20th century after the First World War. The construction of a number of hydraulic control structures and reforestation interventions was funded by the Law n. 3267 (1923), which was very effective. The Plan lamented that this successful activity ceased around the 1960s and the absence of maintenance had left most of the works in a poor state.
- The Plan also provided an overview of the works requiring maintenance and of the further works needed in order to improve the control of erosion processes and sediment transport.

The philosophy of the Plan was to give priority to the temporary storage of flood waters in areas of low environmental value adjacent to the main course of the Arno and to some of its tributaries, which are still potentially available for controlled inundations. The main structural measures upstream of Florence foreseen by the HRP included:

**Fig. 3-5.** Number of major floods of the Arno River per century starting from the 12th century (modified from 1996 Hydraulic Risk Plan).



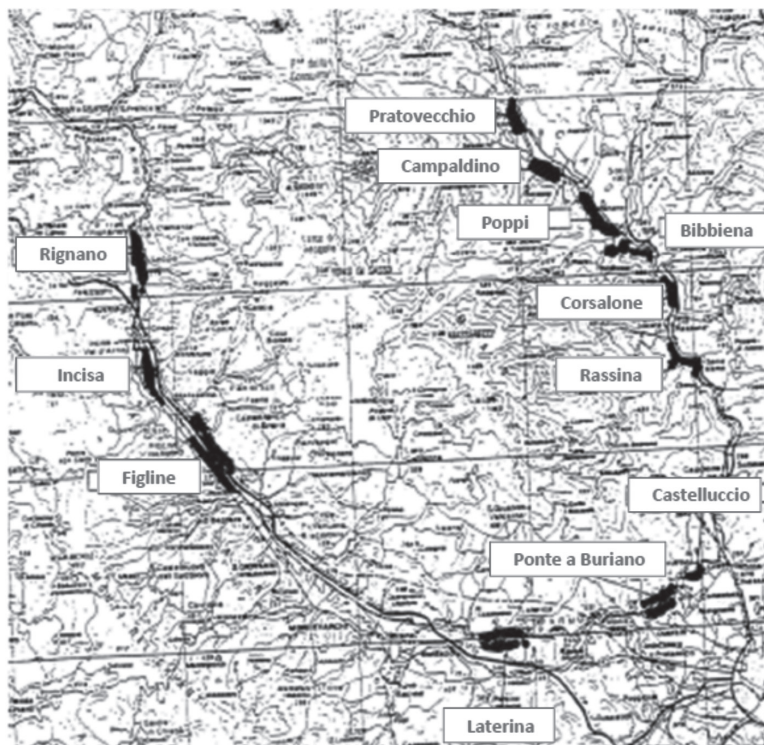
*Flood detention areas along the Arno River*

Flood detention areas are made available for controlled inundation. The structure of a flood detention area normally consists of a spillway with fixed sill, typically aligned with the stream, through which water spills over into a lateral reservoir bounded by levees and equipped with a downstream outlet. In some cases (e.g. Poppi), weirs are also inserted in the river such to generate a backwater effect able to increase the head over the sill and enhance the spillway efficiency.

Upstream of Florence, the Plan foresaw the construction of the following structures (with storage capacity and cost in 1996) located along the Arno River at the sites depicted in Figure 3-5.

- Pratovecchio: 6.1 Mm<sup>3</sup>, 21.35 GL (1 GL = 1 Billion liras)
- Campaldino: 4.33 Mm<sup>3</sup>, 15.22 GL
- Poppi: 6.63 Mm<sup>3</sup>, 23.1 GL
- Bibbiena: 2.55 Mm<sup>3</sup>, 8.75 GL
- Corsalone: 1.87 Mm<sup>3</sup>, 6.3 GL
- Rassina: 1.59 Mm<sup>3</sup>, 5.6 GL
- Castelluccio: 2.13 Mm<sup>3</sup>, 7.7 GL
- Figline: 16.59 Mm<sup>3</sup>, 58.1 GL
- Incisa: 6.53 Mm<sup>3</sup>, 22.75 GL
- Rignano: 12.38 Mm<sup>3</sup>, 43.05 GL

*These storage areas would provide a stored volume of 60.7 m<sup>3</sup> for a total cost of 212 GL. Using the ISTAT (National Institute for Statistics) conversion procedure (2011) the 2016 estimated cost would be about 148 M€.*



**Fig. 3-6.** The plot shows the areas adjacent to the Arno in Casentino and Valdarno superiore chosen for controlled inundation during flood events (modified from 1996 Hydraulic Risk Plan).

Note that Figure 3-6 includes two more structures, proposed by HRP to replace the heightening of La Penna dam, provided opposition by the province of Arezzo would prevail on considerations of flood protection: Ponte a Buriano: 8.21 Mm<sup>3</sup>, 28.73 GL, and Laterina: 6.24 Mm<sup>3</sup>, 21.84 GL

### Dams

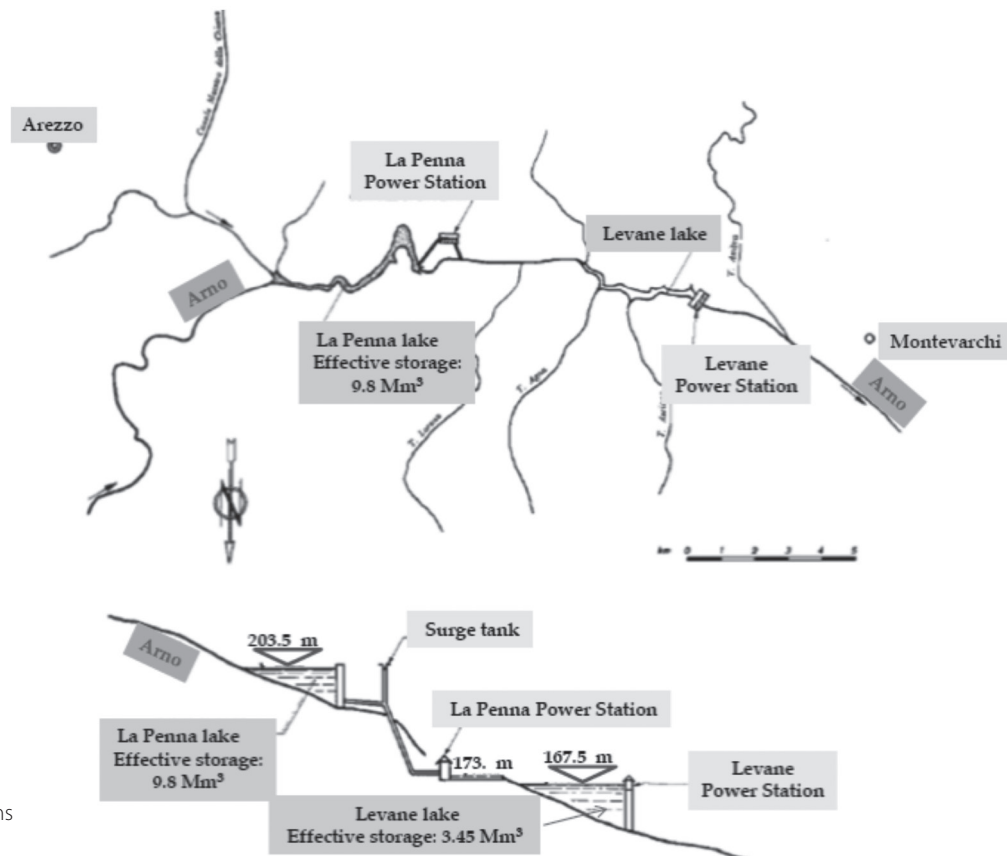
The HRP initially proposed three principal dam-related measures:

- Heightening of the ENEL dams of La Penna and Levane on the Arno River, and
- Completion of the Bilancino dam on the Sieve tributary.

### La Penna

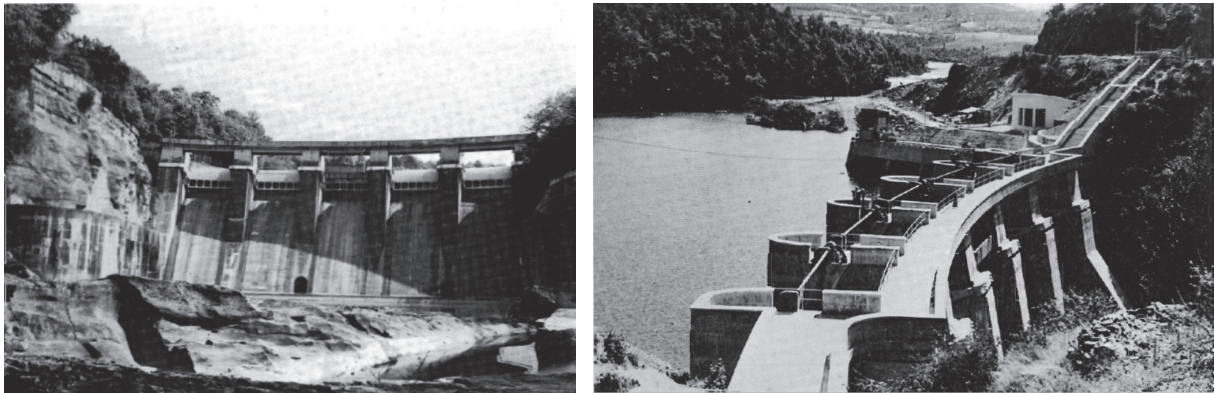
The two dams of La Penna and Levane and their lakes are located at the junction between the Casentino and Upper Valdarno sub-basins (Figure 3-7) about 15 km downstream of the city of Arezzo.

The *La Penna* reservoir is used for daily-weekly regulation of La Penna Power Station. It drains a catchment area of 2 251 km<sup>2</sup> and has a total storage capacity of 16 Mm<sup>3</sup> with an effective capacity of 9.8 Mm<sup>3</sup>. The reservoir has partially silted up and has caused a reduction of the storing capacity of the reservoir. Details of the dam are



**Fig. 3-7.** Sketch of La Penna and Levane artificial lakes and dams (modified from ENEL, 1980).





found in the comprehensive publication of ENEL (1980) reporting the characteristics of all the Italian dams for hydroelectric use.

La Penna dam is a gravity arched overflow structure in concrete (Figure 3-8), with height, from the crest to the downstream bed, of 32 m and length of the arch crest of 101 m. The dam is equipped with a surface spillway, with a maximum discharge capacity of 1 670 m<sup>3</sup>/s, a diversion bottom outlet with a discharge capacity of 380 m<sup>3</sup>/s and a bottom outlet with a discharge capacity of 250 m<sup>3</sup>/s.

The original Plan proposal consisted of heightening the dam, such that:

- the 'regulation' for hydroelectric purposes could be kept at the present elevation of 203.5 m;
- the water level could be raised to 206.0 m, with additional 10 Mm<sup>3</sup> made available for flood protection;
- in emergency, the water level could be further increased up to 209.0 m providing for a further storage volume of 15 Mm<sup>3</sup>.

**Fig. 3-8.** The La Penna dam: view from downstream (top) and from the right bank (bottom) (reproduced from ENEL, 1980).



**Fig. 3-9.** The Buriano Bridge connects the banks of the Arno River along the Cassia Vetus, the old road which connected Rome to Florence, crossing Arezzo. It may possibly incorporate a preexisting Roman bridge. Buriano Bridge and Ponte Vecchio are the only historical bridges remaining along the course of the Arno River. The heightening of La Penna dam would lead to its submergence for less than 24 hours during exceptional floods (recurrence time of the order of a century) (Reproduced from 1996 Hydraulic Risk Plan).

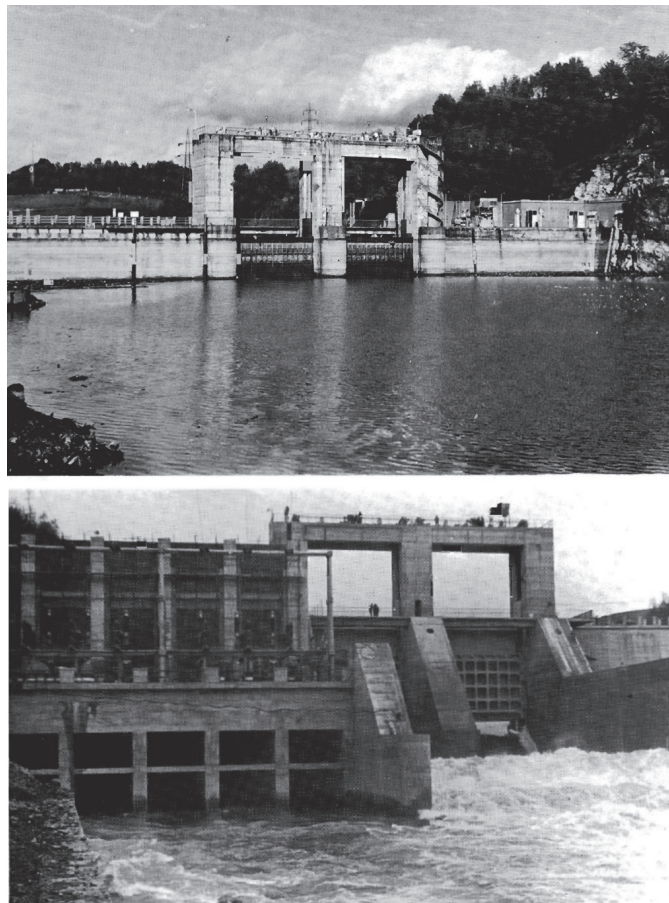
This would require restructuring the present dam, building a new spillway as well as a second bottom outlet, such to increase the outlet discharge up to 1 350 m<sup>3</sup>/s. Moreover, the town of Ponte Buriano would require protection from inundation and Buriano bridge (Figure 3-9) would be submerged during exceptional flood events.

Finally, the Plan included the removal of part of the silt stored behind the dam, which interferes with the bottom outlets.

The Province of Arezzo opposed the above solution and proposed to replace heightening of La Penna dam by the construction of two new dams:

- a second dam on the Sieve River at Dicomano, with a storage capacity of 15 Mm<sup>3</sup>, such that the 1966 flood peak (1 340 m<sup>3</sup>/s) could be reduced by 400 m<sup>3</sup>/s;
- a dam on the Ambra tributary at Castello di Montalto, with a storage capacity of 8 Mm<sup>3</sup>.

*Due to Arezzo's opposition, the final version of the Plan formally adopted by the Arno Basin Authority (July 5, 1999) and approved by the President of the Council of Ministers (November 5, 1999) did not include heightening of La Penna dam but only the construction of its new bottom outlet and the partial removal of silts deposited in the reservoir.*



**Fig. 3-10.** The Levane dam: (top) upstream view; (bottom) downstream view (reproduced from ENEL, 1980).



*Levane*

The Levane dam complex provides daily regulation of Levane Power Station. It drains a catchment area of 2 407 km<sup>2</sup> and has a total storage capacity of 4.9 Mm<sup>3</sup> with an effective capacity of 3.45 Mm<sup>3</sup>. The dam (Figure 3-10) is a gravity straight overflow structure in concrete, with height, from the crest to the downstream bed, of 36 m and length of the crest of 35.4 m. The dam is equipped with a surface spill-way and a bottom outlet.

The Plan proposal consisted of heightening the dam, such that:

- the 'regulation' for hydroelectric purposes would be kept at the present elevation of 167.5 m;
- the water level of maximum storage would be raised up to 172 m, with additional 10 Mm<sup>3</sup> made available for flood protection.

This would require restructuring the present dam, construction of protection works for the town of Laterina and removing part of the silt stored behind the dam.

The Plan estimate for the cost of restructuring the two dams amounted to 325 GL of 1996, equivalent to 230 M€. In the finally approved Plan, which did no longer include the heightening of the La Penna dam, the cost was reduced to 114 GL of 1999, equivalent to 76 M€ (2011).

The expected benefit was also reduced as the volume available for storage of flood waters decreased from 43 Mm<sup>3</sup> to 20-22 Mm<sup>3</sup>.

**Fig. 3-11.** The Bilancino earthfill dam in the upper Sieve basin (Photo reproduced from Caporali et al., 2005).



### *Bilancino*

The Bilancino reservoir (Figure 3-11) is a multipurpose reservoir mainly designed for water supply to solve the problems of water demand for the city of Florence and provide the minimum water discharge needed by the Arno River in the dry period (June to September) for environmental purposes. The latter was estimated at the time of the Plan to be approximately  $8 \text{ m}^3/\text{s}$ , taking account of the fact that  $2.5 \text{ m}^3/\text{s}$  are withdrawn by the aqueduct. Note that the natural flow in the dry season does not exceed an average of about  $3.5 \text{ m}^3/\text{s}$ . These values have been modified since the Plan publication.

According to the Plan, out of the total storage of  $84 \text{ Mm}^3$  generated by the earth fill dam (Figure 3-11),  $69 \text{ Mm}^3$  are used for the above regulation and  $15 \text{ Mm}^3$  are employed to reduce the peak discharge of the Sieve tributary which affects significantly the flood propagation in the Arno river (but see sect. D.3 for further information).

## 3.8 Structural measures foreseen for the Arno tributaries

The Plan also considered various structural measures tributaries of the Arno River. They include:

- Improvements of the conveyance capacities which, for some of them, are locally insufficient.
- Construction of further detention areas.
- Construction of further dams.

In particular, upstream of Florence, the Plan called for works on four tributaries:

### 1. *Corsalone*

Two alternative solutions are considered:

- Dam for flood mitigation:  $6 \text{ Mm}^3$ , 45 GL (31.5 M€).
- Flood detention area:  $1.5 \text{ Mm}^3$ , 5.5 GL (3.85 M€).

### 2. *Canale Maestro della Chiana*

Two alternative solutions are again considered:

- Increasing the conveyance capacity of the channel through widening and levee construction: 1.5 GL (1.05 M€).
- Flood detention area:  $9.3 \text{ Mm}^3$ , 35 GL (24.5 M€) (estimated reduction of the flood peak in the tributary, around  $290 \text{ m}^3/\text{s}$ ).

### 3. *Ambra*

Solutions for flood risk mitigation in the Ambra sub-basin have been proposed in the past. Evangelisti proposed to construct a dam located close to the confluence between Ambra and Arno: with a dam height of 25 m the volume available for storage would be  $22 \text{ Mm}^3$ , providing a significant reduction of the flood peak

discharged into the Arno River. Unfortunately, this solution is no longer feasible due to extensive use of the areas that would be impacted for agricultural, urban and industrial purposes.

A smaller reservoir, later proposed by Chiarini (in a study commissioned by the province of Arezzo), is located at Castello di Montalto, at the closure of the mountain part of the basin. With a dam height of 24 m the volume available for storage would be 8 Mm<sup>3</sup>, 6 of them needed to contain the 200-year flood in the Ambra River. This would be insufficient, however, to have a significant effect on flood propagation in the Arno River. The Plan thus identifies a number of smaller areas for flood detention located in the lower part of the basin. The total volume storage available was estimated at 8.5 Mm<sup>3</sup>, sufficient, according to the Plan, to reduce the peak discharge into the Arno River for a 200-year flood from 790 m<sup>3</sup>/s to 220 m<sup>3</sup>/s.

A gross estimate of the cost of all the above works amounts to 45 GL (31.5 M€).

#### 4. *Sieve*

Two alternative solutions are again considered:

- A sequence of small flood detention areas (storage 8.6 Mm<sup>3</sup>) plus a reservoir located at Le Motte (storage 2.8 Mm<sup>3</sup>); cost 47 GL (32.9 M€).
- A sequence of small flood detention areas (storage 8.1 Mm<sup>3</sup>) plus a larger reservoir located at Dicomano (storage 15 Mm<sup>3</sup>); cost 118.5 GL (83 M€).

The estimated reduction of the peak of the hydrograph recorded for the 1966 flood (1 340 m<sup>3</sup>/s) due to the above interventions, according to the Plan, would be quite significant, but no action has taken place.

### 3.9 The HRP strategy

The original 1996 Plan called for a general project (with four possible variants), to be implemented within 15 years. The implementation of the general project (or any variant) would proceed in three distinct phases. The first phase should allow the Arno River and its main tributaries to contain the 1992 flow event safely. At the end of the third phase containment of a 1966-like event was sought.

Considering only works upstream of Florence, the general project included:

#### Phase 1

- Dams:
  - Heightening of La Penna Dam (209 m); Heightening of Levane Dam.
- Flood Detention areas along the Arno River:
  - Campaldino, Poppi, Figline, Incisa, Rignano.
- Flood Detention areas along tributaries:
  - Ambra (50 %), Sieve (50 %).

**Phase 2**

- Dams:
  - None.
- Flood Detention areas along the Arno River:
  - Pratovecchio, Bibbiena, Corsalone, Rassina, Castelluccio.
- Flood Detention areas along tributaries:
  - Ambra (50 %), Sieve (50 %).

**Phase 3**

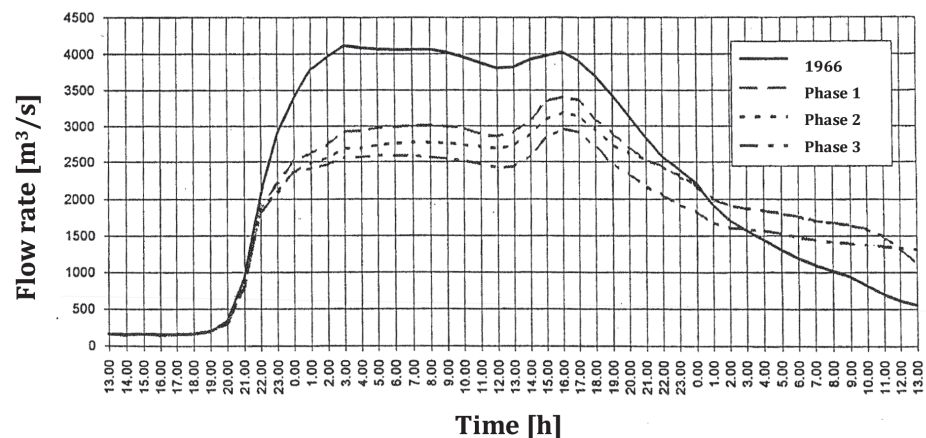
- Dams:
  - None.
- Flood Detention areas along the Arno River:
  - None.
- Flood Detention areas along tributaries:
  - Corsalone (100%), Chiana (100%).

The public debate following the presentation of the Plan led to some modification of the original strategy. The measures foreseen by the Plan were distinguished into Class A measures (ready for design) and Class B measures (needing supplementary investigations before proceeding to design and realization).

*Except for Levane dam, all the dam interventions originally considered in the Plan (heightening of La Penna, construction of new dams along the tributaries Corsalone, Ambra and Sieve at Dicomano) as well as the Laterina detention area were not included in the list of interventions in Class A.*

### 3.10 Hydraulic simulations to estimate the beneficial effects of the works in the Plan

The 1996 Plan included an estimate of the beneficial effects of the works foreseen in the plan. Figure 3-12 provides a comparison, reported in the Plan, between the



**Fig. 3-12.** Comparison between the hydrograph observed at Nave a Rovezzano in the 1966 event and those predicted at the end of each planned phase (modified from 1996 Hydraulic Risk Plan).

hydrograph observed at Nave di Rovezzano in the 1966 event and those predicted at the end of each planned phase.

The comparison indicates that

- At the end of the first phase, the peak of the 1966 flood at Nave a Rovezzano would decrease from 4 000 m<sup>3</sup>/s (estimated for the actual 1966 event) to 3 400 m<sup>3</sup>/s. According to the simulations, 50% of the works on the tributaries Ambra and Sieve, would give rise to a reduction of the flood peak at Nave a Rosano of 150 m<sup>3</sup>/s. The remaining reduction (450 m<sup>3</sup>/s) would arise from the effects of storage in the two dams and in the detention areas of the upper Valdarno (Figline, Incisa, Rignano).
- At the end of the second phase, the peak of the 1966 flood at Nave a Rovezzano would be further reduced reaching about 3 200 m<sup>3</sup>/s and the works on the tributaries, Ambra and Sieve, would be responsible for a total reduction of the flood peak at Nave a Rosano of 250 m<sup>3</sup>/s. Note that this implies that, according to the simulations, the effect of the whole set of flood detention areas in the Casentino region on the reduction of peak floods in Florence is fairly small (around 100 m<sup>3</sup>/s).
- At the end of the third phase, the peak of the 1966 flood at Nave a Rovezzano would be slightly less than 3 000 m<sup>3</sup>/s. This further reduction of the flood peak in Florence results from the effect of flood detention areas in the Corsalone tributary and regulation of the Chiana Canal.

*Attainment of the proposed reductions depends on the assumption of heightening of La Penna Dam. The total cost of the above program concerning only works located upstream of Florence is about 500 M€*

*To the ITSC's knowledge, the construction of Bilancino reservoir is the only work with some impact on the city of Florence and included in the Plan that has so far been completed.*





## Chapter Four

# The 2005 Hydro-Geological Plan (PAI – Piani di Assetto Idrogeologico)

### 4.1 Introduction

The PAI represents the outcome of the effort of AdB to update the 1996 Hydraulic Risk Plan, formally adopted in 1999, in compliance of the new legislation, most notably the Law n. 180. The Introduction to the PAI is devoted to illustrating the content of the Plan, i.e. its objectives, its organization, its relation to the legislation. The main point stressed in this introduction is an emphasis on the novel features of PAI with respect to the previously adopted 1996 Hydraulic Risk Plan. After discussing the developments undergone by the legislation on this subject (see Sect. 2.1 of this report), the PAI describes the content of Law n. 180 (1998), called Sarno Law, issued after the catastrophic mudflows occurred in the Sarno area on May 5, 1998.

This Law (and the guidelines that followed a few months later) was the response of the State to this catastrophe. It provides a methodology to be followed in order to map the areas ‘at risk’, distinguishing between ‘hydraulic risk’ and ‘risk of landsliding’. The proposed methodology employs the scientific definitions of vulnerability and risk and provides a rational framework to define the interventions required to insure protection of the territory at risk. A deadline (June 30, 1999) was also prescribed for AdB’s to adopt their Plans.

This deadline was postponed to June 30, 2001 by the Law n. 226 (1999). Moreover, Art. 1 of the new Law prescribed that AdB’s were allowed to approve ‘Exceptional Plans’ aimed at removing the most risky situations, involving human life, economic activities as well as environmental and *cultural heritage* (with priorities for areas where state of emergency had been declared). A number of ‘exceptional tools’ were authorized in order to implement these ‘Exceptional Plans’: in particular, Regions were allowed to assume multi-year expenditure programs and hire technical personnel if needed to complete the mapping process of risky areas.

The philosophy of ‘Exceptional Plans’ was clearly not supported in the Introduction, which emphasized the ‘reductionist’ viewpoint underlying the Law n. 180, as opposed to the ‘holistic’ viewpoint of Law n. 183 that had established the Water Basin Authorities.

The Foreword to the 2005 PAI indicates that, in formulating this new Plan, the Technical Committee of the Water Basin Authorities (AdB), with the help of valuable

researchers and engineers, was inspired by a ‘*great vision*’, encompassing all the aspects involved in the Plan.

## 4.2 Hazard and risk

In the section on hazard and risk, PAI discusses extensively the classical notions of *hazard*, *exposure* and *vulnerability*, which lead to the definition of *risk*. Discussion includes both the risk of flooding and the risk of landsliding, treated separately.

Note that the guidelines for the preparation of PAIs (issued by the Ministry of Environment) include among the elements to be considered in the risk analysis:

- Human lives.
- Urban areas.
- Industrial areas.
- Infrastructures and strategic communication routes.
- Environment and cultural heritage.

## 4.3 Identification and mapping of hazardous areas

The section in the PAI on identification and mapping of hazardous areas, provides a general discussion on different methods of mapping, based on historical data or predictive models followed by a review of 1-D and 2-D models available in the literature to simulate flood propagation in river networks and associated flood-plains. However, this appears to be a fairly academic exercise as, in practice, AdB still relied on 1999’s model by Paris et al., which has been briefly described earlier in this ITSC report.

### *Mapping approaches*

Two mapping approaches are employed in the PAI.

- *Synthetic approach*. This approach is based on the previous mapping performed for the ‘Exceptional Plan’ prepared by AdB to comply with the prescriptions of Law n 180 (1998). It establishes four levels of Hazard:

PI4 – *Very high hazard*. Areas flooded by the 1991, 1992, 1993 and by the 1998-1999 events (i.e. fairly weak events)

PI3 – *High Hazard*. Areas frequently flooded (distinct from PI4 based on some bureaucratic criterion).

PI2 – *Moderate Hazard*. Areas flooded during the 1966 event but not subject to frequent flooding.

PI1 – *Low Hazard*. Areas external to the envelope of the great historical floods.

*In this map the historical center of Florence falls in the “Moderate Hazard” area.*

- *Analytic*: This approach is based on hydrologic analysis that, for any given recurrence interval, is able to associate a flood hydrograph to any cross section of the

fluvial network and on a hydraulic model able to predict free surface elevations and inundated areas adjacent to the river network. Based on the results of simulations employing these models, areas inundated with a recurrence interval less or equal to 500 years are mapped in the classes PI1, PI2, PI3 and PI4, depending on the criterion described in Table 4-1.

**Table 4-1.** Hazard classification of areas inundated with a recurrence time less or equal to 500 years.

Recurrence interval [years]	Transfer areas	Storage areas	
		$h \leq 0.30$ m	$h > 0.30$ m
$0 < Tr \leq 30$	PI3	PI3	PI4
$30 < Tr \leq 100$	PI2	PI2	PI3
$100 < Tr \leq 200$	PI2	PI2	PI2
$200 < Tr \leq 500$	PI1	PI1	PI1

$Tr$  denotes the recurrence interval.  $h$  denotes the water depth (in meters) in flooded area where waters are stagnant.

Note that PAI makes a distinction between areas where flooded waters are stagnant (storage areas) and areas where flooded waters flow, hence they do not remain in the flooded area beyond the duration of the event (transfer areas). Moreover, in the areas where flooded waters are stagnant, hazard is higher if the water depth exceeds a threshold of 30 cm.

#### *The hydrologic model employed*

The Hydrologic model adopted by the PAI differs from the model that was used for the previous plan. The PAI discusses the limitations of the adopted model, and emphasizes that there is room for future refinements.

In detail, the model employed is called ALTO (Alluvioni in Toscana). It is a lumped model, developed in 1997 by the University of Florence for a study aiming at a regional approach for peak flow estimation in the Tuscany region. The model uses a Geomorphological Instantaneous Unit Hydrograph (GIUH) to generate synthetic flood events. The GIUH parameters are estimated based on the geomorphological characteristics of the contributing catchment, and in particular the shape of the river network. Net rainfall is estimated by first subtracting a constant initial abstraction from gross rainfall and then reducing the subsequent rainfall by a constant infiltration rate. Gross rainfall is simulated, for a given recurrence time, using a synthetic hyetograph generated through a regional depth-duration-frequency equation for rainfall. The whole simulation procedure assumes that the recurrence intervals of rainfall and induced flood flow are coincident.

The simulation models (rainfall and rainfall-runoff model) were calibrated using observations collected by the National Hydrographic Service of Italy and other public offices. Rainfall observations were collected in automatic rain gauges with an average spatial resolution of one station covering an average area of 75 km<sup>2</sup> (40 km<sup>2</sup> if one also considered the manual rain gauges working at daily time scale). The GIUH was calibrated using information on the geometry of the river network, which was derived from detailed information on the elevation of the considered region (a digital elevation model with resolution 400x400 meters was

used), information on soil use at 400x400 meters resolution, as well as geologic maps at the same resolution. Calibration of the GIUH was also performed using 66 flood events for the whole Tuscany region for which rainfall and river flow data were available.

The following parameters were calibrated for each flood event:

- Initial rainfall abstraction.
- Infiltration rate at saturation.
- $n$  and  $k$  parameters of the Nash model (which represents a watershed by a cascade of linear reservoirs).

From the calibration results, the PAI concluded that:

- Initial abstraction varies between 10 and 30 mm.
- Infiltration rate at saturation varies between 1 mm/h and 3.5 mm/h.
- $n$  and  $k$  vary significantly, but their product is quite stable.

The PAI then describes in detail the procedures adopted for the regionalization of the extreme rainfall, the rainfall-area reduction factor, and the parameters of the GIUH. In particular, parameters of the Nash model were regionalized analyzing the distribution of the product  $n k$ , which represents the travel time of the catchment, and can be in turn related to the catchment's characteristics. In particular, the travel time was related to the Horton bifurcation, length and areal ratios, through a regression that was characterized by  $R^2 = 0.9$ . Initial abstraction and infiltration ratios were regionalized basing on land-use and geological characteristics.

The overall simulation model was validated by comparing the generated probability distributions for the flood volumes with those estimated using in-situ observations. A second check was performed comparing generated hydrographs with the envelope curves obtained analyzing observed data. The PAI reports that the results of the validation procedure were satisfactory but no performance statistics are given. A sensitivity analysis was also carried out to identify the most influential parameters.

Finally, the PAI describes in detail the procedure used to estimate lateral inflows.

#### *The hydraulic model*

The *IDRARNO* hydraulic model employed by PAI does not seem to differ from that previously used for the Hydraulic Risk Plan (see Sect. 2.5.2). In PAI it is described in some more detail. Essentially, it is a 1-D unsteady model for flood propagation in the river channel, coupled with a 'static' model describing the storage process within the inundated areas. Solution of de Saint Venant equations is obtained numerically using an implicit scheme. The inundated areas are subdivided into cells exchanging water fluxes through their sides which are treated as weirs, either free or submerged, satisfying some exchange rule depending on free surface elevations on the two sides of the weir. Needless to say, there are no dynamics. Flooding occurs synchronously in all the flooded cells and the stored volume



is given some power law form, with coefficients calculated from the knowledge of bed topography.

Mapping based on the above procedure shows that the critical portions of the basin are the lower and the middle part.

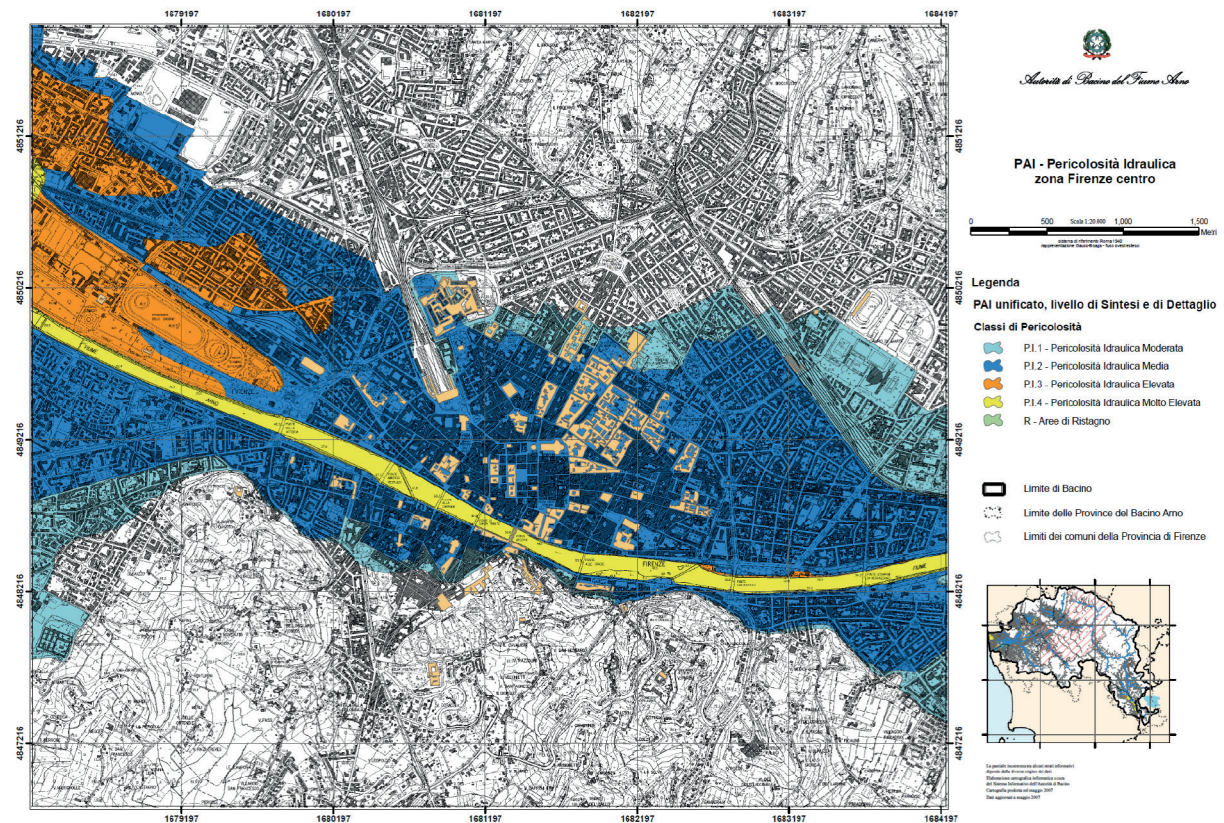
In particular:

- The areas classified as PI4 include the Regional Park of Migliarino, S. Rossore and Massaciuccoli, part of the historical city of Pisa, the town of Pontedera, the 'Comprensorio del Cuoio' (*Leather District*) (an area of 300 km<sup>2</sup> including the towns of S. Miniato and Fucecchio), the towns of Empoli and Vinci, the area of Montelupo Fiorentino, most of the area of the Ombrone and Bisenzio basins.
- In upper Valdarno and Casentino some local hazard is present in the city of Arezzo and diffused hazard is distributed along the floodplain in Casentino, though the latter affects areas mostly for agricultural use.

*Taking into account both the 'synthetic' and the 'analytic' criteria, the historical center of the city of Florence is not included among the very high or high hazardous areas.*

The latter statement is detailed in the plot of Figure 4-1.

**Fig. 4-1.** Map of Hazardous Areas in the center of Florence according to the unified PAI, which accounts for both synthetic and analytic mapping.



#### 4.4 Identification of risk areas

##### *Exposure*

In order to proceed from mapping of hazardous areas to mapping of risk areas, the first step is to identify areas *exposed* to risk. The choice of the typologies of structures to be considered and the degree of exposure associated with each of them were based on the guidelines contained in the Decree issued in 1998. The classification adopted by PAI is reported in Table 4-2. Note that exposure is defined (PAI, Part II, pg. 31) as the **number or value of elements exposed to risk** (e.g. number of human lives, economic value of goods exposed to risk).

It may be appropriate to note, at this stage, that **no special status is given to urban settlements where cultural heritage is dominant**.

**Table 4-2.** Classification of the degree of exposure associated with areas of different typologies.

Class	1998 Decree
E1	Uninhabited or unproductive areas
E2	Isolated buildings and agricultural areas
E3	Urban areas, minor industrial and commercial settlements
E4	Urban areas, major industrial and commercial settlements, areas where public or private service activities are performed, sports and recreational facilities, communication routes of strategic relevance.

##### *Vulnerability*

Vulnerability is defined (PAI, Part II, pg. 31) as the ‘attitude of elements to be damaged by flooding waters’. It is expressed in terms of some vulnerability coefficient varying in the interval 0- 1 (0=no loss, 1=total loss).

In the mapping of the Arno Basin, the vulnerability coefficient is set equal to one for each element exposed.

Different classes of *risk* are finally associated with different pairs of values of exposure and hazard, according with Table 4-3.

**Table 4-3.** Risk classification for areas characterized by different degrees of exposure and hazard.

		<i>Hazard</i>			
		<i>P1</i>	<i>P2</i>	<i>P3</i>	<i>P4</i>
<i>Exposure</i>	<i>E1</i>	<b>R1</b>	<b>R1</b>	<b>R2</b>	<b>R2</b>
	<i>E2</i>	<b>R1</b>	<b>R2</b>	<b>R3</b>	<b>R4</b>
	<i>E3</i>	<b>R1</b>	<b>R3</b>	<b>R4</b>	<b>R4</b>
	<i>E4</i>	R1	R3	R4	R4

The four classes of risk arising from this classification are as follows (Law n. 180/98):

- R.I.1, *moderate risk*, such that social and economic losses are marginal.
- R.I.2, *average risk*, such that minor damage to buildings and infrastructures is possible, whilst human life as well as economic activities are not affected.
- R.I.3, *high risk*, such that human safety may be affected and functional damage to buildings and infrastructures may occur and affect economic activities.
- R.I.4, *very high risk*, such that human life may be affected and serious damage to buildings and infrastructures may occur to the extent to ruin economic activities.

*It is important to note that the above classification has been introduced in PAI but it has not been implemented.* The only stage when this document makes some estimate of the actual value of potential losses associated with a flood similar to the 1966 flood is in Sect. 6 of the PAI, when the financial requirements to implement the Plan are analyzed and economic benefits resulting from its implementation are sought.

It is then stated that the economic loss generated by the occurrence in 2005 of a flood in Florence similar to the 1966 flood can be estimated at 15.5 Billion €.

*No detail is given about the approach used to perform such an estimate, but it is clearly stated that losses do not include losses of human lives and cultural inheritance.* Although within many countries considerable effort has gone into assessing loss of life in economic terms, the challenge is difficult if not unacceptable. Assessment of the value of cultural inheritance is an open important issue in the field of environmental economy. More recent estimates (Arrighi et al., 2014) suggest that the 15.5 Billion € loss figure might be over-estimated.

This notwithstanding, PAI evaluates the risk associated with the occurrence of such an event in Florence, by multiplying the above estimate by the probability of occurrence. Estimates for the benefit obtained from implementing the protection works follow from the reduction of the probability of occurrence of the event. Results are shown in Table 4-4.

**Table 4-4.** Risk associated with a 1966 flood in Florence. Present state and 50 year projection (Source: Table 5, page 268, PAI).

Temporal span [years]	Risk at present [M€]	Risk after work implementation [M€]	Risk reduction from Levane and La Penna [M€]
2	154	124	30
5	384	307	77
10	758	609	149
20	1478	1194	284
50	3435	2814	621

This Table shows that the whole budget required to implement the protection works in the whole basin (estimated at 1.6 Billion € in 2005) is roughly equivalent to the risk for a period of 25 years. Also, note that the entire investment needed to real-



ize the works needed at the dams of Levane and La Penna (71 M€) is recovered after 5 years in terms of risk reduction.

#### 4.5 Interventions needed and funding required

This Section does not contain anything new with respect to the 1996-1999 Plan. Interventions planned by PAI to reduce the hydraulic risk in the Arno Basin are those foreseen by the Hydraulic Risk Plan, except for the heightening of La Penna dam, an action removed from the 1996 HRP list.

Thus, summarizing: a volume of 156 Mm<sup>3</sup> stored in flood detention areas along the main course and 152 Mm<sup>3</sup> along tributaries; 25 Mm<sup>3</sup> additional storage in Levane-La Penna and 24 Mm<sup>3</sup> additional storage in new reservoirs on tributaries, plus a few floodways in the lower valley. Essentially, an area of 200 km<sup>2</sup> was planned to be used for artificial storage (note that this must be compared with an area of 1200 km<sup>2</sup> flooded in 1966).

In particular, upstream of Florence, roughly 1/3 of the stored volume is located in Casentino, 1/3 in Levane-La Penna and 1/3 in upper Valdarno (Table 4-5).

**Table 4-5.** Volume stored in flood detention areas and reservoirs along the Arno River upstream of Florence and costs for the implementation of these measures (Table 2, page 263, PAI).

Groups of interventions	Volumes [Mm <sup>3</sup> ]	% Volume	Costs [M€]	% Costs
Flood Detention Areas – Casentino	25.20	29%	45.4	28%
Enel Reservoirs	25.50	30%	54.2	33%
F.D.A. – Valdarno	35.50	41%	64.0	39%
	<b>86.20</b>	<b>100%</b>	<b>163.6</b>	<b>100%</b>

Finally, PAI devotes some attention to the amount of funds required to complete the Plan. Moreover, it provides an assessment of the funds already used to implement actions aimed at reducing the hydraulic risk in the basin.

In the decade 1989-1999, out of 160 Billion Liras allocated for environmental interventions (flood protection, landslides, pollution, coastal erosion), 55 Billion Liras have been used for flood protection!

These figures may be compared with the updated estimate of the funding required to implement the whole Plan (Table 4-6).

**Table 4-6.** Funds needed to implement structural interventions aimed at Hydraulic Risk Reduction in the Arno Basin (PAI, 2005).

<b>Funds needed for Structural interventions aimed at Hydraulic Risk Reduction</b>			
<b>Intervention</b>	<b>Funds required [€]</b>	<b>Funds allocated [€]</b>	<b>Funds to be allocated [€]</b>
Works included in the Hydraulic Risk Plan (1966-99)	1.557.014.259	46.389.192	1.510.625.067
Urgent works required to protect the most risky areas	152.421.925	13.352.477	139.069.448
Urgent works required to reduce the risk in areas hit by 2000 catastrophic events	69.641.994	8.617.471	61.024.523
<i>Total</i>	1.779.078.178	68.359.140	1.710.719.038



## Chapter Five

# The Management Plan of Flood Risk (PGRA)

### 5.1 The PGRA

PGRA (Piano di Gestione del Rischio di Alluvioni, i.e. Flood Risk Management Plan) is a planning tool foreseen by EU directive 2007/60/CE. (It is commonly called the '*Flood Directive*', <<http://www.envir.ee/sites/default/files/flooddirective.pdf>>, 07/17). This Directive was adopted by the Italian Parliament in 2010 through Decree n. 49/2010 that assigns the task to draft the Management Plan to the Water District Authorities (AdD).

As the latter Authorities have not been established yet, this task has provisionally been delegated to Water Basin Authorities (AdB). More precisely:

- AdBs, with the help of Regions, are expected to formulate the part of the Plan concerning hazard maps, risk definition and measures required to insure risk prevention and risk mitigation.
- The National and Regional Departments of Civil Protection are given the task to define procedures and measures to be taken before and during the occurrence of a flood event.

The PGRA of the Arno River Basin Authority was adopted by the deliberations n. 231 and 232 taken on December 17, 2015 and has been finally approved by the deliberation n. 235 (March 3, 2016). After its approval, PAI is no longer in force and therefore the PGRA is the current basis for planning future actions. An effort has been made to support the PGRA with innovative research efforts, which have been pursued through a concertation between the responsible authorities and the Academia. The crucial issue is to critically ascertain whether the PGRA provides an improved and effective strategy.

The first PGRA draft was published in December 2014. A consultation of citizens and Institutions, as required by EU Directives and Decree n. 152/2006 was then initiated. Later, the latter consultation merged with a similar consultation required for the so-called *Environmental Strategic Evaluation* (VAS), a procedure aimed at ascertaining the environmental impact of the Plan. *The ITSC has been unable to read the observations raised in the consultation, so we cannot state whether any observation did concern the problem of the persistent risk of flooding affecting the historical center of Florence.*

The PGRA of the Arno River Basin authority is meant to be open to further improvements of the scientific basis and related operational changes.

## 5.2 Goals foreseen by PGRA

Goals of PGRA are described in Art. 7, 2 of the EU Directive. Essentially:

[...] Member States shall establish appropriate objectives for the management of flood risks [...] focusing on the reduction of potential adverse consequences of flooding for human health, the environment, **cultural heritage** and economic activity [...]; [...] and, if considered appropriate, on nonstructural initiatives and/or on the reduction of the likelihood of flooding.

Following the above guide, PGRA sets the following goals:

- Human health
  - reducing risk for life and health
  - mitigation of damage to strategic systems (electric and water supply networks, hospitals, schools, etc.).
- Environment
  - reducing risk of flood driven pollution in protected areas and deterioration of the ecologic state of water bodies.
- Cultural Heritage
  - reducing risk for cultural, historical and architectural inheritance as well as for the landscape.
- Economy
  - mitigation of flood driven damage to major infrastructures, productive system, real estate, etc.

Cultural heritage is clearly stated as one of the major assets to be preserved.

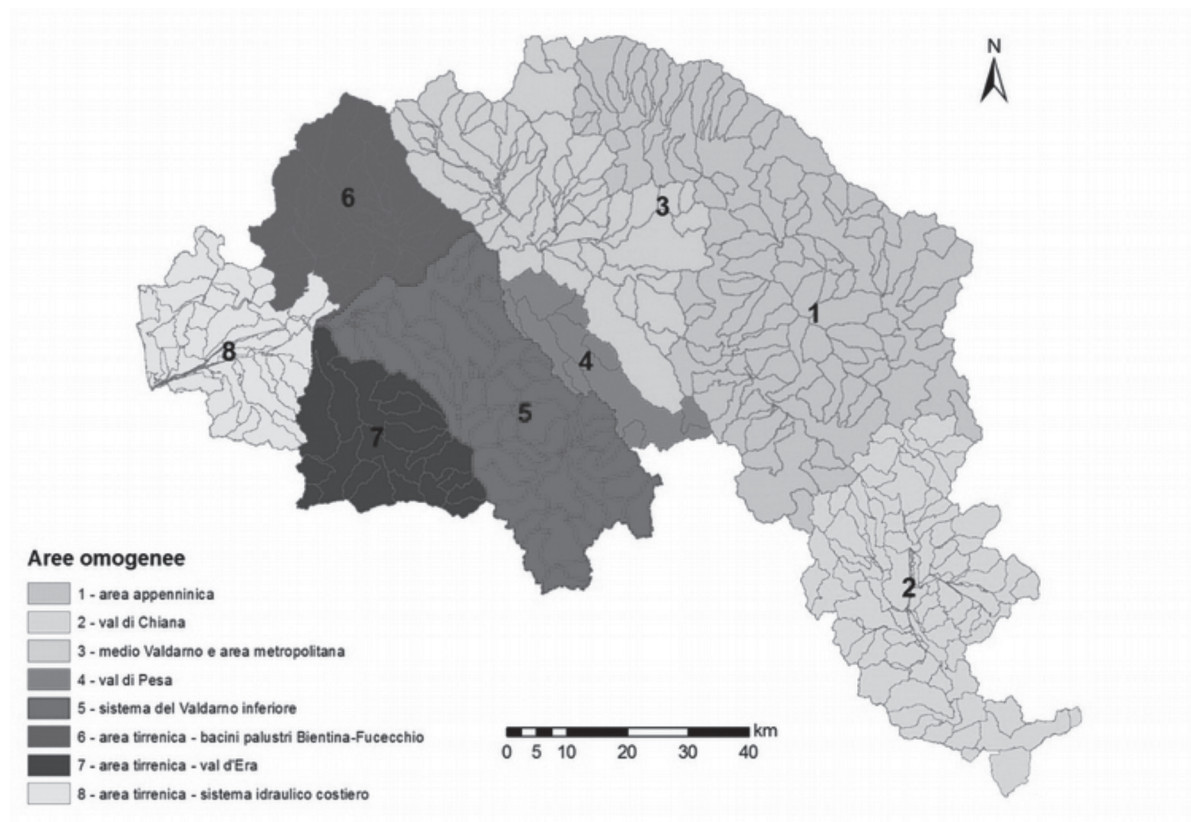
## 5.3 Homogeneous areas

PGRA identifies '*homogeneous areas*' in the basin, such that the various measures are distinctly planned for each area. Eight such areas have been identified for the Arno River Basin, as illustrated in Fig. 5-1. The city of Florence lies within Area 3.

For each area, Hazard Maps and Risk Maps have been drawn and measures to be undertaken are specified.

## 5.4 Hazard maps

Hazard Maps are updated versions of those contained in PAI, adapted to the different criterion adopted by the Flood Directive, which defines three, rather than four, hazard levels (P1:  $T$  (recurrence interval)  $< 30$  years; P2:  $30 < T < 200$ -



years; P3:  $T > 200$ -years). As in PAI, both modelling and historical data have been employed.

PGRA has refined the analysis of the flood risk with respect to previous plans, by using a detailed hydraulic model of the Florentine flood plain and the Florence area. According to information provided by AdB, the innovation that was introduced is related to:

- A better definition of the hydraulic hazardous maps, based on simulations of several synthetic flood events (with recurrence times of 30, 200-years and beyond).
- Further reconstruction of the 1966 flood event and evaluation of what its effects would be should it occur at the present time.
- Development of a Quantity Risk Forecast (QRF) model for prediction of inundation events along the Arno River (from Levane dam to Pisa) 12-24 hours in advance.

Models have been improved through recent developments that were presented in acknowledged scientific publications. It is also noted in the PGRA that the Civil Engineering Department of the Tuscany Region has further improved the modeling capabilities in the reach upstream of Florence for the design of the off-river storage

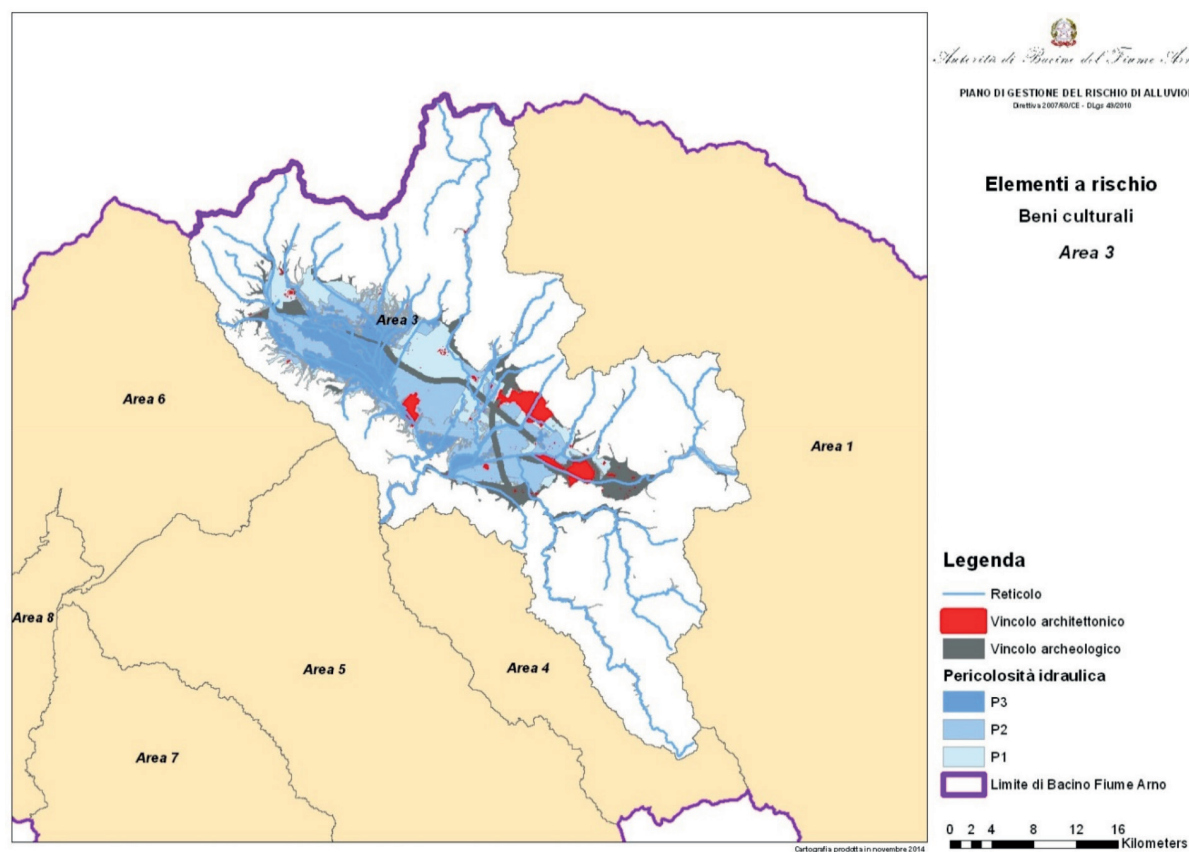
**Fig. 5-1.** Homogeneous areas of the Arno Basin according to PGRA (2016).

areas in the Figline municipality, and that further improvements are in progress for the design of the raising of the spillway of the Levane Dam.

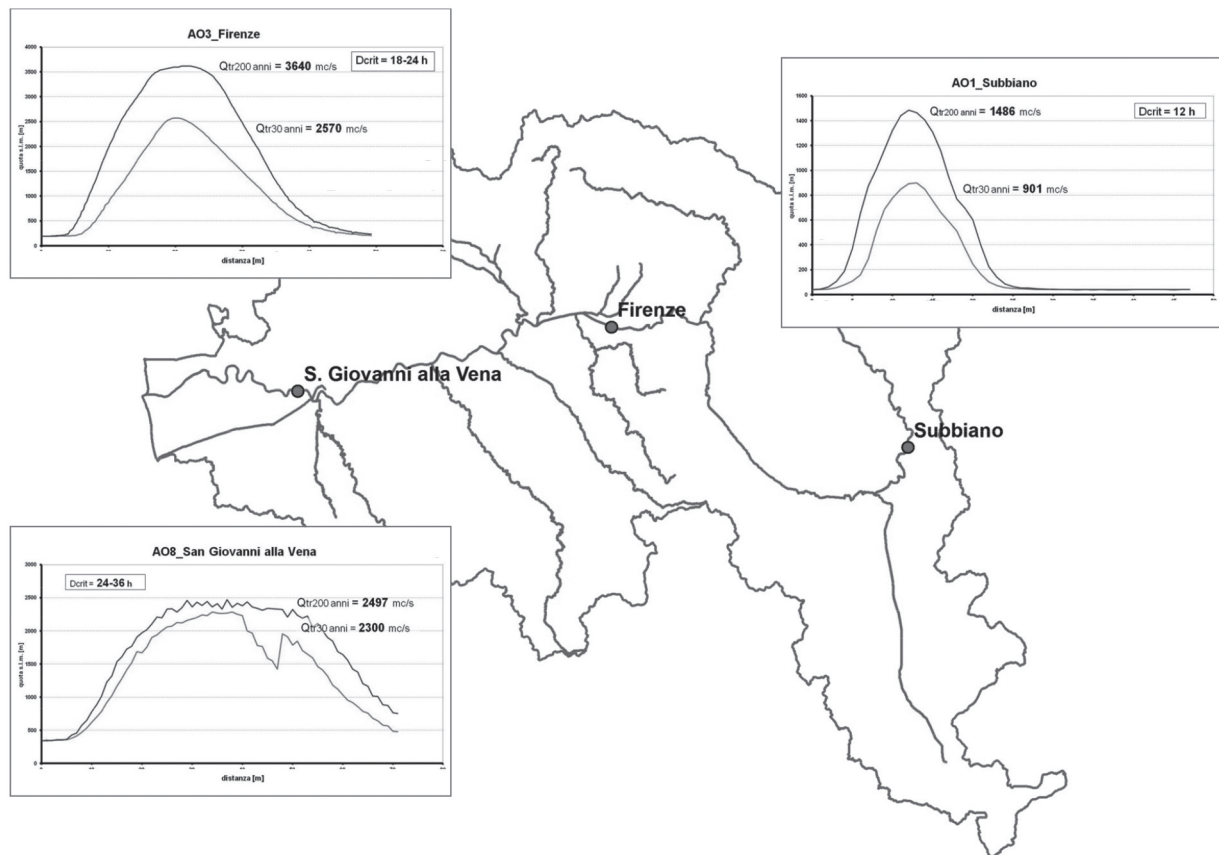
According to the available information, however, it is not clear whether additional efforts have been made to improve the hydrological modeling of the upper parts of the basin. Hydrology provides the boundary conditions for hydraulic modeling and therefore, from a practical point of view, deciphers the mitigation effect of the actions that are taken in the upper Arno River. Apparently, the input hydrographs to the lower Arno reach that are represented by the hydraulic model are still computed through the regionalization procedure that has been used for PAI. According to information provided by the AdB, for the major tributaries – including the Sieve – hydrographs have been estimated through hydraulic modeling. Details are not available, but it seems that the same models that were used for PAI have been applied for preparing the PGRA.

The hazard Map concerning Area 3 is plotted in Figure 5-2. It shows that the historical center of Florence is rated P2, i.e. is characterized by moderate hazard. It also shows areas subject to so called architectural (red) or archeologic (gray) constraints: they limit the free usage of a private or public property and constrain the owner to insure, with the help of the State, the protection and conservation of cultural assets (D. Lgs 22 gennaio 2004, n. 42 – Codice dei beni culturali e del paesaggio, ai sensi dell'articolo 10 della legge 6 luglio 2002, n. 137).

**Fig. 5-2.** Hazard map for Area 3 with indication of areas subject to architectural (red) or archeologic (gray) constraints (reproduced from PGRA, 2016).







Also, results of the new analysis predict a peak discharge in Florence for a 200-year-flood of  $3\,640\text{ m}^3/\text{s}$  (Fig. 5-3), a value significantly lower than the previously suggested value of  $3\,792\text{ m}^3/\text{s}$ , reported by Eng. Massini, of the Tuscany Region in the First meeting of ITSC (2014). The latter uncertainty is, of course, not surprising and suggests the need for caution when relying on modelled events rather than actually recorded events.

**Fig. 5-3.** Hydrographs of 30-year and 200-year synthetic floods in three cross sections of the Arno River (reproduced from PGRA, Part One, p. 34).

## 5.5 Risk maps

According to Decree n. 49 /2010 risk must also be mapped, associating an evaluation of the potential damage foreseen in hazardous areas, classified according to four classes:

- D4 (Very high potential damage): areas where loss of lives or huge damage to economic, natural, historical or cultural assets are feared.
- D3 (High potential damage): areas where people safety and the functionality of the economic system may be affected, areas hosting important infrastructures or significant productive activities.
- D2 (Average potential damage): areas where effects on people safety and the functionality of the economic system is limited, hosting infrastructures of minor importance and agricultural productive activities.

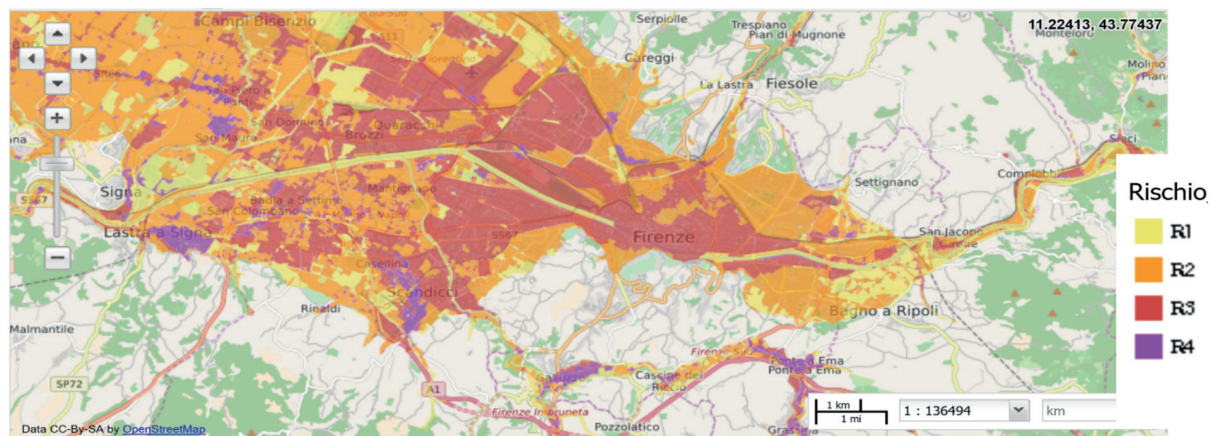
- D1 (Moderate or no potential damage): areas with no urban or productive settlements where floods may flow freely.

The *crucial choice* made in PGRA is to adopt the following *risk matrix*:

**Table 5-1.** The risk matrix adopted in PGRA (2016).

	P3	P2	P1
D4	R4	R3	R2
D3	R3	R3	R1
D2	R2	R2	R1
D1	R1	R1	R1

R4: very high risk areas
R3: high risk areas
R2: average risk areas
R1: low risk areas



**Fig. 5-4.** Risk Map of the Florence Area (PGRA, 2016).

*Fig. 5-4 indicates that the risk at Scandicci and Lastra a Signa is higher than the risk in Florence an observation that one can hardly reconcile with the notation found in the same document that, in spite of the ‘moderate’ hazard of the Florence center (Fig. 71), the associated risk would be quite high due to the “[...] incommensurable artistic and cultural value [...]” of the city of Florence. («[...] È tuttavia indubbio che i possibili danni che possono colpire la città nel caso di eventi estremi determinano una situazione di rischio fortemente elevata data la peculiarità della città ed il suo incommensurabile valore artistico e culturale [...]», PGRA, Part 2, p. 151). This contradiction is only apparent, as it is embodied in the choice of the risk matrix of Fig. 5-4: due to this choice, very high risk can only be associated with highly hazardous areas.*

## 5.6 Measures to be undertaken

As regards the types of measures to be undertaken they are classified into four classes, following the indications of Guidance for Reporting under the Floods Directive, (2007/60/EC) n. 29 (14 October 2013) (Table 5-2). Note that the task of

planning suitable measures of Prevention and Protection is assigned to AdBs, whilst Preparation and Recovery must be managed by Regions, with the cooperation of the National Department of Civil Protection.

**Table 5-2.** Typologies of measures to be undertaken according to PGRA (2016).

	<b>Prevention</b>	<b>Protection</b>	<b>Preparation</b>	<b>Recovery and Review</b>
<b>Measures</b>	Actions and governing rules of territory, approaches to soil use, delocalizations, urban planning, adaptation	Hydraulic defense works (dams, flood detention areas, levees, etc.), maintenance, hillside stabilization, floodplain reactivation	Forecasting, warning systems, actions and civil protection plans, management protocols for protection works	Reactivation of pre-event conditions, medical and psychological support, financial and legal assistance, reanalysis

PGRA discusses diffusely the novel philosophy underlying the plan, which may be summarized as follows: “from the culture of safety to the culture of risk management”. This is an interesting development discussed in the new Regulation prepared by AdB to replace PAI starting from January 2016. The regulation reads:

The management and non-increment of risk may be pursued, provided it is deemed appropriate, also by actions such that possible negative consequences of floods are distributed over equally hazardous areas with lower economic value.

In order to understand the implications of the latter sentence, one must read further. In Part One, p. 19-20, PGRA essentially states that, unlike in previous Plans, which assumed that protection could achieve nearly complete safety, ‘more recent research’ would show that the latter goal is out of the reach of modern society, due to the high cost of structural measures, high cost/benefit ratios and widespread opposition of the population. As a result, PGRA proposes an alternative strategy, based on the management of flood events, the use of cost/benefit analysis and the acceptance of residual risks and sustainable risks.

How is this strategy implemented is clarified further on (p. 73), where one reads:

[...] re-analysis has led to a set of interventions where a major role is played by ‘green infrastructures’ (labeled M31), whose aim is to reestablish the natural system and, simultaneously, allow for flood lamination [...]. The Plan does not include, except for extreme cases with reduced priority, protection measures with strong impact like dams... In most cases, interventions consist of flood detention areas of small sizes, with low impact, which do not modify the normal flow regime but act only during the most destructive flood events.

The result of this new philosophy is a list of structural interventions (PGRA, Part Two, pg. 158), where the protection of Florence rests on:

- The four flood detention areas in the Figline region (one of them under construction, the remaining three in the planning stage with very high priority).

- Heightening of the Levane dam (in the planning stage with very high priority).
- Four small flood detention areas in the Sieve basin (in the planning stage with high- very high priority).
- Removal of silt deposits from Levane and La Penna reservoirs (high priority but not even started yet).
- Flood detention areas and Castello di Montalto reservoir in the Ambra Basin.

The Table also includes ‘la Penna dam and modification of its outlet’. This is a new re-entry which is given very high priority! But PGRA warns that the design phase has not started yet and the feasibility of this work will be analyzed in the next years, before the update of PGRA, taking into account the environmental impact of this intervention as well as its high cost. Some new measures like ‘natural expansion areas’ or ‘green infrastructures’ are also included in the Casentino, upper Valdarno and Sieve.

*No evaluation of the impact of the whole set of planned structural measures on flood propagation, sediment transport, and hydraulic risk in the basin (most notably in Florence) is reported in PGRA.* The PGRA only reports a mitigation effect of about 10-15% of the peak flow in Florence for a 200-year flood as a result of the additional storage that may be retained by the Levane Dam and the Figline area, but modeling details are not provided. However, according to information received by Prof. Montanari from the Arno River Basin Authority, activities would be on-going regarding the hydraulic modeling of the effects of heightening the Levane Dam.

While the PGRA reports on how much a 200-year flood would be mitigated with some of the proposed measures, it pays no attention to the amount of sediment transported during an event of such magnitude and the impact this would have on the morphology and flow conveyance in the Arno River, despite the fact the 1966 flood event deposited tons of mud all over Florence (Nencini, 1966).

It must also be noted that nonstructural measures are also foreseen by PGRA, as this plan adopts the concept of integrating several different measures for flood risk mitigation, according to the guidelines of the European Union. In particular, it is proposed that “hard” measures like structural defenses are coupled with “soft” and “green” measures like preparedness and real time flood management. Indeed, the suggested strategy is in principle correct. However, it is well known that soft and green solutions require continuous updating and maintenance and therefore their efficient implementation is a challenging task that requires a rigorous coordination.

*In the web page presenting the PGRA, it is in fact declared that improving preparedness is not a task of the Arno River Basin Authority. In fact, this is a task of the Civil Protection at the National and regional level [...]. Therefore, measures for increasing flood preparedness are treated in a separate part of the PGRA that will be prepared by the National Department for Civil Protection and the Departments of the Tuscany and Umbria Regions.*

While this practice agrees with the Italian laws and practice, *it is concerning that the integration of the measures set out by the PGRA may be undermined by administrative fragmentation.* It is unlikely that different bodies may effectively cooperate in the development and implementation phases of an integrated flood risk mitigation plan.

### 5.7 Monitoring and VAS procedure

As mentioned in the chapter introduction, the EU and Italian guidelines also require an *Environmental Strategic Evaluation* and monitoring as an essential element of the VAS procedure allowing for evaluation of the progress made in the realization of the goals of the Plan, such that possible deviations from the foreseen path may be corrected. PGRA introduces several indicators that would be helpful in the monitoring procedure. This exercise, in the cultural domain appears to be quite formal and unlikely to provide meaningful information (e.g. the indicator of progress made in the protection of cultural assets would consist of assessing the variation of the number of works of art located in hazardous areas as the implementation of PGRA progresses). *In other words, monitors will have to conceive an approach able to 'count how many works of art' contained in Santa Croce, in the Duomo or in the National Library will no longer be at risk when the 'green infrastructures' will be realized.*

These documents appear to have been prepared to comply with a law, being aware that this law may never be applied. *Given that many of the deadlines foreseen in the 1996-1999 HRP have not been met, it will be important to ensure that appropriate monitoring is pursued.*





## Chapter Six

# Observations and Recommendations of the ITSC

### 6.1 The ITSC Review

Over the course of the past 30 months the ITSC has conducted a detailed review of the potential for future flooding in Florence under current and climate change impacted hydrologic and hydraulic conditions. The purpose of this chapter is to provide the ITSC's observations and recommendations concerning the flood risk in Florence. The ITSC believes it is important to begin this part of the report by providing its principal observation:

Florence remains at risk to significant flooding and this risk grows each day. It is not a question of whether a flood of the magnitude of 1966 or greater will occur, but when. In fact, the level of protection that exists in Florence at the present time does not yet provide the risk reduction needed for this city and is not on a level appropriate to the citizens and treasures that rest within the city.

### 6.2 Planning for and implementing flood risk reduction measures

Since ancient times, those responsible for Florence's well-being have sought and tried many measures to reduce the impact of high water in the Arno on Florence. As the earlier parts of this report indicated, success has been sporadic and fleeting. Following the 1966 flood, mitigation measures were initially accelerated and led to the lowering of the aprons of two major bridges in a reasonable time. Efforts to develop plans that would better protect the city and reduce the probability that a major event would cause catastrophic consequences were much slower. *Comprehensive plans have been completed at several points over the last 20 years, but implementation of these plans has fallen far behind what was called for in the earliest of the post-1966 documents.*

Florence is recognized as one of the world treasures in art, culture, and Renaissance history. It is a UNESCO heritage site and internationally visited tourist attraction. The importance of its legacy cannot be understated. Its preservation is important to the community, to Italy, and to the nations of the world. Although the population of Florence has decreased since the 1970s, the density of occupation of risk areas has

increased. Moreover, the cultural and societal relevance of Florence has grown further world-wide and has produced a marked increase in the economic value of tourism. If, under current conditions, a 1966-like flood occurred, the consequences to human lives, treasures, other properties and community infrastructure would be much more catastrophic than they were in 1966.

### 6.3 The Plans

The ITSC, assessed the documents detailing the solutions planned to mitigate the flood risk in Florence (Part Two of this report), received briefings from key officials on these documents and the actions taken in response to the documents, and visited locations in the Arno River basin most relevant to the developed plans. The principal plans are reviewed in the following sections and where appropriate, more important points are highlighted in bold.

#### *Hydraulic Risk Plan*

The original Hydraulic Risk Plan, prepared by the Arno Basin Authority in 1996 and approved in 1999 (more than thirty years after the Great Flood) indicated that:

- protection from a catastrophic event might need to store in the Arno Basin a water volume as large as 350-400 Mm<sup>3</sup>, with roughly 200 Mm<sup>3</sup> needed upstream of Florence;
- according to the Bologna tests performed on a physical model in 1972, lowering of the aprons of Ponte Vecchio and S. Trinita Bridge and raising of walls along the river, should have increased the conveyance of the Arno River in the urban reach from 2 500 m<sup>3</sup>/s to about 3 100 m<sup>3</sup>/s (around 3 400 m<sup>3</sup>/s with no safety allowance). However, numerical simulations reported in the *HRP* suggested that the maximum discharge safely contained within the banks did not exceed 2 800 m<sup>3</sup>/s. *The ITSC notes a great deal of uncertainty in the estimates for flows presented in the HRP and subsequent plans;*
- the area downstream of the Levane and La Penna dams, the part of the floodplain naturally inundated by floods, was no longer available for this purpose, as the floodplain was protected by levees. As a result, the peak river flow in the lower Valdarno and the Florentine plain (including Florence) should now be significantly higher than it was in 1966, though this does not clearly emerge from the *HRP*.

Using the 1992 flood event and the much more severe 1966 event as reference events for risk mitigation, the HRP indicated that:

- in order to allow for a 1966 type flood event to flow safely through Florence, a total storage volume of roughly 140 Mm<sup>3</sup> would be required upstream of Florence. The above volume would be obtained by the construction of a number of flood detention areas (60 Mm<sup>3</sup> along the Arno, 21 Mm<sup>3</sup> along its tributaries), a new reservoir along the Ambra tributary (4 Mm<sup>3</sup>), heightening of Levane and La Penna dams (42.5 Mm<sup>3</sup>) as well as the use of 15Mm<sup>3</sup> storage of the Bilancino reservoir;

- the general project (or one of four possible variants) was to be completed within 15 years after approval of the HPR. (2014).

*Hydro-Geological Plan (Piano di Assetto Idrogeologico – PAI)*

The next document in the planning process was the PAI which was adopted by the Arno AdB on 15 February 2005. The first novel feature introduced by *PAI* was the fact that, following the guidelines of the Ministry of Environment, PAI included environment and *cultural heritage* among the five elements to be considered in the risk analysis. A further novel feature was the mapping of *hazardous* areas in the basin. This was an important development, although *exposure* and *vulnerability* of those areas (hence *risk*) was not assessed. As a result, the historical center of the city of Florence was not included among the *very high* or *high* risk areas, although the economic loss generated by the re-occurrence of a 1966 type flood (excluding loss of human lives and cultural assets) was estimated at 15.5 Billion €.

A risk analysis reported in PAI indicated that the total budget required to implement the protection works in the basin would be roughly equivalent to the financial losses estimated for a flood with a return interval of 25 years. The same analysis indicated that the entire investment needed to realize the works planned for the dams of Levane and La Penna (71 M€) would be recovered, in terms of risk reduction, after 5 years. The measures planned in the PAI to reduce the hydraulic risk in the Arno Basin were those foreseen by HRP, except for the heightening of La Penna dam, an action definitively removed from the list of planned projects.

*PGRA (Piano di Gestione del Rischio di Alluvioni)*

The final planning document in the sequence of plans was the PGRA, i.e. the *Management Plan of Flood Risk*, approved in 2016 in compliance with decrees 152/2006, 49/2010 and 219/2010. The PGRA offered a novel philosophy, simply stated as: *from safety to risk management*. In fact, PGRA adopts 4 different types of measures: prevention, protection, preparation, recovery and review. The ITSC supports the concept, which complies with the European Flood Directive, but notes that the different types of measures should be developed with a rigorous coordination, otherwise their positive effects would not be additive. Such coordination requires a strong interaction among the different institutions that are in charge of managing the different categories of measures. The ITSC believes that such institutional coordination may be difficult to achieve in Italy in view of the existing administrative fragmentation.

The PGRA also states that “The management and non-increment of risk may also be pursued through actions such that possible negative consequences of floods are distributed over equally hazardous areas with lower economic value”. *This new philosophy, which is supported in concept by the ITSC, is stated in PGRA but does not appear to have been applied in the PGRA.*

*The measures planned by PGRA were taken from the PAI with some modifications that do not seem to be inspired by the need to preferentially protect areas of enormous value like Florence (or Pisa).* On the contrary, as a result of the new philosophy of AdB, the Plan does no longer include, except for extreme cases with reduced priority, protection measures that are now considered characterized by strong impact,

like dams. Conversely, a large number of flood detention areas as well as some new measures like ‘natural expansion areas’ or ‘green infrastructures’ in the Casentino, upper Valdarno and Sieve are included. *No evaluation of the impact of the whole set of planned structural measures on flood propagation, sediment transport, and hydraulic risk in the basin (most notably in Florence) is reported in PGRA.* It is not clear to what extent their impact will be effective in significantly reducing the risk in Florence, nor is it clear whether these choices are supported by cost-benefit analyses. *Finally, while the PGRA identifies cultural heritage as one of the major assets to be protected, the suggested measures appear inadequate to provide this protection.*

## 6.4 Progress

### *Figline Storage*

The ITSC notes favorably the progress made by Tuscany Region in moving forward with plans and implementation of off-river storage in the Figline area. However, it appears to the ITSC that progress has been delayed by major bureaucratic hurdles that require multiple approvals and time stretching reviews. *There is clear need for an effort, to be undertaken at the national level, to examine the processes involved in developing these non-structural approaches with a view to simplifying procedures in order to reduce the time scale of the approval activity.*

### *Levane Dam*

It appears to the ITSC that the proposed raising of the spillway of the Levane Dam will provide much needed storage and that the work should be accelerated, including a sediment management plan to control siltation and preserve storage capacity. Proposed funding from the Government should move the project forward.

### *La Penna Dam*

The ITSC acknowledges with pleasure the inclusion in PGRA of the previously abandoned plan to raise the spillway of the La Penna Dam to provide additional flood storage among those that will be reexamined in the near future. ITSC feels that consideration should also be given to periodic swapping of flood and hydroelectric storage in its pool to provide increased flexibility in its use. As for the Levane Dam, a sediment management plan also will be needed to maintain the storage gained by raising the La Penna Dam. Also worrisome is the lack of any mention in PGRA regarding watershed sedimentation. There is no point in raising any of the dams if the storage capacity gained by doing so is eventually lost to accumulation of sediments behind them. *The ITSC is also aware of local concerns over the implementation of additional storage at La Penna, but believes that the impact of these concerns is much smaller than the impact of potential downstream losses without the raising of the dam.*

### *Off-river Storage*

The ITSC also acknowledges with pleasure that PGRA shares its view that the use of Sieve River basin off-river flood storage remains a logical and feasible ap-

proach to reduce flood risks although, regrettably, it sees that the earlier proposal of a reservoir at Dicomano is no longer included among the planned measures. This is difficult to understand as early works, mentioned in Sect. D3, suggested the significant impact that such a reservoir would have on reducing the peak flow in Florence for 1966 like events. Planning of off-river storage should be accelerated as the longer implementation of the off-river storage measures is delayed, the greater the possibility that development in the region will make use of the land infeasible. The planned storage to be obtained along the Ambra tributary, which played a major role during the 1966 flood, should also be implemented, recalling that De Marchi Commission (1969), estimated that Ambra contributed to the 1966 flood with  $1030 \text{ m}^3/\text{s}$ . *Use of off-river storage on the Arno and its tributaries will require skilled management of the operation of these facilities and coordination among all the institutions and individuals engaged in the process. Such a management program does not yet appear to be in place.*

## 6.5 Further Investigations

### *Open Questions on Flood Risk*

The plans outlined above were prepared by adopting simplified procedures for estimating the boundary conditions (inflowing hydrographs) for some of the tributaries. It seems that these techniques may not allow a proper evaluation of actions that are taken along these inflowing catchments.

*Furthermore, the ITSC's review suggests that there is no clear agreement or understanding of the target conditions to be achieved as a flood passes through Florence i.e. the flow that must be passed without overtopping the banks: the peak flow of the 1966 flood or the peak flow for some other flood return period?* Similarly, there is no clear agreement on the flood volume to be considered. Even the fundamental question of what is the maximum flow discharge the Arno River can pass through Florence without overtopping its banks does not seem to have been conclusively answered. The issue of sediment transport associated with floods has not been properly addressed either, even though the 1966 event deposited vast amounts of mud throughout Florence. Ignoring the dynamics of sediments in both the Arno River itself as well as in its drainage basin could potentially reduce the effectiveness of any measures taken to protect Florence and its surroundings against floods. The scientific community may provide much needed support in tackling these delicate issues, which require advanced modeling and visualization techniques. It is regrettable in this respect to note that little work has been published in the last fifty years by academic institutions on the hydrology, sedimentation and hydraulics of the Arno River. This is in contrast with the enormous attention, in terms of involvement of scientific institutions and research funding received in the same period by Venice with the aim of finding appropriate solutions to protect the city from high water events and preserve wetlands.

### *Open Questions on Risk for Cultural Heritage*

At present, there is no assessment available of the impact of a flood in Florence on cultural heritage. Hence, no cost-benefit analysis has been employed to justify

choices concerning what structural measures are needed and what is the residual risk that may be allowed for a city like Florence. Although specific security procedures for the single sites and museums have recently been elaborated (Acidini, 2016), they do not appear to be part of a comprehensive flood management plan based on modern monitoring techniques and advanced modelling tools. A detailed socio-economic analysis is needed to identify priority for intervention and strategies for real time flood management to preserve cultural heritage.

#### *Global and Regional Data Management*

Collection and storage of data and the provision of access to these data will be critical as planning continues and sophisticated flood management begins. *The ITSC believes that the Water District Authority should be focal point where the knowledge from the relevant actors converges.* It is necessary to bring together the expertise of local administrations, advanced scientific knowledge to profit from recent scientific and technical innovations, and 21<sup>st</sup> century monitoring techniques. The ITSC also recommends considering the use of global scale environmental information, provided by the European environmental services and forecasting systems, to promote an optimal and transparent integration of local and large scale open-access observations.

### **6.6 The Arno River channel in Florence**

Any solution for Florence will require consideration of modifications to the Arno River channel and its control structures as it flows through Florence. Since there are any numbers of potential solutions, it becomes imperative that both physical and numerical modeling of alternative approaches be undertaken and supported. Indeed, the Arno River in Florence has infrastructure that limits its ability to safely convey water and sediments downstream. While further structural changes of bridges might be extremely complex in implementation and thus not as critical for further study, *it is important to thoroughly investigate the hydraulics of the bridges as well as the effects of possible modifications of other hydraulic structures in the Arno channel such as weirs (i.e. pescaie)*, since their only role these days is to maintain a pool of water. However, it should also be noted that the impact of channel modifications and upstream structural measures could have unforeseen influences on groundwater in the region. These potential impacts need to be thoroughly studied, and at the present time have not been.

#### *Protecting the Arno River Ecosystem*

Channel modifications, especially in the city of Florence, will have impacts on the natural environment of the river water quality and its carrying capacity and need to be thoroughly considered. During its meetings, the ITSC was not able to determine what actions have been taken to investigate the removal of sandbars, islands and vegetation from the channel both from a flow and an environmental perspective and to consider what alternatives might provide a combination of increased flow and environmental enhancements within this channel. The ITSC is pleased to note that



the latest version of PGRA appears to realize the importance of this problem, which will require attention in the future. The ITSC also believes that engineering studies underway at the University of Florence will add considerably to the corporate knowledge of what geomorphological actions are underway and what actions need to be taken to ensure the safe passage of flood flows through the city.

#### *Reliable Hydraulic Data*

The ITSC remains concerned over the lack of reliable hydraulic data. In particular, rating curves of monitoring stations appear to be mostly unreliable, preventing an adequate support to the validation of hydrologic predictive activities. The hydraulic discharge characteristics of bridges and weirs are not known thus pointing to the need to conduct both laboratory experiments in tandem with 3D hydrodynamic modeling to assess the flow rating curve for each one of these structures along the Arno River in Florence. Efforts should be made and resources identified by national and regional governments to overcome these shortcomings and promote advanced research.

### **6.7 Communicating the flood risk to the public**

The ITSC believes that, while the citizens of Florence may be aware of some potential flooding from the Arno River, it does not believe that they have adequate understanding of the magnitude and significance of this flooding. It is critical that national, regional, and local governments work together to communicate these risks to the public and develop an integrated plan to deal with the hydrologic risks they face.

#### *An Arno River Museum*

The ITSC believes that the development of a permanent museum of the Arno in Florence and dedicated to the story of the 1966 Flood, the community and international efforts in support of recovery and the continuation of risk reduction efforts since the flood, would serve not only as an effective reminder of the continuing flood challenge but also as an important stop for visitors to the city. The museum would also be an ideal location for the siting of the needed hydraulic model of the river flow through Florence. Installation in the city of a physical model of the Arno River as it flows through Florence would serve not only the technical purposes of hydraulic analysis but could be a method of communicating risk reduction activities to the people of the community.

#### *Use of Books and Films*

The ITSC also suggests that publishing new editions of some of the books and films produced since the 1966 flood (e.g. Batini's *4 November, 1966: The River Arno in the Museums of Florence*, Zeffirelli's film, *Florence: Days of Destruction*, etc.) could be a good way to refresh the memory of the impact the 1966 flood had on Florence. It could also help people understand, in particular younger generations, what is meant by risk of flooding in Florence and the devastating impact a large flood could

have if no measures are taken. The media could be made available in modern formats in the Arno River Museum and in stores throughout the city.

### 6.8 Climate change impacts

The ITSC was asked to take into account, in its review, the potential impacts of climate change on flooding in Florence. Because the Arno Basin is relatively small on a global scale and covers a small geographic area, it is very difficult to find reliable projections for potential changes in precipitation in the Arno Basin. Downscaling from global models to small basins is filled with uncertainty. This is especially true because large errors develop in areas with very complex orography, characteristic of the upper reaches of the Arno. Initial calculations by climate scientists indicate that there may not be major shifts in precipitation amounts on an annual basis in central Italy, however as the IPCC notes, a hazard may result from intense rainfall events during short time periods which create ideal conditions for flood events. It is the opinion of the ITSC that, given the uncertainties currently present in forecasting precipitation under climate change, the focus on protecting Florence should be on a 1966-like flood event. In whatever way climate will evolve, re-occurrence of a flood with a discharge peak and volume similar to that in 1966 is a real possibility. For all practical purposes, the 1966 event should be considered as the “design flood” regardless of the recurrence a hydrologic frequency analysis might assign to this catastrophic flood.

### 6.9 Principal Observations and Recommendations

Throughout this report, the ITSC has identified areas of concern and that merit further attention by relevant parties. It has also provided, in several cases, recommendations for action. Listed below are those observations and recommendations that are judged by the ITSC to be the most significant for decision makers and the public at large.

#### *Observations of the ITSC*

*Florence remains at risk to significant flooding and this risk grows each day.* It is not a question of whether a flood of the magnitude and volume of 1966 or greater will occur, but when. In fact, the level of protection that exists in Florence at the present time does not yet provide the risk reduction needed for this city and is not on a level appropriate to the citizens and treasures that rest within the city. Since 1966 actions have been taken to reduce the risk to flooding. These actions have not been sufficient to provide the standards of protection that one should expect for a city like Florence.

*At the current pace of activity, ongoing flood risk reduction efforts will not ensure the safety of the city and its patrimony for many decades to come.*

*While the preservation of Florentine treasures is an important concern of Italy and the nations of the world, the principal responsibility for Florence protection rests with*

*the governments of the city, the region and Italy.* It is also important for these governments to understand that the time and resources that would be required to recover from the shock of another flood would be much longer and much larger than in the past and therefore the economic consequences would last longer. The latter implication is even more concerning in view of the current international economic crisis.

*There is no single approach that will address all of Florence's flood problems and that will be successful in reducing the risk to a reasonable level.* Success will require development and implementation of a portfolio of measures, both structural and non-structural, including increasing preparedness and real time management of floods. Flood storage in the Levene and La Penna reservoirs may contribute to risk reduction, provided that management policies, including sedimentation control, ensure that the storage is actually available at the time of the flood peak. An effective integration of different measures requires a strengthened coordination among institutions. Therefore, reducing administrative fragmentation in flood risk management is imperative.

Some of the above measures are already found in the latest version of PGRA; others must be conceived or more fully developed and considered as implementation of the plan or its modifications move forward. The ITSC recognizes that the structural measures mentioned above represent only one part of the portfolio needed to deal with flooding and that nonstructural measures also should be part of the portfolio. *The use of such measures as land-use planning to reduce future occupancy of higher hazard areas, relocation of non-historical structures at most risk, early warning systems, flood insurance, and flood-proofing, where they have not already been put into place, should be part of the risk reduction portfolio and will complement other emergency measures already in place or being considered.*

*The ITSC notes a positive change in the approach of the Government of Italy to face longstanding issues concerning hydrologic and hydraulic hazards.* Without National support of the risk reduction programs of the region, significantly reducing the risk to Florence will not be possible.

#### *Recommendations*

The ITSC recommends that:

The Italian Government, being aware that the protection of Florence is an issue of national and international relevance, should urge the appropriate Institutions (Florence, Municipality, Tuscany Region, Water Basin Authority, National Civil Protection) to prepare, on an accelerated time-schedule, and submit to its attention a comprehensive plan, which integrates structural and non-structural measures.

The plan should be structured so as to maximize the coordination among mitigation measures being employed therefore resolving the current fragmentation among responsible bodies. It should be detailed enough to define what further interventions are needed, with their feasibility based on a cost benefit analysis and a realistic time scale for their implementation. The plan should also include a comprehensive assessment of the socio-economic impact of a flood similar to the 1966 event on Florence and its cultural heritage. *ITSC also suggests that the Italian Government should appoint an independent international committee (including no member of ITSC) to*

*serve as an advisory body in the preparation of the comprehensive plan.*

*A number of structural measures that have been suggested or are in the process of being implemented be reviewed* to consider, where appropriate, alternatives or modifications to these projects which were initially developed nearly 20 years ago, should be undertaken. Sedimentation processes should be included in the evaluation of different alternatives, particularly in the case of the Levane and La Penna Dams since siltation could drastically reduce the amount of storage available for flood control.

*An international 'call for ideas to save Florence', similar to the successful initiative undertaken in the 1970s for Venice, might also help.* An interesting precedent can be found in LA CITTÀ E IL FIUME, ARCH / UNDER, Trenta progetti per Firenze (Milan: Electa 1987) which features 30 urban planning projects submitted by young European architects on the theme of Florence and its river, the Arno.

Since any solution for Florence will require consideration of modifications to the Arno River channel and its control structures as it flows through Florence and there are any numbers of potential solutions, both *physical and numerical modeling of alternative approaches be undertaken and supported.*

#### 6.10 Time for action – final words

Priority must be given to acceleration in the realization of the planned and evolving measures. Waiting for major flooding to occur to provide a reason for risk reduction implementation, is not in consonance with our collective responsibility to care about Florence and its world treasures. The clock is ticking.

## Appendices





## Appendix A

### References\*

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## Appendix B

### ITSC Members

**Günter Blöschl** is a Professor of Hydrology and Water Management at the Vienna University of Technology where he is heading the Institute of Hydraulic Engineering and Water Resources Management. His research interests revolve around understanding hydrological processes and predicting hydrological risk. He is a strong advocate of bridging the gap between fundamental process understanding and the practice of water resources management. He designed an online system of flood risk mapping in Austria and the flood forecasting system for the Upper Danube River. The German flood design guidelines are based on his concept of Flood Frequency Hydrology. Recently he was awarded an ERC Advanced Grant on River Flood Changes. The fruits of his research (over 300 articles and 17000 citations) have been recognised by his receipt of numerous honours including the Horton Medal from the American Geophysical Union. He is an Editor of Water Resources Research and other journals, Corresponding Member of the Austrian Academy of Sciences and Member of the German Academy of Science and Engineering. He chairs the Scientific Advisory Council of the German Federal Institute of Hydrology, was Past President of the European Geosciences Union, and is the incoming President of the International Association of Hydrological Sciences.

**Gerald E. Galloway**, PE, PhD, (Committee Chair) is a Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park, Maryland, where his focus is on water resources policy, resilience, and disaster risk management under climate change. He serves as a consultant to several international, federal, state and non-governmental agencies and has been involved in water projects in the US, Europe, Asia and South America. He recently chaired a National Research Council (NRC) Study on Levees and is currently a member of the US National Academies' Resilient America Roundtable, the Louisiana Governor's Advisory Commission on Coastal Protection and Restoration and the Maryland Coast Smart Council. In 2014, he was appointed by the government of Singapore to a panel of experts advising on sea-level rise challenges. He is currently serving as a consultant on flood risk management for Army Corps of Engineers, and as an elected member of the National Academy of Engineering, the National Academy of Public Administration, and the National Academy of Construction. He is a 38-year veteran of the US Army, retiring as a Brigadier General and Dean (Chief Academic Officer) at the US Military Academy at West Point.

**Marcelo H. Garcia**, PhD, is M.T. Geoffrey Yeh Chair in Civil Engineering and Professor and Director of the “Ven Te Chow” Hydrosystems Laboratory at the University of Illinois Urbana-Champaign. His research interests are in fluvial hydraulics and water resources engineering. He served as Editor of the International Journal of Hydraulic Research (IAHR) and the ASCE Manual of Engineering Practice 110 “Sedimentation Engineering”. Delivered the Borland Hydraulics Lecture at Colorado State University, the Enrico Marchi Lecture, Florence, and the Donald Harleman Lecture at Penn State. For his work on hydraulics and sedimentation engineering, he was recognized with the Hunter Rouse and H.A. Einstein Awards from ASCE and the Ippen Award from IAHR. He held invited professorships at the University of Genoa, the Ecole Polytechnique Federale de Lausanne, and the California Institute of Technology. He has worked on flooding in the Chicago and Illinois Rivers, providing also expertise in the Fargo-Moorhead Metropolitan Flood Risk Feasibility Study, flood protection schemes in Guayaquil, Ecuador; sedimentation in the Sacramento-San Joaquin Delta, California, and flood protection schemes in the Bogota River, Colombia. He is a Distinguished Member of the American Society of Civil Engineers and Corresponding Member of the National Academy of Engineering of Argentina.

**Alberto Montanari** is Professor of Hydrology and Hydraulic Works University of Bologna, where he is chairing the Department of Civil, Chemical, Environmental and Material Engineering. He is currently teaching “Hydraulic Works”, “Sustainable Design of Water Resources Systems” and “Coastal Engineering”. His research activity mainly focuses on the use of innovative information and techniques for flood risk estimation and mitigation under environmental change. He authored more than 100 peer reviewed publications in international scientific journals which collected more than 3000 citations. He is a co-author of the National Strategy and Plan for Climate Change Adaptation in Italy and a consultant for several national and international projects for water resources and natural hazards management, including the Millennium Dam in Ethiopia. He is the Editor in Chief of Water Resources Research and the President of the International Commission of Water Resources Systems of IAHS. He was the founding chair of the Panta Rhei Scientific Decade 2013-2023 of IAHS, which focuses on Change in Hydrology and Society. He was President of the Hydrological Sciences Division of the EGU and Chair of its Union Award Committee. He is a recipient of the Union Service Award of the European Geosciences Union and is fellow of the American Geophysical Union.

**Giovanni Seminara**, graduated in Civil Engineering at the University of Genoa and was awarded a PhD in Applied Maths at Imperial College, London. He held a chair at the University of Genoa until November 2015, when he retired. His academic and professional interests include bio-fluid- dynamics, hydro-, morpho- and eco-morphodynamics of rivers, estuaries and lagoons. Correspondent Fellow of the Accademia dei Lincei, Fellow of the Ligurian Academy of Science and Humanities, Fellow of Venetian Institute of Sciences Humanities and Arts. Has served in the European Mechanics Council, the governing body of the European Mechanics Society. Author of papers published in several major journals (*Ann. Rev. Fluid Mech.*, *J. Fluid Mech.*, *ZAMP*, *Proc. Roy. Soc.*, *Physics of Fluids*, *Appl. Mech. Review*, *Earth Surf. Proc.*

Landforms, Water Res. Res., J. Geoph. Res., Geomorphology, Geoph. Res. Letters). Worked on several river projects, including Tanaro, Magra, Bisagno and Carrione. Served as expert in various National Institutional bodies, including Magistrato per il Po, Magistrato alle Acque di Venezia and Commissione Grandi Rischi. He represented the Ministry for scientific research in the inter-ministerial committee convened by the Prime Minister Prodi in 2006 to assess the feasibility of the MOSE project for the safeguard of Venice.

**Luca Solari**, PhD, has a background in Civil Engineering. He obtained a PhD in Hydraulic Engineering from the University of Padua on 2001. He is Associate Professor of Hydraulics at the Department of Civil and Environmental Engineering of the University of Florence from 2011. He obtained the national scientific qualification for Full Professor of Hydraulics on January 2015. His research activity is mainly in the field on sediment transport, river and lagoon hydro- morphodynamics. Research methods include laboratory experiments, field observations and mathematical modeling. He is author of scientific papers in major peer-reviewed international journals (e.g., Water Resources Research, Journal of Geophysical Research, Geomorphology); Associate Editor for the Journal of Hydraulic Engineering (ASCE) and the Journal of Geophysical Research- Earth Surface; Reviewer for many leading international journals, and for national and international research projects. He is involved in various scientific projects funded by various Institutions (e.g., Tuscany Region, Italian Ministry of Education, KTH in Sweden). He has supervised and co-supervised 8 Ph.D. candidates (5 already graduated). He is currently teaching 'Fluid mechanics' and 'Environmental fluid dynamics' at the Engineering School of the University of Florence.



## Appendix C

# The Arno River, Florence and Flood History

### C.1 Background

The purpose of this appendix is to provide a brief overview of history of flooding in Florence, the origins of the hydraulic problems related to the flow of the Arno River through Florence, information on the most significant floods that occurred in the past, and the variety of solutions proposed through the centuries to reduce the vulnerability of Florence to flooding. Sections of this appendix are found in Chapter 1. Because the topic is so vast, this report does not pretend to be exhaustive.

### C.2 The Arno River in Florence

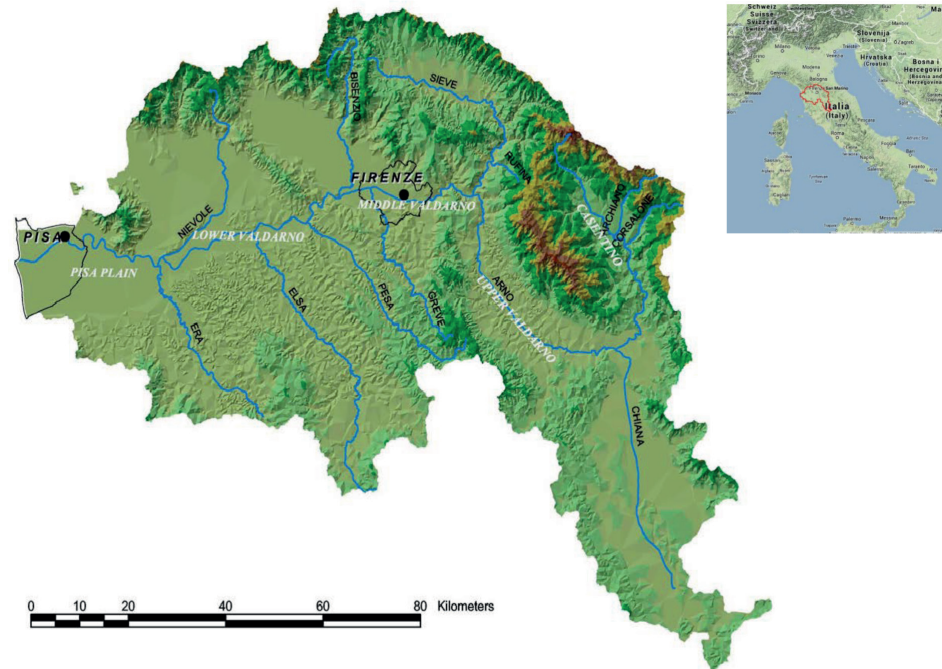
#### The drainage network of the Arno River

The Arno River Basin is mostly confined within the region of Tuscany in Central Italy. The length of the river is 241 km. The catchment area is about 8 238 km<sup>2</sup>. Its mean elevation is 353 m a.s.l.

The Arno Basin (Fig. C-1) is composed of four major reaches: starting from upstream the *Casentino*, the *Valdarno superiore* (upper Arno valley), the *Valdarno medio* (middle Arno valley) with the Florence plain, and the *Valdarno inferiore* (lower Arno valley) with the Pisa plain. The Casentino drains the valley bounded by the Alpe di Catenaiola (east), the Falterona mountain (north) and the Pratomagno mountain (west). In this reach it receives the waters of the Corsalone tributary. The river then turns northward, receives the waters drained by the Valdichiana near the city of Arezzo, and flows into the upper Arno River Valley, bounded westward by the Chianti mountains. After receiving the waters of a major tributary, the Sieve, the Arno turns westward, crosses the Florence plain and flows into the middle Arno Valley.

The middle Valdarno drains the Tosco Emiliano Appennine northward, the Chianti and the Albano mountains southwest and the secondary chain adjacent to the Valdichiana westward. In this reach, the Arno receives the waters of various tributaries, notably the Ombrone and the Bisenzio from the north and the Greve from the south.

**Fig. C-1.** The Arno basin with its main tributaries, and location map. Also shown are the four major reaches Casentino, the Valdarno superiore (upper Arno valley), the Valdarno medio (middle Arno valley) with the Florence plain, and the Valdarno inferiore (lower Arno valley). (Reproduced from Caporali et al., 2005; location map from Mazzanti, I meeting ITSC, 2014).



**Fig. C-2.** Google map of the Florentine reach of the Arno River with indication of bridges and weirs.



It then enters the Gonfolina canyon to flow into the lower Valdarno where it receives the waters of several tributaries, notably the Pesa, the Elsa and the Era on the left and the Nievole on the right. In its final reach, the Arno crosses the Pisa plain to debouch into the Tyrrhenian Sea.

Understanding the characteristics of the Arno River in Florence from a historical perspective is crucial to understanding the origins of some of its distinct features, most notably bridges and weirs which significantly affect both the hydrodynamics and the morphodynamics of the fluvial stream.

The sequence of weirs and bridges which control the river in the Florence reach are indicated in the Google map of Fig. C-2 and briefly described below.

### Pescaie (weirs)

While the word ‘Pescaie’ can literally be translated into ‘fishing ponds’, the functions of pescaie were much wider than the latter expression would suggest. This emerges from a number of writings of ‘mathematicians’ and engineers involved in the management of the Arno basin through the centuries (see in particular Bacialli, 1774).

Pescaie were originally used to prevent bank and bottom erosion and allow for the storage of water to be employed as a natural supply for the city and to produce the energy required by the great number of water driven plants located along the river.

Le Pescaie son di due sorti, se si abbia riguardo [...] a’ diversi fini pe’ quali si fabbricano. Poiché altre si fanno per impedire l’enorme corrosione delle ripe ne’ fossi di scolo, e ne’ torrenti, come pure la corrosione de’ loro fondi: altre poi per alzare facilmente il pelo dell’acque nei fiumi, onde poter poi derivare de’ canali per uso della navigazione, e per molti altri utili oggetti, e vantaggiosi, come sono l’adacquare i campi, muovere i mulini, magli, gualchiere, filatoi, ed altri moltissimi edifizii di tal sorte (Bacialli, 1774, p. 284)<sup>1</sup>

In particular, processing wool and fabrics required *fulling mills* (*gualchiere* in Italian), i.e. mills which undertake the process of fulling, namely the beating and cleaning of cloth in water, a process whereby the loose fibres of the cloth shrank, making it a denser fabric. The Wool Merchants’ Guild owned a number of such facilities distributed along the river.

Various further uses motivated the construction of pescaie as a source of water for irrigation and for the defense of Florence from possible attacks of its enemies sailing along the Arno River.

Four weirs are located in the urban area of Florence:

- the *Pescaia di Nave di Rovezzano* at the upstream end of the urban area;
- the *Pescaia di San Niccolò*, situated in the vicinity of the Porta di San Niccolò (gate);

<sup>1</sup> The Pescaie are built for two main purposes: to prevent the erosion of channel beds and banks, to increase the free surface level in rivers and divert water into channels for various purposes, such as navigation, irrigation, mills, water driven machineries.

- the *Pescaia of Santa Rosa* located downstream of the city center, near the Parco delle Cascine;
- the *Traversa dell'Isolotto* (or *delle Cascine*) located at the downstream end of the urban area.

*Pescaia di Nave di Rovezzano*

The first reports about the mill of Sant'Andrea a Rovezzano (Figure C-3) go back to the beginning of the 15th century. The original complex included mills with an annexed village, belonging to the Alessandri family. This complex underwent a sequence of damages associated with the floods of 1547, 1557, 1589 etc., until regulation works were constructed at the beginning of the 18th century. In 1826, the complex was acquired by a Swiss family, which modernized the milling system and built a mechanical laboratory for repairs needed by the mill, so that in 1863 about twenty people were employed for the management of the mills. After the First World War, the use of the mill was changed. It was transformed into a small hydroelectric plant which produced enough energy for the needs of the surrounding area.



(a)

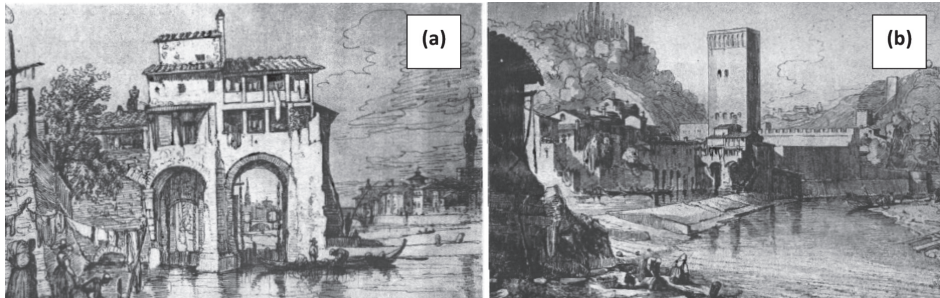


(b)

**Fig. C-3.** Different views of the Pescaia Nave di Rovezzano and the mill.

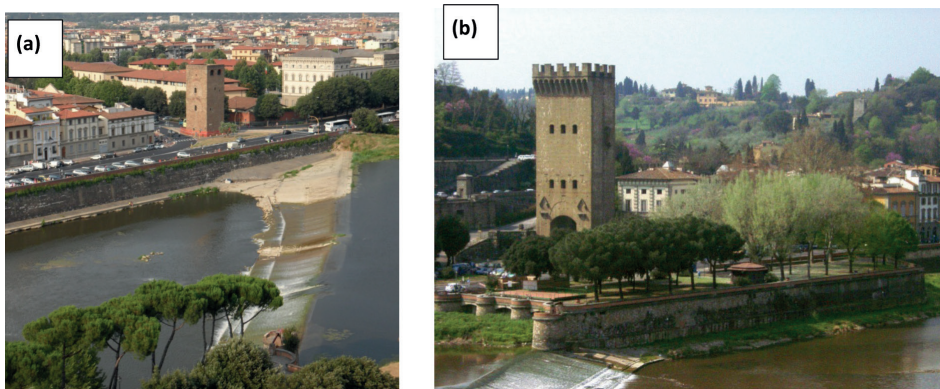
*Pescaia di San Niccolò (San Niccolò Weir)*

The San Niccolò weir (Figure C-4) furnished water for water supply to the population and water to the mills used for various manufacturing activities. At the right bank, the old Florentine mint exploited the Arno waters since the 14th century. This historical settlement was demolished in 1865, when a new city plan with new embankments (Lungarni) constructed along the river was designed by Poggi. Only the old mint tower survived and is still visible today (Figure C-5).



**Fig. C-4.** The S. Niccolò mill (a) and the S. Niccolò weir with the S. Niccolò gate (b) (Drawing of E. Burci, Museum 'Firenze com'era').

On the left bank, just below the San Niccolò tower, mills for bakery and other manufacturers were located close to a small village where people working at those factories lived. In the 19th century, as a result of Poggi's plan, these activities were removed, the city walls were demolished and the above area became the site of the new "Fabbrica dell'Acqua" (the first modern aqueduct of Florence). The mills were replaced by three large hangars where big pumps were located. They were initially driven by the Arno waters and by steam engines. Later, steam engines were replaced by powerful diesel engines, needed to distribute to the city the water arriving from the Anconella reservoirs. The whole complex was demolished in 1959, when the plant was moved to Anconella.



**Fig. C-5.** Two different pictures of the S. Niccolò weir today. (a) At the right bank note the old mint tower, the only part remaining of the mint buildings built in the XIV century and removed in 1865; (b) at the left bank note the S. Niccolò tower.

In 1875, the structure of S. Niccolò weir was reinforced and two stone tunnels crossing the Arno were constructed upstream of the weir (Figure C-6). Inside one of them a large pipe for the new aqueduct was laid down. The second tunnel was intended



to be used as a filtering tunnel for the water of the Arno. However, the tunnels were eventually used by residents as a means of crossing the river. Notably during the second world war, partisans were able to transfer food and munitions across the Arno River. In 1959, when the 'Fabbrica dell'acqua' was demolished, the tunnel was also abandoned. With no maintenance, the tunnel deteriorated rapidly and is now inundated.

**Fig. C-6.** Cross section of the Pescaia di S. Niccolò.

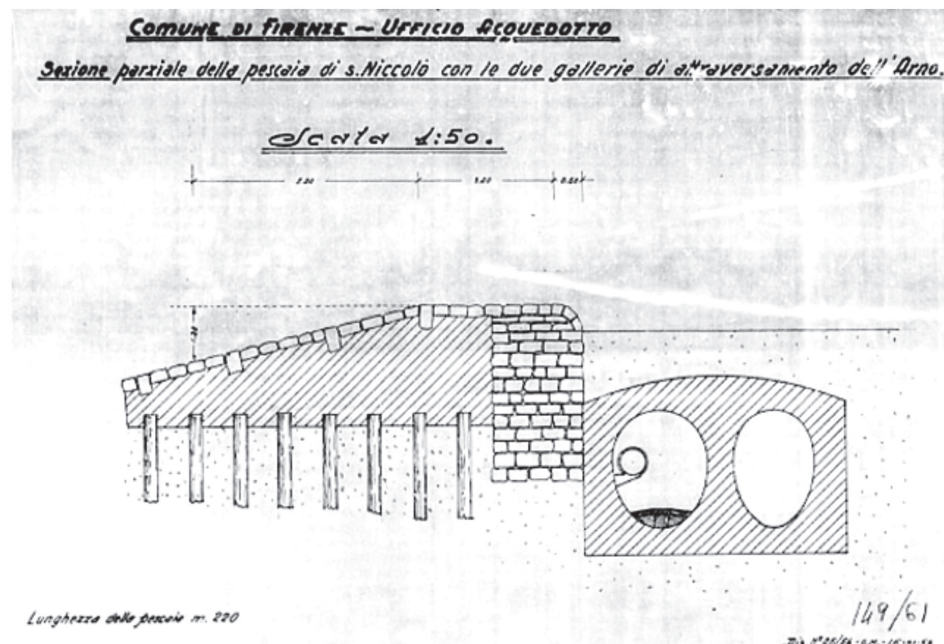
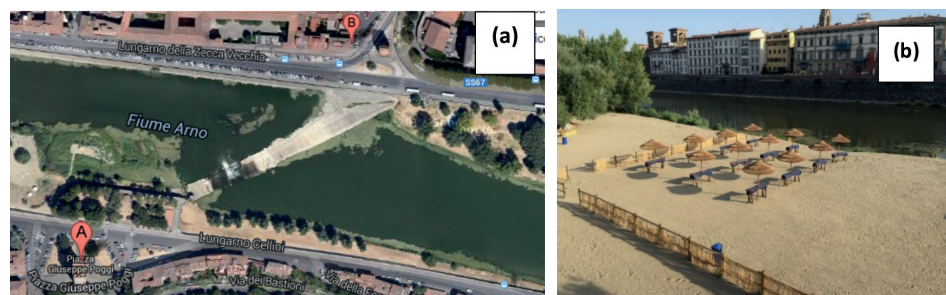


Figure C-7 illustrates that one of the effects of the Pescaia of S. Niccolò is to induce strong deposition both upstream at the right bank and downstream at the left bank where an artificial balcony protrudes into the river, leading to flow separation and enhanced settling of sediment particles. A sort of vegetated 'beach' has thus formed that is used today as a recreational beach (Figure C-7b).

**Fig. C-7.** (a) View of the Pescaia di S. Niccolò showing the strong deposition induced both upstream (right bank) and downstream (left bank); (b) The Arno 'beach' in the same site.



For centuries, the formation of sand bars has been the source of a rewarding activity pursued by the so called 'renaioli' ('rena' is a Florentine word for sand) (see Figure C-8)

who extracted sand from the Arno River. Renaioli dredged the river from small oak boats (“navicelli”), then sieved the sand, such to separate its coarser component from its finer one, which was then used to refine the wall plasters of the splendid Florentine buildings. Renaioli were able to extract an average of two cubic meters of sand per day, which were paid around 15-18 Italian Liras at the beginning of the last century by the so called ‘barrocciai’, who transported the sand to the construction sites with the help of ox carts.



**Fig. C-8.** Stanislas Poin-teau, “I renaioli d’Arno”, 1861, Private Collection.

#### *The Santa Rosa Weir*

The Arno was a navigable river up to the Pescaia di S. Rosa and since 1300 was used to transport heavy goods (Figure C-9). The boats used for this purpose (‘navicelli’) were two mast boats with flat bottom. An Arno Port thus developed close to the Pescaia and a new village (“Il Pignone”) grew around it. The word Pignone derives from ‘Pigna’, a buttress built to reinforce the left bank of the river, where boats docked. The Arno Port is mentioned since the 11th century and the Pignone quarter was described as a crowded village where ‘barrocciai’, ‘navicellai’ and shipping agents were active.



**Fig. C-9.** The Arno Port in 1700 (Anonymous painter).



The pescaia di Santa Rosa owes its name to the so called 'torrino di Santa Rosa' a small tower located near the Pescaia. Indeed, the old city walls of the 14th century reached the Arno River at San Frediano gate and ideally continued, crossing the river through the pescaia. The guard tower was located at the wall corner and was also called 'Torre della Sardigna', i.e. 'Garbage Tower' as the area outside the city walls was used to dump garbage mostly derived from butchery.

The Pescaia di Santa Rosa (Figures C-10 and C-11), was constructed by the friars (Umiliati) in the vicinity of the so called Ponte Nuovo (New Bridge) or Ponte alla Carraia. Indeed, at the Ponte alla Carraia, where the Mugnone (a tributary of the Arno) flowed into the Arno River, the presence of a small island led to the formation of a natural channel, which addressed the stream towards the weir where it could be employed to generate the hydraulic energy for mills and gualchiere.

**Fig. C-10.** The Pescaia di S. Rosa in a painting of 1744.



**Fig. C-11.** The Pescaia di S. Rosa today.





A long canal originated from the Arno at the Pescaia di S. Rosa and ran parallel to a park, nowadays called Parco dell Cascine: this canal was called ‘Fosso Macinante’ (literally *milling trench*) so called because a sequence of mills was located along its course. Only one of them, the “San Moro” mill, still exists. Note that, originally (the first news about this canal go back to 1321) the ‘Fosso Macinante’ was part of a network of artificial canals (“bisarni”) which collected the flooding waters of the Arno River to spread them in the countryside. Today, the ‘Fosso Macinante’ runs across the Parco delle Cascine, flows under the Mugnone and eventually drains into the river Bisenzio, another tributary of the Arno River.

#### *The Isolotto Weir*

This Isolotto weir is located close to the Cascine Park. It consists of an upstream weir followed by a ‘counter-weir’ downstream. Its length is about 90 m. The main body of the structure is in very bad state, due to evident structural failures (Figure C-12). Moreover, diffused syphoning of the structure is present. The counter-weir is in good state.



**Fig. C-12.** The Isolotto weir and counter-weir.

### **Bridges in Florence**

Florence bridges (Figure C-13) connect the right bank, where the historical city was located, to the left bank, a more popular area until, in the 16th century, Cosimo I moved his residence there.

**Fig. C-13.** The Arno River and its Florentine bridges: photo taken by Bob Tubbs from Piazzale Michelangelo.



*Varlungo (or Marco Polo) bridge*

Named after Marco Polo, the Varlungo Bridge is a one span modern bridge, with span length of 127 m and maximum height of 18 m. Besides crossing the Arno River, it also connects the Province Road n. 127 to the highway A1. The total length of the bridge is 375 m. Its structure is a mixed steel-concrete structure. It was built between 1979 and 1981.

To meet the various functions of the bridge the designers (Eng. L. Scali and Arch. A. Montemagni) have divided the structure into three lanes, two expressways at higher elevation and a lower lane for local traffic and pedestrians (Figure C-14, left).

**Fig. C-14.** The Varlungo bridge (left) and the Giovanni da Verrazzano bridge (right).



*Da Verrazzano bridge*

Named after Giovanni da Verrazzano (1485–1528), a well known Florentine who explored North America, this bridge (Figure C-14, right) is a one span modern bridge, with span length of 113 m and maximum height of 12 m. Its structure is a mixed steel-concrete structure. It was completed in 1980.

The designers (Engs. C. Damerini and V. Scalesse; Arch. L. Savioli) have also divided the structure into three parts: two of them, symmetric and in concrete, connect directly the two opposite banks and contain rest areas for pedestrians. The central part, in steel, joins the other two parts.

*San Niccolò bridge*

The original bridge, built in 1836-1837 not far from the Pescaia di S. Niccolò, was named after the Grand Duke Ferdinand III and had a quite modern conception, being a suspended bridge designed by a famous French firm (the Marc and Jules Séguin firm) specialized in metal structures (Figure C-15). Unfortunately, the San Ferdinando Bridge did not last long, as the great 1844 flood of the Arno River washed it out. It was reconstructed in 1853 and further modified in 1890, though keeping its metal structure, which explains its popular name “Ponte di Ferro” (iron bridge).

Just like all the other Florentine bridges (with the exception of Ponte Vecchio), the San Ferdinando bridge (in the meantime renamed S. Niccolò bridge with the fall of the Gran Duchy) was mined and blown up by the German army during its retreat from Italy in 1944. After World War II, in 1949, it was rebuilt as a single-span reinforced concrete bridge designed by the engineer Riccardo Morandi (Fig. C-16).



**Fig. C-15.** The Arno River and the S. Ferdinando bridge (the old S. Niccolò suspended bridge) in a painting of the XIX century.



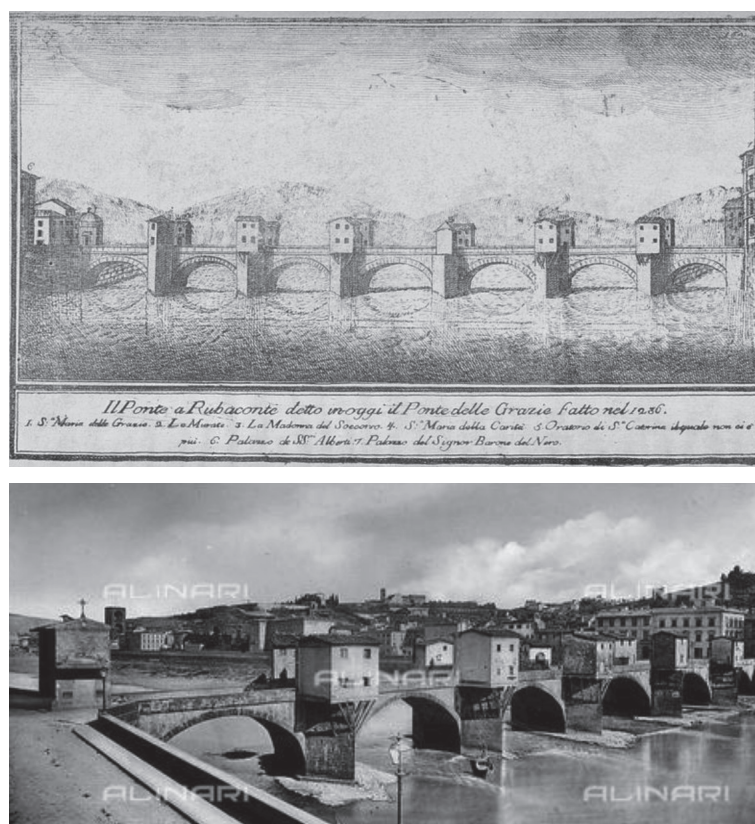
**Fig. C-16.** The San Niccolò bridge today.



*Ponte alle Grazie (Alle Grazie bridge)*

The original bridge was built in 1227 and was commissioned by the ‘podestà’ Rubaconte da Mandello. For this reason, it was called “Rubaconte”. According to Giorgio Vasari, it was designed by the architect Lapo i.e. Jacopo Tedesco. The structure, in stones, consisted of nine spans. It was the oldest and longest bridge, being older than Ponte Vecchio which, in its present form dates back to 1345. It survived all the large floods, including the 1333 flood, which washed out both the Ponte Vecchio and the Ponte Santa Trinita. The bridge has undergone a number of modifications. Two banks were removed in 1347 in order to widen Piazza dei Mozzi (*Mozzi square*) (Figure C-17 top). Later, in the 19th century, the number of spans was reduced to six (Figure C-17 bottom) when Lungarni (embankments along the Arno River) were built.

**Fig. C-17.** Ponte a Rubaconte (upper: XVII century; Lower: XIX century, photo Alinari).



Over the piles of the bridge, starting from 1292, a number of chapels, cells for hermits (called ‘romitori’) as well as small shops (just like those seen on the Ponte Vecchio today) were built. Two of these buildings were monasteries, for nuns of the orders of ‘Romite del Ponte’ and ‘Murate’. The latter nunnery was occupied initially in 1320 by a small community of secluded nuns, who were eventually moved to the Ghibellina monastery. Over the first pile of the bridge two tabernacles were erected. One was devoted to Saint Catherine, the other to the Madonna del Soccorso (The Lady of Succour). This was called “Santa Maria alle Grazie” due to the popular credence that

it would work magic. This work has been attributed to the Maestro della Santa Cecilia (end XIII- beginning XIV century) and, from it, the present name of the bridge originated. All these buildings, which had been abandoned, were demolished in 1876 to make way for railway. In August 1944, the Ponte alle Grazie, which was the only Medieval bridge which had proven able to survive all the historical floods of the Arno River, was blown up by the German Army retreating before the Allied forces!

In 1945 a competition was held to choose an appropriate design for a new bridge to replace the old one. The competition led to an intense debate, concerning the use of concrete, a material which was not thought to fit into the harmony of Florence's architecture. The final compromise was to allow for the use of concrete with an external treatment in 'pietraforte.'

The winning solution consisted of a five span bridge with slender piers and thin arches connecting them. The structure consisted of a Gerber beam in reinforced concrete. The construction of the new bridge (Figure C-18) was completed in 1957.



**Fig. C-18.** The modern Ponte alle Grazie.

#### *Ponte Vecchio*

The Ponte Vecchio ("Old Bridge") is located where the urban reach of the Arno River has its narrowest cross section.

Slightly upstream, Romans had built the first stable crossing of the Arno River, a bridge which is believed to date back to the 1<sup>st</sup> century B.C., short after the foundation of the city of Florence. This structure was widened and consolidated around the year 123, under the emperor Adriano to serve as crossing for the via Cassia Nuova. The bridge piers were likely in stones whereas the framework of beams laid over the piers was in wood. This bridge likely collapsed around the 6<sup>th</sup>-7<sup>th</sup> century due to lack of maintenance and possibly to devastations produced by floods and wars. However, little historical evidence is available of the frequent inundations of the Arno River and bridge collapses before the year 1000. Giovanni Villani mentions a bridge that

was constructed under Carlo Magno (9<sup>th</sup>-10<sup>th</sup> century) and was destroyed by a flood in 1117. It was reconstructed in stones and was also swept away by the 1333 flood, except for its central piers (Giovanni Villani, *Nuova Cronica*).

The new bridge, which has survived till present was built in 1345 (Figure C-20). Giorgio Vasari attributed its design to Taddeo Gaddi, whilst modern historians attribute it to Neri di Fioravanti. The bridge consists of three segmental arches, with the main arch spanning 30 meters and the two side arches spanning 27 meters each. The rise of the arches is between 3.5 and 4.4 meters and the span-to-rise ratio 5:1. Ponte Vecchio represents an outstanding achievement of civil engineering of the Middle Ages. The segmental arch design required fewer piers than the Roman semicircular-arch design and offered less obstruction to navigation and to the passage of floodwaters.

**Fig. C-19.** Hypothetical view of Ancient Florence in the XV century (painting of Fabio Borbottoni, 1820-1902).



The characteristic feature of Ponte Vecchio is its two-story structure. The lower story was destined to shops and merchants, subject to authorization of a local authority called the Bargello. In 1442, the butcher association monopolized the use of the shops. Butchers were later replaced by gold merchants and jewelers. This was a 1593 decision of the Medici Grand Duke Ferdinando I. Note that the 'retrobotteghe' (back shops) were added in the seventeenth century. The upper story was a gallery connecting Palazzo Pitti to the Uffizi, and other palaces. Moreover, in 1565 Cosimo I de' Medici asked Giorgio Vasari to design and build a corridor (the Vasari Corridor, Figure C-20) connecting the Palazzo Vecchio (Florence's town hall) to the Palazzo Pitti.

Various inscriptions on stones of the bridge record historical events. Ponte Vecchio is the only bridge of Florence that was not destroyed by Germans retreating before the Allies in August 1944. The Ponte Vecchio was saved by the providential intervention of the German representative in Florence Gerhard Wolf, who was awarded the honorary citizenship of Florence after the war. However, the bridge was severely damaged by the destruction of the buildings at both ends (Figure C-21), which were hastily rebuilt after the war (Figure C-22).





**Fig. C-20.** Vasari Corridor.



**Fig. C-21.** View of damage to the Ponte Vecchio from the east. The Germans destroyed all the bridges over the Arno River, with the only exception of the Ponte Vecchio, before evacuating Florence on August 11th 1944. The Ponte Vecchio was blocked by demolishing the houses at both ends and placing explosives on the bridge.



**Fig. C-22.** The Ponte Vecchio today, photo taken from S. Trinita bridge. The Ponte Vecchio was severely damaged by the 1966 flood of the Arno (see Fig. C-46).

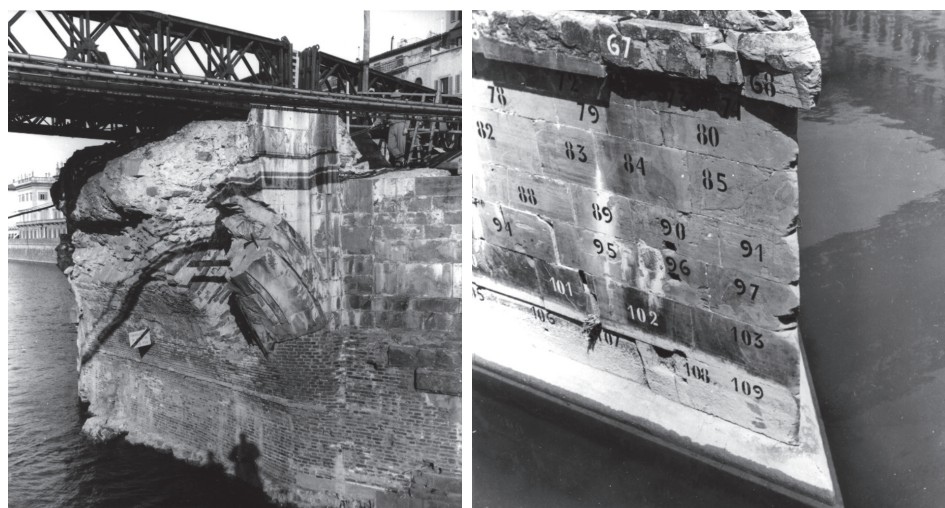
### *Santa Trinita bridge*

The Ponte a Santa Trinita (Holy Trinity Bridge) is named after a church located nearby. It has two piers connected to each other and to the bridge abutments through flattened elliptical arches (described as ‘archi a manico di paniere’ i.e. basket handle arches), a structural and stylistic mannerist innovation which made the bridge famous. The lateral and central spans have widths of 29 m and 32 m respectively.

The original bridge was designed by Bartolomeo Ammannati and was constructed in 1567-1569. Before then, a wooden bridge, built in 1252 in the same site, had been destroyed by the 1259 flood and later replaced by a new one in stone, which was also swept away by the 1333 flood. It took 69 years (1346-1415) to reconstruct it as a five arch bridge designed by Taddeo Gaddi. When the latter was again destroyed by a flood in 1557, Cosimo I commissioned Ammannati to design a new bridge, apparently with some help from Michelangelo. The works lasted four years (1567-1571). The bridge was later adorned by statues of the Seasons of various sculptors in order to celebrate the wedding of Cosimo II de’ Medici with Maria Magdalena of Austria in 1608 (Spring by Pietro Francavilla, Summer and Autumn by Giovanni Caccini and Winter by Taddeo Landini).

The Ammannati bridge did not survive the German army: it was mined and fired in the night between August 3 and 4, 1944 (Figure C-23). The decision to reconstruct the bridge in its original form was taken immediately after the war. However, the technique to be employed was the subject of investigations and a 11 year long debate (Belluzzi and Belli, 2003).

**Fig. C-23.** Left: The ruin of one of the piers of the Ponte a Santa Trinita: note the temporary Bailey bridge placed over the remaining piers by the Allies soon after the war. Right: The various parts of a remaining pier were numbered before being dismantled (Gizdulich Archive, Florence, reproduced from Belli).



It suffices here to mention that, at the end of August 1944 the National Liberation Committee of Tuscany commissioned Riccardo Gizdulich, an Architect at the *Soprintendenza ai Monumenti* (Government department responsible for monuments), to supervise the operations to recover from the bed of the Arno fragments of the collapsed structure. This effort lasted longer than one year, but the missing



head of Primavera was recovered only in October 1961, after the bridge had been reconstructed!

The main subject of the debate concerned whether it was advisable and legitimate to employ modern techniques for the reconstruction and restoration of the bridge and, in particular, whether an internal frame in reinforced concrete should be used to strengthen the structure. Art historians and architects strongly opposed the latter idea. Famous, in this respect, the statement of Carlo Ludovico Ragghianti: «la caratteristica di un'opera d'arte consiste anche nella sua tecnica, che non è scissa dalla sua forma» (“the characteristic of a work of art consists also of its technique, which is not independent of its form”). The intellectual prestige of Ragghianti and the support he received from the international community (notable the contribution of André Chastel in “Le Monde” in 1951) led to a final decision in favor of an integral reconstruction. The borough of Florence then commissioned the architect Riccardo Gizdulich, and the engineer Emilio Brizzi in 1952 to propose a new design, which was completed in January 1954. Between August and December 1955 the remaining structure was completely demolished and the reconstruction of both piers and arches initiated following the original design. However, the original materials are a minor portion of the reconstructed bridge. The original quarry of ‘pietraforte’ in Boboli, used in the 16th century, had to be reopened as stone material was insufficient to complete the covering of the structure. One of the most challenging problems the designers encountered was the reproduction of the original profile of the arches. Eventually, Gizdulich chose a reversed catenarian, which was found to fit the profiles quite well (Figure C-24).



**Fig. C-24.** Left: The Ponte a Santa Trinita during the reconstruction of the central arch, 1956; Right: The bridge just after its completion, 1958 (Gizdulich Archive, Florence, reproduced from Belli).

The bridge construction required two and a half years. On March 16, 1958, the bridge, reconstructed “dov’era e com’era” (where it was and the way it was), was inaugurated (Figure C-25). Even the statues, though damaged by explosions, could be wholly recomposed with the exception for the Spring which had lost its head.

**Fig. C-25.** Santa Trinita bridge today. View from Palazzo Bardi Guicciardini's terrace.



### *Ponte alla Carraia*

This bridge was originally built in wood and its existence was first mentioned in 1218. Destroyed by a flood at the end of the XIII century, it was reconstructed with stone piers, but fell down again and was the first bridge rebuilt after the 1333 flood. The new design (possibly by Giotto) was entirely in stone. Having been damaged by the 1557 flood, it was widened and reinforced under the supervision of Bartolomeo Ammannati, who had been assigned its design by Cosimo I de' Medici.

The bridge owes its name to its feature of being wide enough that 'Carri' (carts) would be able to go through it. The bridge was further widened in 1867, when embossed walkways were added. The bridge was demolished by the retreating German Army. The current bridge is a design by Ettore Fagioli: its strong curvature has motivated its popular name of "ponte gobbo" (hunchbacked bridge) (Figure C-26).

**Fig. C-26.** Ponte alla Carraia today.



### *Ponte Amerigo Vespucci*

A bridge to service the San Frediano quarter, planned in 1908, was never realized. It was only in 1949 that a bridge (ponte di via Melegnano) was built using remains

of ponte alla Carraia and ponte San Niccolò that had been destroyed by the German army in 1944.



**Fig. C-27.** The Amerigo Vespucci bridge.

The current bridge (Figure C-27), named after the famous Florentine explorer, was constructed in 1957. It was designed by a group of architects (G.G. Gori, E. Gori and E. Nelli), jointly with the engineer R. Morandi. It is a three span bridge with two piers connected by three thin and weakly curved arches, which give an overall impression of a single flat arch.

#### *Ponte alla Vittoria*

An old suspended bridge, named after S. Leopoldo, twin of the old S. Niccolò suspended bridge, supported by steel cables 90 m long with no piers or arches (Figure C-28), was originally built in 1836 by will of the Granduke Leopoldo II. A model of the bridge was built in the garden of one of the residences of Medici family (in Poggio a Caiano). The design and construction of the bridge was commissioned to the French Seguiz firm, which was also given the right (for 104 years) to manage the bridge, charging one 'soldo' per person. Florentines protested but only in 1914 was its use by pedestrians made free (not so for cattle, nor for cars which were charged up to 40 cents).

The bridge was quite important from the commercial viewpoint as, besides connecting one the most important factories in Florence (Pignone) to the railway (Leopolda) and to the sea, it also connected three important provinces. At the four vertices of the bridge, pillars were constructed, on the top of which marble lions in neoclassic style were laid. These sculptures were moved when the bridge was dismantled to be modified.

The first design of a new traditional stone bridge at Cascine was proposed by eng. Tognetti just before the First World War. Its building was delayed by the war, and was reconsidered after the war as a means to celebrate the victory through the construction of a work of public utility. The bridge was completed and opened in 1932 (Figure C-28). However, it did not last long, as it was destroyed by the German army on August 4, 1944.

Just after the Second World War, the military administration of the Allies ordered that the bridge should be reconstructed and the design of a group of Florentine architects (Baroni, Bartoli, Gamberini and Maggiara) jointly with eng. Focacci was cho-



sen. The bridge structure was designed such to be covered by ‘pietra forte’ and bronze. However, insufficient funding did not allow construction of the bridge according to the design. The structure was then built in bricks and, as a result, the bridge (Figure C-29) did not meet the expectations of the people of Florence, who then named it “Il Ponte della Vittoria Mutilata” (The bridge of the mutilated victory).

**Fig. C-28.** This 1932 photo shows both the Ponte alla Vittoria, just completed, and the Ponte Sospeso, shortly before it was dismantled.



**Fig. C-29.** The Ponte alla Vittoria in its present shape.



### C.3 Flooding of the Arno River in Florence: a survey

#### Sources of Information on Floods

A number of writings help us trace the records of historical floods of the Arno River through the centuries. A fairly accurate assessment of the known sources on this subject is found in Losacco (1967).

Among the old historians who provide information about the floods of the 12th and 13<sup>th</sup> centuries, the most important one is definitely Giovanni Villani (Figure



C-31). The first four chapters of the XII book of his monumental *Cronica* are devoted to a live description of the catastrophic 1333 flood and its possible causes:

Qui comincia il Libro duodecimo, il quale, nel suo cominciamento, faremo memoria d'uno grande diluvio d'acqua che venne in Firenze e quasi in tutta Toscana [...]. (Villani, *Cronica*, Tomo III, Libro XII, I)<sup>2</sup>

and its possible causes:

D'una grande questione fatta in Firenze se 'l detto diluvio venne per iudicio di Dio o per corso naturale [...]. (Villani, *Cronica*, Tomo III, Libro XII, II)<sup>3</sup>

In the Renaissance (15<sup>th</sup> and 16<sup>th</sup> centuries) the main sources come from a number of historians (Adriani, Ammirato, Buoninsegni D., Buoninsegni P., Bruni) as well as diarists (Landucci, Lapini, Masi) and hydraulic engineers (Lupicini).

In the 17<sup>th</sup> century, major sources are the writings of the engineers-mathematicians Perelli and Viviani and in the XVIII century those of the engineers Morozzi and Targioni Tozzetti (Figure C-32).

In the 19<sup>th</sup> century various engineers have contributed to the analysis of the causes of inundations and to the search for solutions, most notably Aiazzi, De Vecchi, Fossombroni, Giorgini, Michelacci and Rossini.

Finally, in the last century, a quite complete report (Natoni, 1944) was published by the engineer Edmondo Natoni. This book serves as a reference publication as it provides a thorough survey of the knowledge available around the half of the last century (Figure C-33).

A number of further publications have appeared after the great flood of 1966.

<sup>2</sup> At the beginning of the XII Book, we recall a big flood that occurred in Florence and almost everywhere in Tuscany.

<sup>3</sup> [...] the great debate in Florence was on whether the flood occurred for God's will or for natural causes [...].

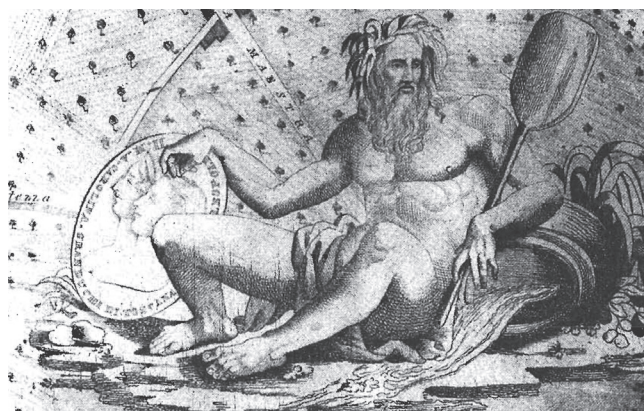
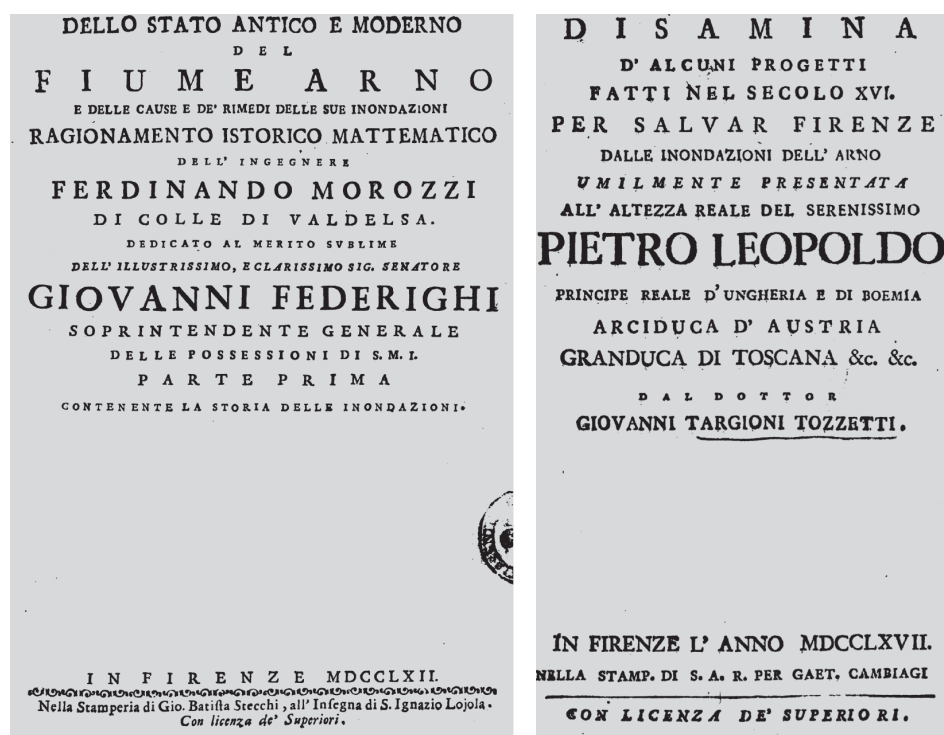


Fig. C-30. Allegorical image of the Arno river in a map of Rosaspina (1826): the Arno is represented as an old uncouth man holding an amphora pouring a rivulet of water (reproduced from Losacco, 1967).

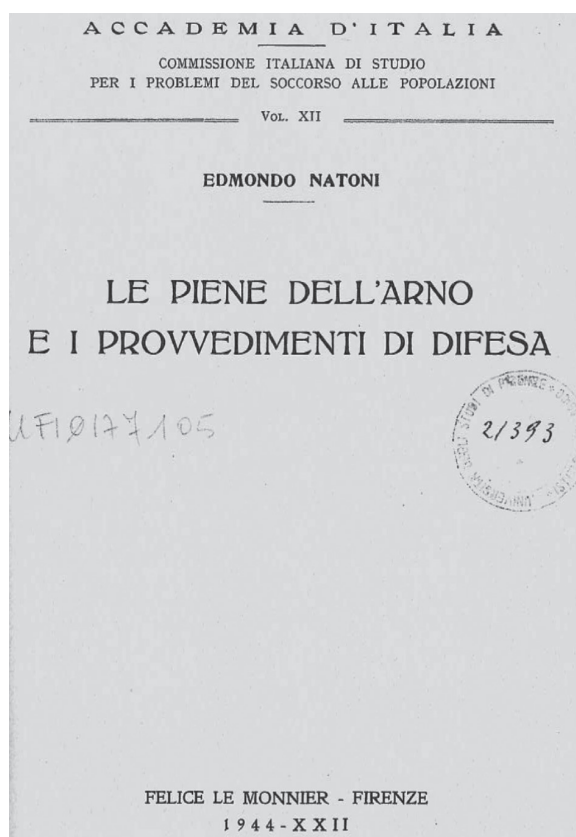


Fig. C-31. Statue of Giovanni Villani in the Loggia del Mercato Nuovo.

**Fig. C-32.** The frontispieces of two major works of the XVIII century reporting information on the flood events occurred in the Arno Basin.



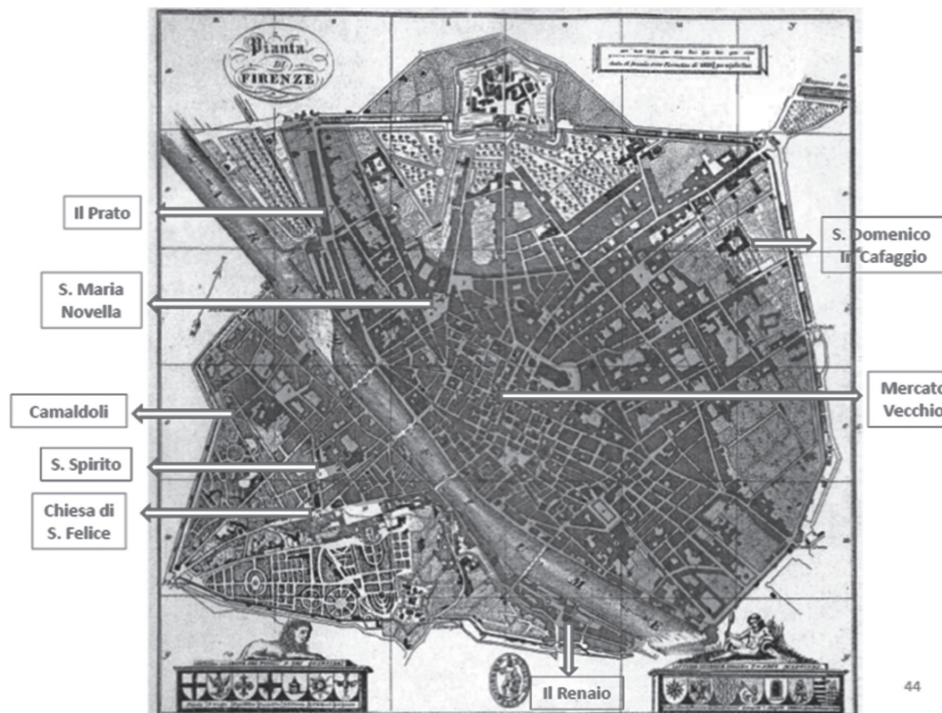
**Fig. C-33.** The frontispiece of Natoni's thorough report on the floods of the Arno River and the works envisaged for flood protection.



The great floods of the past include:

#### *The 1333 flood*

The flood occurred on November 4, 1333<sup>4</sup>, is the second largest flood recorded in the history of Florence. The flooded area of the city is vividly described by G. Villani and is represented in Figure C-34. Villani also provides detailed information about the height reached by waters at various sites of the city.



**Fig. C-34.** Map of the area of Florence inundated by the big flood of 1333 (reproduced and modified from Losacco, 1967).

The effects of the flood were catastrophic: the Pescaia d'Ognissanti (today Pescaia di S. Rosa) as well as many bridges (Ponte alla Carraia, Ponte a S. Trinita, Ponte Vecchio), were washed out. Only the Ponte Rubaconte (today Ponte alle Grazie) resisted the fury of the flood. The height of the water would have been even higher had not the city walls failed at various locations.

About three hundred people died and the damage of the city was enormous. The reconstruction of bridges and city walls cost about 150,000 golden 'fiorini'. It took about six months to remove the silt deposited by waters throughout the city.

It is of interest to mention some of the speculations reported by historians on the possible causes of this great flood.

<sup>4</sup> Note that this date refers to Julian rather than Gregorian calendar that was introduced in 1582. Hence, the actual date of the flood, referred to the present calendar, would be around mid-November.



Fecesi quistione per li savi Fiorentini antichi, che allora viveano in buona memoria, quale era stato maggiore diluvio, o questo o quello, che fu gli anni di Cristo 1269. I più dissono, che l'antico non fu quasi molto meno acqua, ma per lo alzamento fatto del letto d'Arno, per la mala provedenza del comune di lasciare le pescaie a coloro, che avevano le mulina in Arno, ch'era montato più di sette braccia<sup>5</sup> dallo antico corso, la città fu più allagata e con maggiore dannaggio, che per lo antico diluvio; ma a cui Id-dio vuole male gli toglie il senno. Per lo qual difetto venuto per le pescaie incontanente fu fatto decreto per lo comune di Firenze, che infra i ponti nulla pescaia né mulino fosse, né di sopra al ponte Rubaconte per ispazio di 2000 braccia, né di sotto a quello della Carraja per ispazio di 4000 braccia, sotto gravi pene; e dato l'ordine, e chiamato ufficiale a fare i ponti e mura cadute [...] (Villani, *Cronica*, XI book, Chapter 1)<sup>6</sup>.

Essentially, the popular feeling was that the presence of Pescaie had led to river aggradation amounting to more than 3 meters and this was the reason why devastations produced by the 1333 flood had been much more intense than in the previous flood of 1269. The Municipality of Florence then issued a decree according to which no Pescaia nor mill should be present in the Arno River in the reach between a cross section at a distance of about 1 150 m upstream of the Rubaconte bridge and a cross section located 3,300 m downstream of Ponte della Carraia. Although there is no proof of the occurrence of the aggradation process, these speculations suggest that, at that time, people were already aware of the possibility that Pescaie may have negative effects on the safety of the city of Florence when the Arno River is subject to intense events. It must also be pointed out that not many people respected the above decree, hence mills and Pescaie continued to work, as proved by a number of subsequent decrees issued by the Florence municipality.

The role of Pescaie returns in Villani's *Cronica* where he states that their collapse avoided a new inundation of the city the next year (December 5, 1334) when a new flood propagated through the Arno River. This historian also notes that, luckily, the river bed had undergone degradation by more than three meters as a result of the previous flood. This statement must be interpreted in the light of the apparently contradictory claim that the effect of Pescaie would be to induce bed aggradation of the river profile.

### *The 1557 flood*

This flood, which occurred on 13 September 1557, is the third largest flood recorded in the history of Florence. Its catastrophic consequences arose from the fact that the peak in the Arno was nearly simultaneous to the peak of its important tributary, the Sieve, which drains the Mugello area. The Ponte a S. Trinita collapsed, two arches of Ponte alla Carraia were swept away, and the arches of the Rubaconte were the only

<sup>5</sup> The Florentine 'braccio' was equivalent to 0.583 m; it was divided into 20 'soldi' (1 soldo = 2.9 cm), each of which was equivalent to 12 'denari' (1 denaro = 2.4 mm).

<sup>6</sup> The question raised by the old wise Florentine people, who had a good memory, was whether this flood was greater than the one on 1269. The majority of people said that the 1269 precipitations were not less intense, but, due to the Arno river bed aggradation, amounting to more than 3 meters and induced by the Pescaie managed by mill owners, the 1333 flood was much more devastating. For this reason, the Municipality of Florence issued a decree according to which no Pescaia nor mill should be present in the Arno River in the reach between a cross section at a distance of about 1,150 m upstream of the Rubaconte bridge and a cross section located 3 300 m downstream of Ponte della Carraia.

part of this bridge which did resist the impact of the flood. Finally, a great portion of the right bank of the river did collapse.

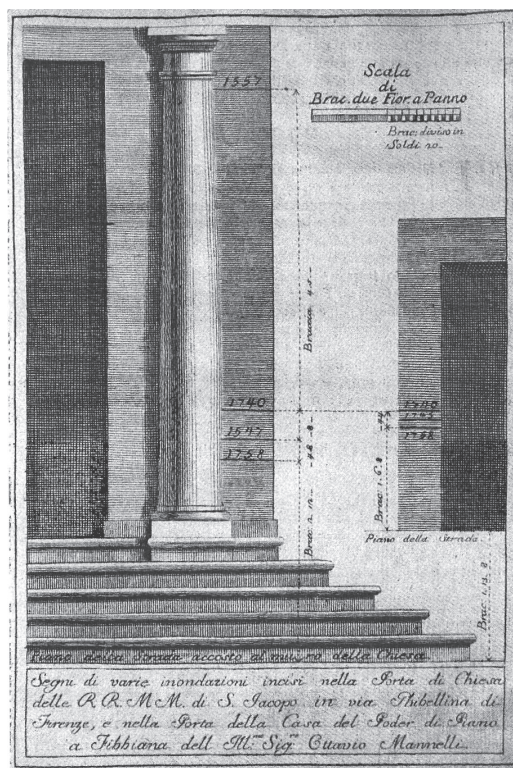
The water level reached the floor of the S. Croce church, the high altar of the baptistery, and the floor of Palazzo della Signoria.

Speculations about the cause of the flood pointed at the effect of floating wooden material (debris) stopped and piled upstream to the bridges as well as to the role of pescaie, which were built “for the benefit of mills” («[...] che si fanno per conto de’ mulini [...]»), ignoring the 1333 decree issued by Florence municipality (Ammirato, *Opuscoli*, 3, p. 401).

#### *The 1844 flood*

The 1844 flood was the last significant flood before 1966 and the one on which detailed information can be obtained from various sources. While the S. Croce quarter was inundated by the flooded waters, part of the center of the city was not affected by the inundation, notably Piazza della Signoria, Piazza del Duomo and Mercato Vecchio. The maximum impact of the flood was on the San Frediano and Camaldoli quarters. Aiazzi gives details of the height reached by the water at various sites, most notably: 5 braccia and 4 soldi at the square opposite S. Niccolò d’Oltrarno, 3 braccia at Piazza S. Croce, 3 braccia at Borgo Ognissanti (Figure C-36).

**Fig. C-36.** Sketch of the area of Florence inundated by the flood of 1844 (reproduced from Losacco, 1967).

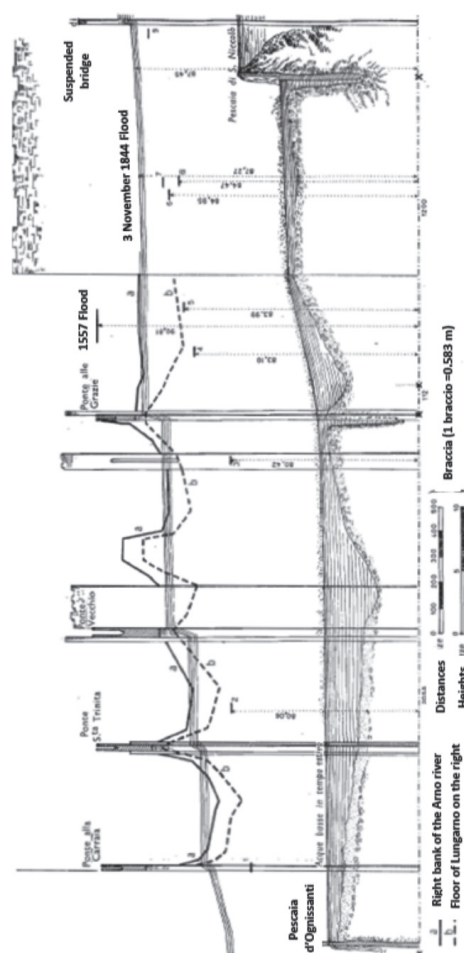


**Fig. C-35.** Marks of the heights reached by various historical floods alongside the door of the church of SS. Jacopo e Lorenzo at Ghibellina street. Note that the flood of November 1966 reached a height 60 cm higher than the 1557 flood (reproduced from Morozzi, Part one, pg. 63).





**Fig. C-37.** Envelope of the profile of the free surface experienced during the 1844 flood, compared with the elevations at various sites of the city (reproduced from Giorgini, Fig. 2, Tav. II).



A plot of the envelope of the profile of the free surface during the flood, compared with the height of the Arno side walls and the altitude at various sites of the city, as reported by Giorgini (Fig. 2, Tav. II), is reproduced below (Figure C-37). Although some features of this plot are not quite realistic (e.g. the flow profile over Pescaia di S. Niccolò), however this picture provides unusually detailed quantitative information on the characteristics of the event.

The flood also led to the collapse of the San Ferdinando suspended bridge.

The flood event involved also the upstream basin (Casentino, Aretino, Chiana, Valdarno superiore, Mugello) as well as the downstream tributaries (Greve, Bisenzio, Ombrone, Elsa, Pesa, Era, etc.). According to Aiazzi (1845), the main cause of the flood was again the fact that the peaks of the flows in the Sieve and in the Arno were nearly simultaneous.

#### *The flood of November 4, 1966*

Although the number of lives lost in the 1333 flood was higher than in

the flood that occurred on 4 November, 1966 the latter is the most catastrophic one that has occurred in the city of Florence, in terms of the extension of the inundated area and the height reached by flooded waters (see fig. C-36). Its emotional impact on the whole international community was extremely great. During the same day, other floods occurred in the Tuscany and Veneto Italian regions. The number of publications devoted to this event is thus fairly large.

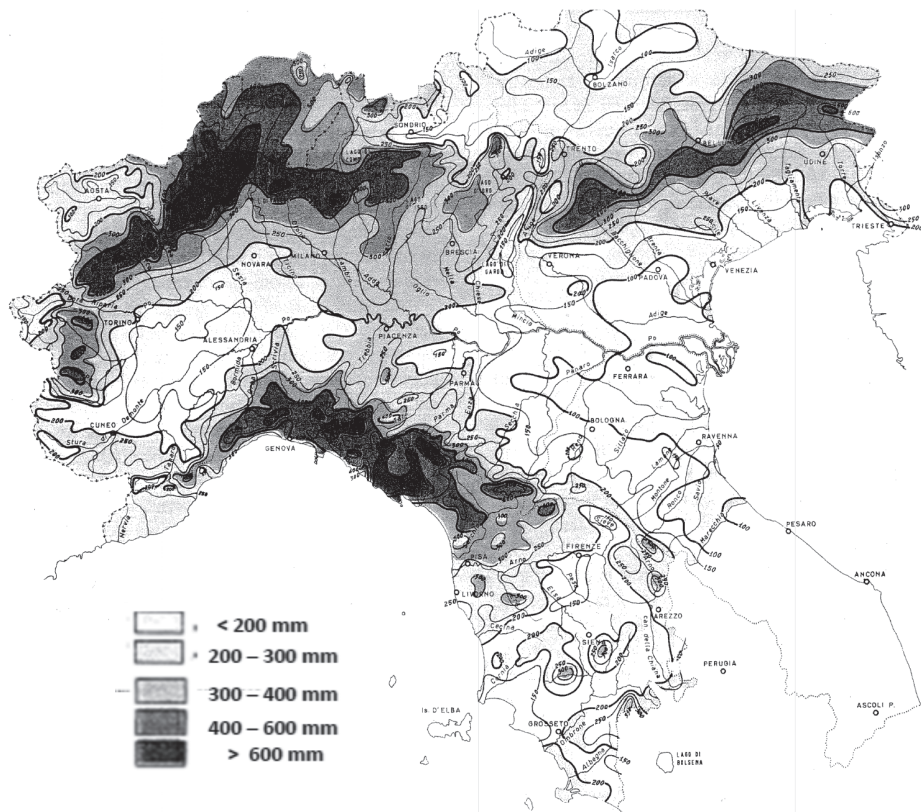
A few papers are of mostly descriptive nature, in particular Principe and Sica (1967) (which contains a map of the flooded area in Florence, with indication of the heights reached by the flooded waters), Losacco (1967), Cicala (1967), Gerola e Materassi (1966), Gerosa (1967), Nencini (1966), Simonetti (1966), Zoli (1967) among others.

Other papers are more scientifically oriented. In particular, a scientific report was issued by a major Commission, appointed by the Ministry of Public Works, called 'Commissione De Marchi', from the name of Giulio De Marchi, Professor at Milan Polytechnic who chaired it. The major task of this Commission was to analyze the hydro-geological problems of the whole Italian territory and propose adequate solutions where problems were encountered. The part of the final Re-

port concerning the November 1966 Florence flood was published in September 1969. The paragraphs below outline some of the report's findings concerning the Arno River.

### *Precipitation*

The hydrology of the 1966 event was analyzed by T. Gazzolo (1969) in one of the papers included in the report. In October 1966 intense precipitation events were recorded everywhere in Italy and several exceptional storms hit a number of regions.

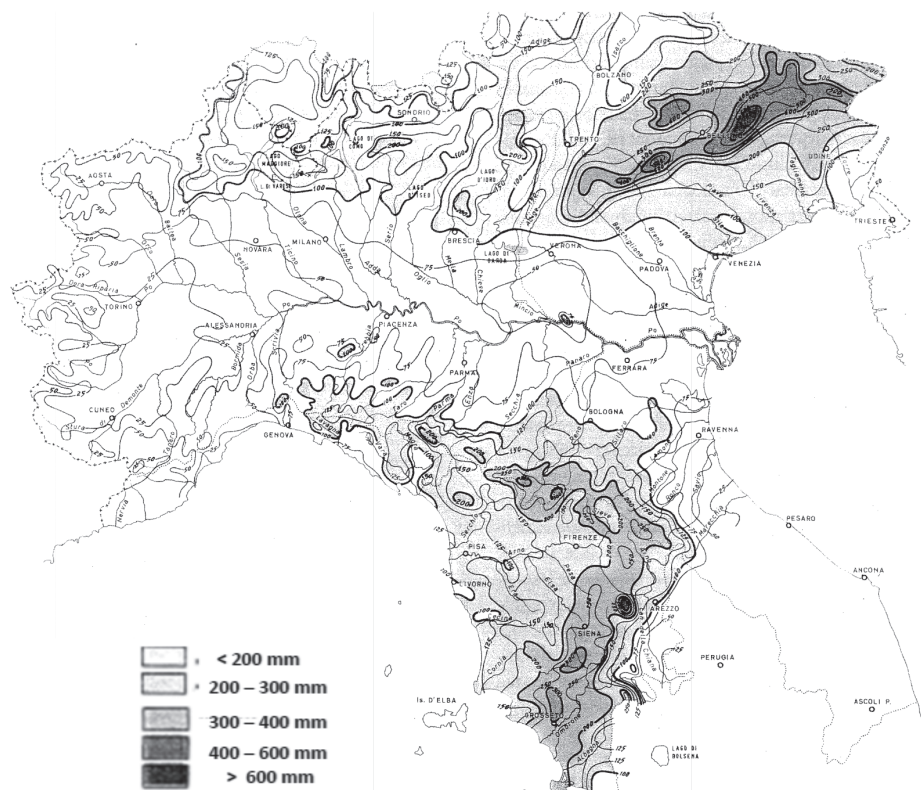


**Fig. C-38.** Spatial distribution of the cumulative precipitation recorded in October 1966 in Northern Italy (reproduced from Gazzolo, 1969).

The precipitation averaged over the whole country was 214 mm, 1.88 times the maximum previously recorded value. In particular, in Northern Italy the average precipitation was 294 mm, 2.27 times the previous maximum value. The spatial distribution of the cumulative precipitation is plotted in Figure C-38. In Tuscany, cumulative precipitations everywhere exceeded 200 mm, with a peak greater than 300 mm near Siena. These values were 1.5-3 times the maximum historical records. However, these exceptional cumulative values did not arise from intense storms (no significant flood occurred in October), but rather from persistent precipitations lasting longer than 10 days with high but not exceptional daily cumulative values.

The storm event started on November 3 in the early morning and, in the region of our interest (Tuscany), it lasted about 26-28 hours.

**Fig. C-39.** Lines of equal cumulative precipitation occurred between November 3, 1966, 9 a.m. and November 5, 1966, 9 a.m. (reproduced from Gazzolo, 1969).



The storm hit the whole Northern Italy, reaching exceptional intensity in the area of the eastern Alps and at the various sites in Tuscany, including Pratomagno, Chianti mountains, Amiata mountain and the wide plain of Maremma. Cumulative precipitations occurred between November 3 1966, 9 a.m. and November 5th 1966, 9 a.m. have been plotted by Gazzolo (1969) and reproduced in Figure C-39.

Cumulative daily precipitations on November 4, exceeded 300 mm only at Badia Agnano in the Arno basin (mm 338.7). The peak of the event occurred in the afternoon and in the evening of November 3. It then decayed in the night and increased its intensity again the next morning with peaks lower than those experienced the previous day, with one important exception: The Sieve basin was hit by the strongest storm on November 4.

More detailed information on the meteorological characteristics of the event can be found in Fea and Evangelisti (1968). A successful quantitative prediction of the observed precipitations using LAM (limited area) mesoscale models forced by the ECMWF global model was pursued by Malguzzi et al. (2006). The simulated forecasting chain resolved the convective scale (about 2 km). Results show that prediction of precipitation is strongly dependent on the initial conditions, especially when precipitation is convective, as it appears to be typical of central Italy and of the Arno River basin.

*Flow discharges*

The exceptional character of the flood experienced in the Arno basin in 1966 was due to three concurrent factors:

- first, the effects of the October event had not vanished yet, so the water levels in the Arno were significantly higher than normal;
- second, the degree of saturation of the soil subject to the persistent precipitations of the previous month was quite high;
- third, as discussed above, the intensity of precipitations was exceptionally high.

The area where floods were most prominent was the upper Arno basin, where flow discharges reached values twice as large as the maximum values recorded previously. During the night of November 3, the water level increased roughly one meter per hour in six hours until levees were overtopped and collapsed at different sites.

The Arno experienced water levels greatly in excess of values historically recorded nearly everywhere (Gazzolo, 1969):

- at Stia (contributing area 62 km<sup>2</sup>) 4.23 m (previous maximum 2.48 m on January 6<sup>th</sup> 1963);
- at Subbiano (contributing area 738 km<sup>2</sup>) 10.58 m (previous 6.24 m on February 17<sup>th</sup> 1960);
- at Nave di Rosano, just downstream of the Sieve confluence (contributing area 4 083 km<sup>2</sup>) 10.30 m (previous 7.80 m on November 2<sup>nd</sup> 1944);
- at Florence (Acciaoli) (contributing area 4 237 km<sup>2</sup>) 8.57 m (previous 7.08 m on November 2, 1944).

Reported estimates for the discharges associated with the above water levels are 312 m<sup>3</sup>/s, 2 250 m<sup>3</sup>/s and 3 540 m<sup>3</sup>/s at Stia, Subbiano and Nave di Rosano respectively (Gazzolo, 1969). The latter values are 2.35, 2.58 and 1.69 larger than previous maxima recorded at the same stations.

Many tributaries also experienced devastating floods.

The Sieve River at Fornacina station which is close to its confluence with the Arno, reached 6.90 m (previous peak was 6.06 m on September 19, 1953) corresponding to an estimated discharge of 1 340 m<sup>3</sup>/s (1 080 m<sup>3</sup>/s on September 19, 1953). The Elsa River at Castelfiorentino reached 6.00 m (previous maximum was 4.52 m) corresponding to an estimated discharge of 612 m<sup>3</sup>/s (previous maximum 380 m<sup>3</sup>/s) and the Era River at Capannoli reached 8.58 m (previous maximum 7.80 m) corresponding to an estimated discharge of 380 m<sup>3</sup>/s (previous maximum 311 m<sup>3</sup>/s) (Gazzolo, 1969).

*The flooding of Florence*

Florence was flooded in the morning of November 4. The stream overtopped the bank protections initially upstream and then next along the Lungarni, where the banks failed at various sites. Figure C-40 shows the dramatic phase when the Arno overtopped the banks at the level of Piazza Cataloger, opposite the Bibliotheca Nazionale (National Library).

The heights reached by the flooding waters (Fig. C-41) exceeded any previously recorded value, with peaks exceeding 6 m.



**Fig. C-40.** The Arno overtops the banks at the level of Piazza Cavalliggeri, opposite the Biblioteca Nazionale (National Library) on November 4, 1966 (Photo Banchi, reproduced from Principe and Sica, 1967).



**Fig. C-41.** Areas of Florence flooded during the event of November 4, 1966 with indication of the height reached by the flooded waters (reproduced from Losacco, 1967).

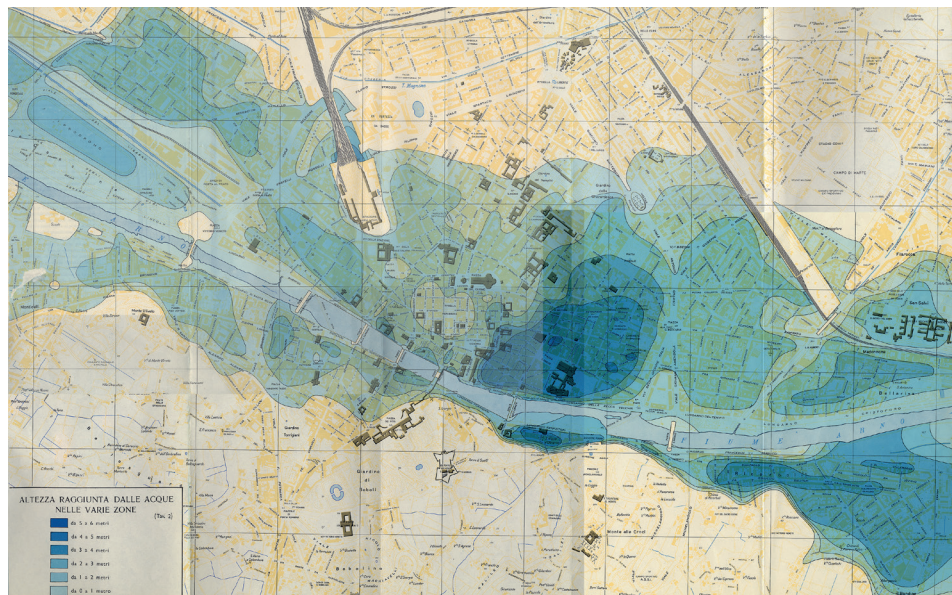
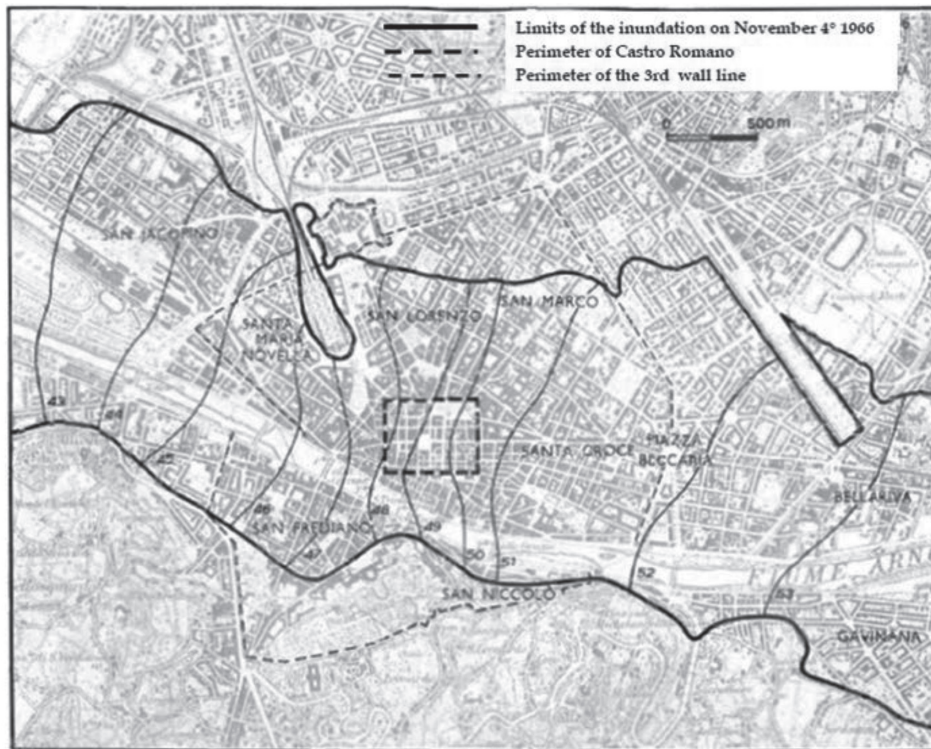


Figure C-42 provides a less detailed map showing the lines of equal elevation (above mean sea level) reached by the waters (Principe and Sica, 1967). The plot shows clearly that the effect of Ponte Vecchio and other bridges close to it determines a significant increase of the average slope of the free surface compared with the values experienced upstream and downstream.





**Fig.C-42.** Lines of equal elevation (above mean sea level) reached by the waters flooded on November 4, 1966 (reproduced and modified from Principe and Sica, 1967).



**Fig. C-43.** Overview of the Arno River showing Florence bridges during the 4 November 1966 flood: note in the foreground the Ponte alle Grazie that was completely submerged (Photo Caldini, reproduced from Principe and Sica, 1967).

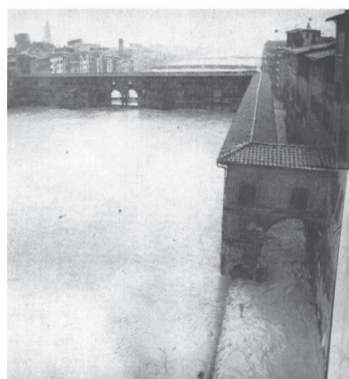
This is further demonstrated by Figure C-43, which gives an overview of the Arno River in Florence during the flood, showing the dramatic impact of several bridges. In particular, it shows in the foreground the Ponte alle Grazie, which was completely submerged!

The significant contribution of bridges and pescaie in determining the location and the intensity of flooding can be seen in Figure C-44. Note, in particular, the

strong backwater effect determined by Ponte Vecchio (Figure C-44a) and Ponte di S. Trinita (Fig. C-44b). Also, note that the Pescaia di S. Rosa was submerged (Figure C-44f) and created an apparently significant backwater effect. Figure C-45 provides some visual feeling of the size of the disaster.

Following three weeks of chaos, the figures indicating the extent of the disaster were finally assessed (Alexander, 1980; Italian National Research Council, Research Institute for Geo-hydrological Protection, 2017):

- **47 deaths in Tuscany (38 in the city of Florence and its province);**
- 800 municipalities affected (including major ones, like Florence and Grosseto);
- 12 000 farms and homes damaged, 50,000 farm animals dead or slaughtered, 16,000 pieces of agricultural machinery damaged or ruined;
- closure of many factories;
- destruction of works of art, early literature and archaeological exhibits, which will never be forgotten and will stand as a cornerstone event in the history of Florence.



(a) Photo Bezzecchi



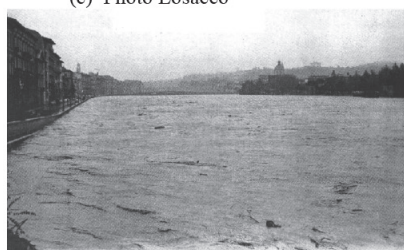
(b) Photo Banchi



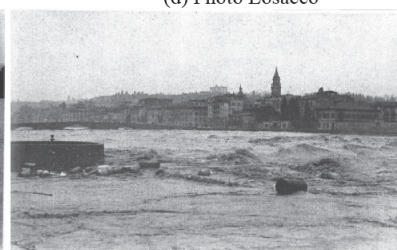
(c) Photo Losacco



(d) Photo Losacco



(e) Photo Losacco



(f) Photo Losacco

**Fig. C-44.** Florence bridges during the 4th November 1966 flood [(a) Ponte Vecchio and Galleria degli Uffizi: the Arno overtops the banks along Lungarno Archibusieri Lungarno Acciaiuoli. In the background: Ponte di S. Trinita and Ponte alla Carraia; (b) Ponte di S. Trinita showing its strong backwater effect; (c) Ponte alla Carraia; (d) Ponte Amerigo Vespucci; (e) The Arno seen from Ponte alla Vittoria; (f) The Pescaia di S. Rosa. [(a) and (b) are reproduced from Principe and Sica, 1967; (c), (d), (e), (f) are reproduced from Losacco, 1967].



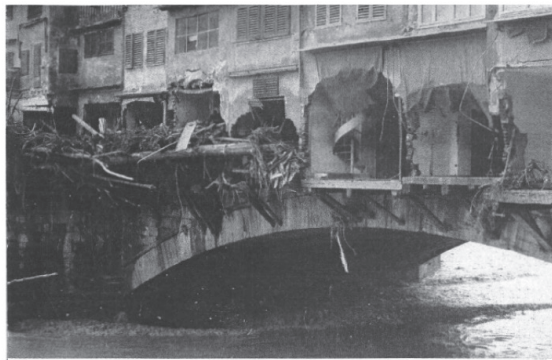
(a) Lungarno Acciaiuoli  
(Photo Caldini)



(b) Ponte alle Grazie  
(Photo Losacco)



(c) Ponte Vecchio  
(Photo Losacco)



**Fig. C-45.** Florence after the 4 November 1966 flood [(a) is reproduced from Principe and Sica, 1967; (b) and (c) are reproduced from Losacco, 1967].

#### C.4 The debate on possible remedies before the establishment of the Water Basin Authority

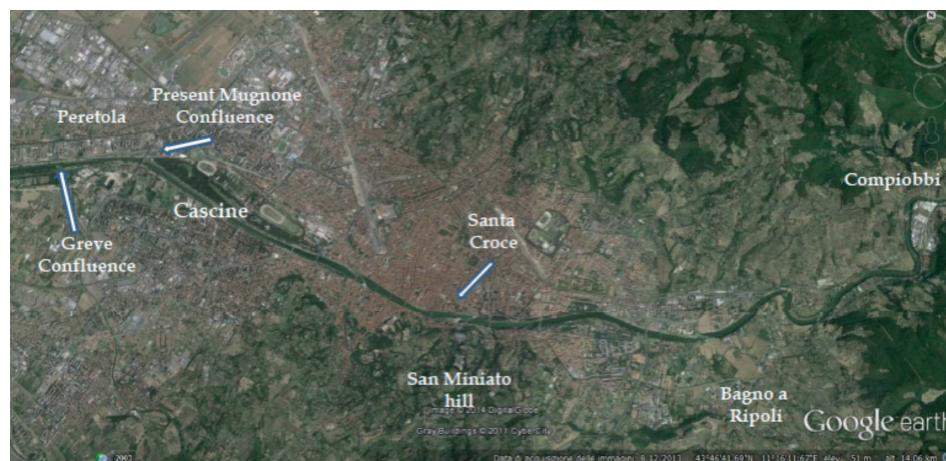
The debate on possible remedies to decrease the vulnerability of the city of Florence to flooding of the Arno River dates back to the Middle Ages and continues uninterrupted till present. This section outlines some of the suggestions that emerged from this debate.

##### Florence and the Arno: a glance at the past

It is of some interest to trace the origin of the present course of the River Arno in the city of Florence. According to Masini (1925), when the Cassia road was built (in

175 B.C.), downstream of Compiobbi (Figure C-46), the Arno wandered through the plain of Bagno a Ripoli, turned towards the San Miniato hill which forced it northward towards the site of the present S. Croce Cathedral. The river then turned towards the Cascine where it took the present course.

**Fig. C-46.** Google map of the Arno River in its urban reach through the city of Florence.



The Roman city of Florence rose up below the Etruscan city of Fiesole. The first circle of fortified walls left the Arno out of the city, hence the floods of the river did not bother Florence too much at that time. This was also due to the fact that the site chosen for the roman city was an alluvial plateau slightly higher than the surrounding plain: indeed this part of the city was inundated only by the most catastrophic floods of 1333, 1557 and 1966. (This was noted by Targioni Tozzetti during the flood of 1740, which surrounded but did not flood the square where the old roman city had been built). The Mugnone, a tributary of the Arno River, at that time flowed into the Arno roughly at the site where the Ponte di S. Trinita is presently located. It was then the moat for the western walls. Today, the Mugnone confluence is located downstream, roughly at the level of the Cascine Park.

The first significant obstruction to the flow of the Arno River in Florence arose when a bridge for the Via Clodia (*Clodia road*) was constructed at the site where the Ponte Vecchio stands today. The construction of this bridge was completed in the year 124. However, more serious problems for the city started in 1172, when the second circle of fortified walls was built such to include the suburbs of the city which had developed along the Via Clodia on the left bank of the river between the old Altafronte Castle and the Ponte alla Carraia (built in 1218-1220). The Mugnone was then moved such to fit the new wall circle and flowed into the Arno at the level of Ponte alla Carraia. As mentioned in Sect. C.2, the Ponte di Rubaconte was built in 1237 and the first Ponte di S. Trinita in 1252.

The third circle of walls was constructed between 1284 and 1333 along the path of the present 'Viali' so that a further reach of the Arno was included inside the walls.

As Natoni (1944) points out, the construction of bridges and pescaie was the cause of a distinct worsening of the conveyance capacity of the river in the urban

reach. As a result, frequent inundations occurred. The lower parts of the city were inundated by backwater effects in sewers discharging into the Arno. Flood flows frequently overtopped the bank walls constructed to protect the city. Inundation originated also from the waters invading two areas most liable to floods upstream of Florence, namely the plains of Rovezzano and Bagno a Ripoli (Figure C-47), from which the water flowed into the city penetrating through the wall openings. In both these plains, most notably in the latter, the Arno had more than one branch (secondary branches were called *bisarni*), of which some evidence still persists.



**Fig. C-47.** A Google map view of the Arno valley upstream of Florence with an indication of the two plains (Rovezzano and Bagno a Ripoli), adjacent to its banks, most liable to inundation.

### Reducing Florence's vulnerability

A variety of ideas to alleviate Florence vulnerability to floods, were proposed through the centuries.

#### *Diverting floods*

The first approach to reducing Florence vulnerability, which attracted the attention of scientists and engineers, was the diversion of part of the flood waters into diversion canals. Leonardo noted the role of Bisarni as 'natural floodways'. Indeed, on one of his drawings showing a Bisarno, he annotates: «trabocca Arno per le piene», i.e. "Arno overflows during floods" (Baratta, 1941, Tav. VIII). Below we outline some of them.

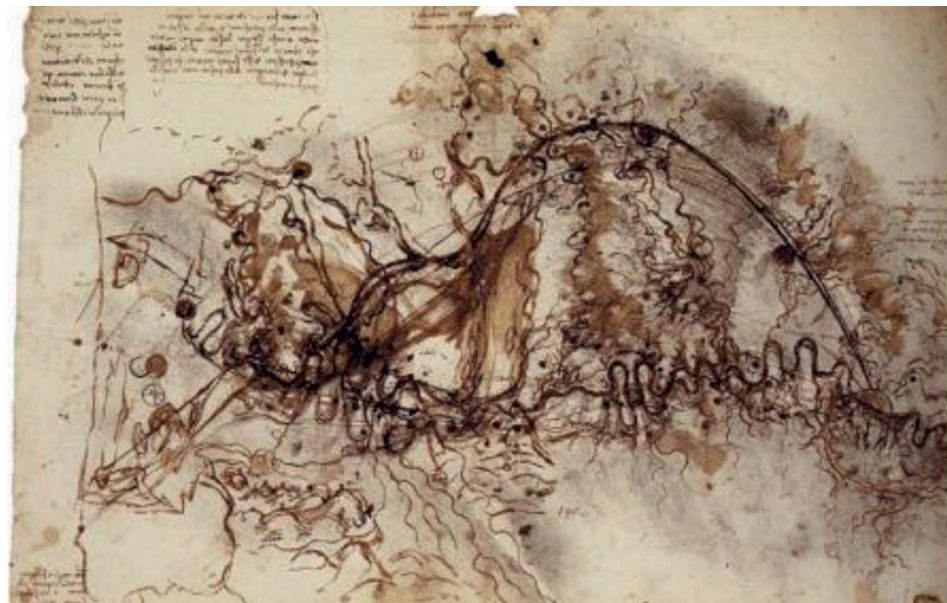
The first such specific proposal for diversion originated from Leonardo whose solution consisted of a floodway connecting Florence to Prato and Pistoia (Figure C-48). Cutting the Serravalle hill, the floodway would then flow into the *Padule di Fucecchio* (Fucecchio swampland) or return to Arno at Vico Pisano (Figure C-49).

Leonardo's very ambitious project was not pursued. However, less ambitious similar ideas returned many times in the technical and scientific debate. In particular, Lupicini (1591) reports about a proposal to construct two canals parallel to the urban reach of the Arno, where the sewer waters would be collected such that the existing



sewers discharging into the Arno could be removed and backwater effects into the lower parts of the city could be avoided. This project, however, suffered from a few shortcomings that prevented its realization. The length of the required canals was very large in order to collect sewer waters from all parts of the city, including the lowest areas. The slope of the designed channels had to be fairly low (and their cross sections consequently quite large) in order for the elevation of the outlet to be high enough not to require the closure of the gates too often. The risk of strong deposition of wastes due to the low flow speed was then feared. Moreover, the construction of large channels deep into the ground was both difficult and expensive. The project was abandoned.

**Fig. C-48.** The floodway Firenze-Prato-Pistoia-Serravalle-Padule di Fucecchio proposed by Leonardo, as sketched in one of his famous drawings.

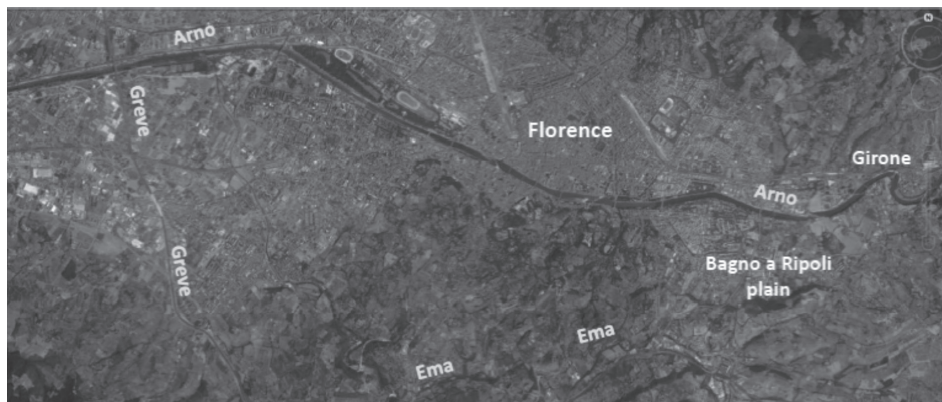


**Fig. C-49.** A Google map representation of the path of Leonardo diversion canal.



Lupicini (1591) also reports on his alternative suggestion to equip the Pescaia di S. Niccolò with a structure consisting of 13 weirs. These would be operated to release downstream a discharge lower than the maximum discharge able to flow with no bank overtopping. The excess discharge would be diverted into a bypass channel connected to the moat surrounding the city walls, which discharged into the Mugnone through which the diverted waters would then return to the Arno downstream of Florence. Perelli (1845) commented that this solution presented the shortcomings typical of bypass channels, the difficulty to control the diverted discharge and avoid deposition in the bypass as well as in the main channel.

In order to avoid these difficulties Perelli outlined the idea to divert the most of the Arno flows at Rovezzano. A new canal cut outside the city would connect Rovezzano with the confluence of Mugnone into Arno, while the original river channel would receive the minimum discharge needed for the operation of mills and other purposes. A similar solution was later proposed by Targioni-Tozzetti (1767): diversion was foreseen at Girone and the path of the new canal would cross the Bagno a Ripoli plain, incise the low hills separating the Arno from the Ema (a tributary of Greve), follow first the Ema and then the Greve down to its confluence into the Arno (Figure C-50). A small discharge was again allowed into the original course of the Arno.



**Fig. C-50.** The map shows the location where Targioni Tozzetti proposed to deviate the Arno (Girone), the Bagno a Ripoli plain crossed by the new canal and the Ema – Greve present courses.

These latter two proposals were not investigated further due to their excessive cost. More recently, however, a proposal for a bypass canal to divert 350 m<sup>3</sup>/s from the Arno at Rignano sull'Arno and deliver them into the Ema and then into the Greve was put forward by Fassò (see quotation in Supino, 1974, p. 121).

#### *Storing flood waters*

The second classical approach to flood protection is the use of reservoirs for flood storage.

The first time a solution of this kind was suggested for the defense of Florence was under Cosimo I de' Medici. The proposal put forward consisted of a 'bridge-dam' to be built *at the Sieve-Arno confluence*. By closing the gates controlling the bridge openings during floods, the bridge could be converted into a dam to store the water flowing in this important Arno tributary. This solution was dismissed as the volume

of water that could be stored (Figure C-51) was insufficient to provide significant benefits and great damage was feared should the proposed dam collapse.

A second suggestion along the same lines of the previous proposal came, in 1558, from Mr. Girolamo di Pace da Prato, an engineer working at the River management Agency (*Magistrato degli Ufficiali dei Fiumi*). His idea was to build a dam just downstream of Compiobbi (Figure C-51).

**Fig. C-51.** Google map picture of the sites where the construction of reservoirs was proposed in the 16th century.



The dam was supposed to release a discharge lower than the maximum conveyance capacity of the Arno in the urban reach of Florence. This project was not pursued either and Targioni Tozzetti (1767) pointed out that this approach to river regulation might be efficient *only if a number of such reservoirs were built both on the Arno river and in some of its tributaries*.

The use of multiple storage sites is given emphasis in the solution proposed by the Commission De Marchi that the Ministry for Public Works of Italy appointed after the 1966 flood (Supino, 1974). It is of some interest to outline the ideas proposed by this Commission. Essentially, the Commission founded its analysis on the premise that the Arno basin should be artificially regulated to deal with an event with the characteristics of the 4 November 1966 flood. The only exceptions concerned two tributaries (the Chiana Canal and the Elsa River) where the peak discharges estimated for the November 1966 event ( $326 \text{ m}^3/\text{s}$  and  $614 \text{ m}^3/\text{s}$  respectively) were significantly lower than the maximum values previously recorded ( $570 \text{ m}^3/\text{s}$  and  $1\,000 \text{ m}^3/\text{s}$  respectively). Moreover, it was assumed that *the value of the peak discharge in Florence was  $4\,200 \text{ m}^3/\text{s}$  and that the latter value had lasted 12 hours*. Using the hydrograph calculated by Cocchi, Giani e Hautmann (1967), the Commission concluded that, in order to reduce to  $2\,200 \text{ m}^3/\text{s}$ , the peak discharge allowed to flow through Florence, *a volume of about  $130 \text{ Mm}^3$  should be stored* in reservoirs located upstream. Note that the choice of the discharge of  $2\,200 \text{ m}^3/\text{s}$  allowed to flow through Florence was made based on a calculation of the maximum discharge allowed safely through Ponte Vecchio (estimated at that time in  $2\,500 \text{ m}^3/\text{s}$ ) reduced by 15% to account for inaccuracy of the estimate.

The number and locations of these reservoirs were chosen according to the following criteria:



- appropriate geological conditions;
- multipurpose reservoirs, used normally for water supply or irrigation and employed for flood protection during strong events;
- prefer many small reservoirs to a few large ones.
- design reservoirs for the Casentino sub-basin such to reduce the regulated peak discharge to its pre-1966 value and in Valdarno Superiore and Sieve sub-basins such to satisfy the constraint that the peak discharge in Florence should not exceed the chosen value of 2200 m<sup>3</sup>/s.

The output of the analysis was a map of five reservoirs to be constructed in the Casentino sub-basin with a total storage of 83 Mm<sup>3</sup>, nine reservoirs in the Valdarno Superiore for a total storage of 75.7 Mm<sup>3</sup> and three reservoirs in the Sieve basin with a total storage of 50 Mm<sup>3</sup>. Moreover, the construction of the previously mentioned Rignano-Ema-Greve-Arno bypass was needed in order to meet the required constraints.

The estimated cost of all these works was 76.7 Billion (1970) Liras. Using the ISTAT (2011) procedure, the latter figure may be converted into 450 M€ in 2011. This figure likely severely underestimates the actual cost of those works should they be constructed today. Note that Commission's program concerned the whole Arno basin and included the construction of six more reservoirs in the Lower Valdarno.

The Commission's plan was not implemented. Only one reservoir has been built since the 1966 Flood. The Bilancino reservoir was built in the Sieve sub-basin and its storage primarily used for water supply (See Appendix D of this report).

A pilot study of the regulation of the Arno basin for flood protection, water supply and irrigation was commissioned in 1978 by the Minister responsible for economic planning jointly with the Tuscany Region to a major consulting company (Lotti & Ass.). The outcome of this study was the proposal to construct 11 multipurpose reservoirs for a total storage of 400 Mm<sup>3</sup>, 117 of which would be used for flood protection. The approach was based on a cost-benefit analysis, with some constraints: in particular, Florence and Pisa should be made safer with respect to the 1966 flood. The study also proposed construction of a diversion canal connecting the Arno River to the Trasimeno Lake, nearly 100 km to the south.

Further studies were performed by Evangelisti (1968) and by the Collegio Ingegneri Toscani (Council of Engineers of Tuscany) (1967) both suggesting solutions consisting of the construction of reservoirs, possibly supplemented by diversion canals.

An early pioneer numerical model able to simulate the propagation of floods in the Arno Basin was proposed by a group of scientist working at the Pisa center of IBM (Panattoni and Wallis, 1979). As pointed out in this paper:

[...] Todini and Buffoni (1976) used a simplified version of the Arno model to predict the individual and combined effects of three proposed flood control measures. The proposals which they studied were (1) channel improvements in the vicinity of Florence, (2) a dam on the Sieve River of 20 Mm<sup>3</sup> capacity in the vicinity of Dicomano, and (3) a dam of 70 Mm<sup>3</sup> capacity at Laterina (just above Levane and below the Chiana-Arno confluence). For the 1966 flood event their conclusions were that the combination of both dams with channel improvements to allow 3500 m<sup>3</sup>/s of flow within the banks would have totally prevented inundation in Florence [...].

This point will be further discussed in Appendix D.

### *Bed aggradation*

In the long standing debate on how to reduce Florence's vulnerability, the issue of whether the bed profile in the urban reach of the Arno is undergoing aggradation has arisen many times.

Villani, in his *Cronica*, reports the opinion of the old Florentines after the catastrophic flood of 1333. Comparing the latter with the 1269 flood, they claimed that precipitations in 1269 had not been less intense and that the much higher elevation reached by the flooded waters in 1333, was caused by bed aggradation driven by pescaie, which they quantified in seven '*braccia*'.

[...] alzamento del letto d'Arno, per la mala provvidenza del comune di lasciare alzare le pescaie a coloro ch'aveano le Molina in Arno [...]<sup>7</sup>.

Indeed, as discussed in previous sections, the Florentine authority issued a decree prohibiting the presence of pescaie within designated reaches of the Arno River, but the decree was ignored by the owners of the mills along the river. The Pescaie had collapsed during the flood and Villani points out that the flood of 5 December 1334 did not have catastrophic effects because the Pescaie had not been reconstructed and severe bed degradation (6 braccia) had occurred during the previous 1333 flood.

The issue of bed aggradation returns after the 1547 flood. Bernardo Segni (1557) again suggests that bed aggradation was the cause of the flood. Aggradation was attributed to periods of higher precipitations coupled with deforestation of the basin. Land reclamation in Val di Chiana was also cited as an additional cause of an increased sediment load in the river.

[...] li temporali piovosi più che di solito avevano di maniera guasto il letto del fiume e sì alzatolo e modificatolo [...]<sup>8</sup>.

And, again, aggradation driven by Pescaie was pointed as the main cause of the catastrophic flood of 1557. Scipione Ammirato (1824) also lamented that the decree issued by Cosimo I had never been actually respected.

Of course, the reliability of opinions based on visual observations is quite limited. Moreover, people tend to interpret local observations as general trends. Monitoring of the bed profile, which is the only reliable practice, was not easy at that time.

The last published results on the bed profile of the Arno River in the reach between the Pescaia of Rovezzano and the Cascine weirs refer to the 1999-2001 survey. The bed profile is plotted in Figure C-52. The profile stays much lower than the tops of Pescaie and is strongly affected by the elevations imposed at the aprons of the various bridges present in the urban reach. Recently, the University of Flor-

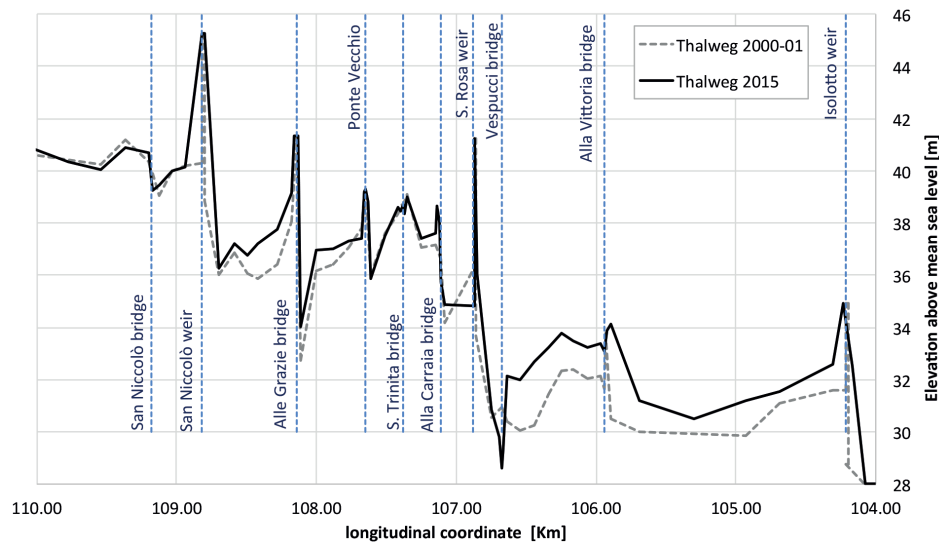
<sup>7</sup> “[...] aggradation of the Arno River bed due to the bad practice of the Municipality to let the owners of the mills in Arno raise the pescaie [...]”.

<sup>8</sup> “[...] precipitations stronger than usual produced damages to the river bed, leading to its aggradation and modification [...]”.



ence (Francalanci et al., 2016) has pursued a bed monitoring campaign on the Arno River between Varlungo bridge and Signa for a length of 18 km. Results are reported in Figure C-53; the comparison between the two surveyed bed profiles suggests an overall aggradation, with some exceptions such as at the Santa Rosa weir and Vespucci bridge.

*This suggests the opportunity to investigate how the hydrodynamics and the morphodynamics of the Arno River in Florence are affected by the presence of Pescaie and bridges and whether improvements may be achieved by modifying the present configuration.*



**Fig. C-52.** The bed profile of the Arno River in the urban reach according to the surveys of 1999-2001 and 2016.



## Appendix D

# Comments on actions taken since 1966

### D.1 Introduction

Actions have been taken since 1966 to address some of the challenges faced in reducing the flows in the Arno River. This appendix describes the three principal projects that have significantly influenced these flows and comments on their efficacy.

### D.2 Lowering of the aprons of the S. Trinita and Ponte Vecchio bridges

The idea that lowering the apron of Ponte Vecchio might increase the conveyance of the Arno River in the urban reach, was suggested after the 1966 catastrophe by Supino (1972). More precisely, Supino presented this solution as the only intervention that was feasible in Florence.

The Italian Ministry of Public Works then decided to investigate the actual effectiveness of Supino's idea. The complex geometry of Florence bridges and the less developed theoretical tools available half a century ago, prompted the need for a physical model, able to test the quantitative effect of various possible measures and enable the designers to choose the most effective and safest solution. The Hydraulic Institute of the Faculty of Engineering of the University of Bologna was appointed to design the model and perform the tests. Two configurations were tested: in the former configuration the bed was fixed, in the latter the bed was mobile. Results of the experiments were discussed in two Reports of the University of Bologna (Cocchi, 1972, 1975) and in a technical paper of Canfarini (1978). The best solution emerging from the experiments was implemented in 1977-1980. The construction process is described in a second technical paper of Canfarini (1984).

#### Fixed bed model tests (Cocchi, 1972, Canfarini, 1978)

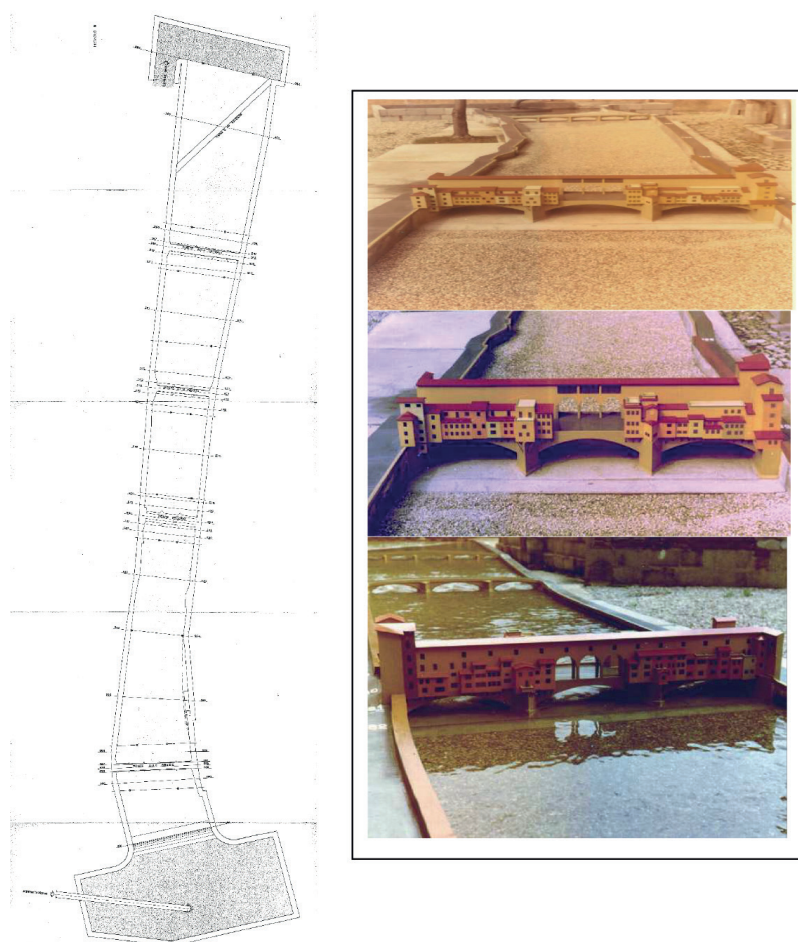
The design of the model, its construction as well as the execution of experimental tests were directed by Prof. Cocchi, at the time Director of the Hydraulic Institute of the Faculty of Engineering of the University of Bologna and colleague of Prof. Supino. The main aim of the tests was to ascertain the maximum conveyance capacity of the urban reach of the Arno River in the 1966 configuration and in the modified

configurations obtained lowering the aprons of the S. Trinita bridge and/or the Ponte Vecchio bridge.

The reach reproduced in the model was the central reach, of length 1580 m, bounded downstream by the Pescaia di S. Rosa and including four bridges, namely: Ponte alla Carraia, Ponte a S. Trinita, Ponte Vecchio and Ponte alle Grazie. The model scale was 1:60. The plan-form of the model as well as a few photos of the bridge models are reproduced from Cocchi (1972 a) in Fig. D-1.

Hydrometers (accuracy 1 mm) were employed to measure water surface elevations. A rough estimate of the *relative error*  $dQ$  in the estimate of the flow discharge  $Q$  may be obtained assuming a dependence of the flow discharge on the  $m$ -th power of the flow depth  $D$ . In this case  $dQ \sim m dD$ . As  $m$  is larger than one and likely lower than  $5/3$ , one may conclude that, at the high discharges,  $dQ$  is of the order of 1-2%.

**Fig. D-1.** The model test performed at the Hydraulic Institute of the Faculty of Engineering of the University of Bologna. (a) Plan form of the model. (b) View of the S. Trinita bridge from upstream: in the background the Ponte alla Carraia and the Pescaia di S. Rosa. (c) View of the Ponte Vecchio bridge: in the background the Ponte alle Grazie.



The *bed roughness* was estimated on the base of visual observations of the river bottom performed in 1970 during an exceptional drought. Observations revealed

the presence of ‘large boulders’, assumed to derive from secular dumping, lying on a very irregular bed surface. The roughness was then created in the model using 8 mm gravel (corresponding to 0.48 m in the prototype). This, quite large, absolute roughness, corresponds, at high stage, to values of the Strickler’s coefficient around 23-24  $\text{m}^{1/3} \text{s}^{-1}$  (Manning’s roughness “n” values of 0.0435-0.0417, respectively). Having such a large boundary roughness in the physical model might have resulted (perhaps without noticing it) in an increased “safety factor”. In other words, since the “real” roughness height in the prototype was on average smaller than the 0.48 m used to scale the model roughness, in order to convey a given flow discharge during the model testing, the resulting flow stage was larger than it would have been in the Arno River under the equivalent flow conditions. To put it simply, the flow depths observed in the model were larger than what they should have been for the fixed-bed model tests, resulting in “conservative” values of flow stage for the Arno River along the reach studied. Obviously, these considerations merit further analysis but there is no question that the fixed-bed model roughness resulted in large values of the so-called grain or skin friction thus making the interpretation of the movable-bed tests results more difficult as it will be explained below.

At the downstream end of the model, a weir allowed to impose the water surface elevation. The *boundary condition* at the weir was determined assuming that, at a ‘sufficient’ distance downstream of the weir, the flow could be assumed ‘uniform’. The free surface elevation at the weir was then estimated by a 1-D calculation of the backwater curve, starting from the uniform state. Cocchi (1972 a) also points out that variations of the free surface elevation imposed at the weir did not affect the profile observed upstream significantly. However, further inspection seems to indicate that the weir used to control the downstream water surface elevation in the model was indeed located very close to the location of the Amerigo Vespucci Bridge and just downstream of the Pescaia di Santa Rosa. Such conditions would indicate that for a fairly wide range of flow discharge conditions, the true control section in the model might not have been the weir itself but rather the water surface elevations imposed by the descending crest of the Pescaia di Santa Rosa. Only for Arno River flows that completely submerge the Pescaia di Santa Rosa, would the weir used in the model effectively control the water levels. This also points to the fact that despite the important role they play in controlling water levels, the hydraulics of all Pescaie is not very well understood so their incorporation into, for instance, numerical models involves a ‘leap of faith’ since we do not know what the discharge coefficient is for such hydraulic structures.

*Calibration* of the model was performed employing the result of a measurement of discharge performed at the Uffizi gage station by the Genio Civile office in Florence on 12 February 1971: 404  $\text{m}^3/\text{s}$  with a free surface elevation of 42.97 m. The elevation measured in the model (43.33 m) was significantly higher than the observed value: indeed, the relative difference [(model value of flow depth-field value)/field value] ( $0.36/2.16 = 16.7\%$ ) is much larger than the relative error associated with the measurement of free surface elevation (2.8 %). This suggests that, in order to reproduce in the model the free surface elevation actually observed in the field, the flow discharge imposed in the model should have been much smaller (roughly 25 % smaller) than the field value.



This significant discrepancy might be due to the possibly overestimated value of the bed roughness as explained earlier.

Five sequences of tests were performed.

1. In the first sequence, the model reproduced the *present (i.e. 1972) configuration* of the river channel. The flow discharge was increased from 400 m<sup>3</sup>/s up to the maximum discharge contained within the banks, which turned out to be **3 090 m<sup>3</sup>/s**. For the latter value of the discharge at both the Ponte alle Grazie and Ponte Vecchio the free surface elevation exceeded the elevation of the apexes of the bridge arches, hence flow through these bridges occurred under head. Under such conditions, it is expected that the hydraulic discharge of the bridge openings was similar to that of an orifice flow, resulting in larger head losses and water surface elevations. Hence, it is not surprising that the right bank was overtopped at Lungarno Acciaiuoli, between Ponte Vecchio and Ponte a S. Trinita.
2. In the second sequence of tests, the model configuration was modified only at *Ponte Vecchio, lowering its apron by one meter*, such that the new apron elevation was set at 39.45 m a.s.l. and the river bed was correspondingly modified in the two reaches of length of 100 m upstream and downstream of the bridge. Of course, this was a 'fixed bed' choice: in fact, the actual configuration assumed by the river bed as a consequence of this intervention was not known, nor mobile bed calculations were feasible at the time. The same sequence of discharges tested in the former case was applied and the main outcome of the experiments was that the maximum discharge contained within the banks reached **3 120 m<sup>3</sup>/s**. The flow upstream of Ponte Vecchio, was characterized by free surface profile 20 cm lower than in case 1, whilst the flow downstream of Ponte Vecchio was practically unaltered, hence overtopping occurred again at Lungarno Acciaiuoli. The two lateral arches of both Ponte alle Grazie and Ponte Vecchio worked under head (i.e. orifice flow), whilst the central arches (three at Ponte alle Grazie, one at Ponte Vecchio) showed free surface flow conditions.
3. In the third sequence of tests, the model configuration was further modified as follows:
  - *the apron of Ponte a S. Trinita was lowered by one meter*, such that the new apron elevation was set at 39.03 m a.s.l. and the river bed was correspondingly modified in the two reaches of length of 100 m upstream and downstream the bridge;
  - *the apron of Ponte Vecchio was left as in case 2.*

Various significant improvements emerged, most notably the maximum discharge contained within the banks increased up to **3 450 m<sup>3</sup>/s**. Note that, for a discharge of 3000 m<sup>3</sup>/s: the elevation of the free surface profile between Ponte Vecchio and Ponte a S. Trinita was 0.5-0.8 m lower than in cases 1 and 2; upstream of Ponte Vecchio it was 0.7-0.9 m lower than in case 1 and 0.5-0.8 m lower than in case 2. Moreover, lowering persisted also upstream of Ponte alle Grazie.

Overtopping occurred at various cross sections along the right bank both upstream and downstream of Ponte Vecchio.

4. A fourth sequence of tests was performed to *check whether lowering of S. Trinita apron only would be sufficient*. In this case, the maximum discharge contained within the banks decreased to **3 320 m<sup>3</sup>/s** and the flow at Ponte Vecchio was highly irregular.
5. The fifth sequence examined the effect of *shaping the new aprons as reverse arches*. Results did not differ significantly from those found in case 3.

The conclusions drawn from the fixed bed experiments were as follows.

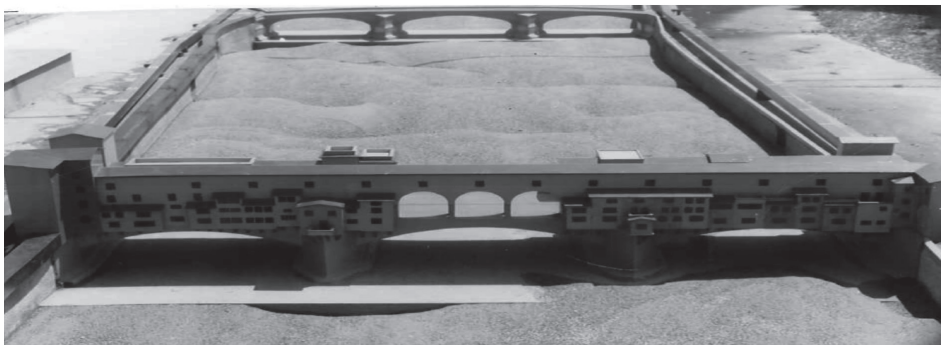
- The benefit of lowering only the apron of Ponte Vecchio by one meter was negligible.
- A significant benefit was obtained lowering both the aprons of the Ponte a S. Trinita and Ponte Vecchio by one meter each: the maximum conveyance capacity of the Arno River in Florence then increased by 15%.
- The backwater effect generated for a discharge of 3 000 m<sup>3</sup>/s at Ponte Vecchio was reduced from 57 cm to 26 cm, at Ponte a S. Trinita from 95 to 18 cm. These reductions appeared to be quite significant, such that further lowering of the aprons were not deemed convenient.
- In fact, the flow of the same discharge (3 000 m<sup>3</sup>/s) through the whole modeled reach turned out to be fairly safe according to the model observations as the available free board was nowhere lower than 1 m, except for Lungarno Acciaiuoli where it reduced to 0.80 m.

These conclusions obviously refer to the reach of the Arno reproduced in the model. The report mentions, however, that possible effects of the proposed modifications on the reach upstream of Ponte alle Grazie would require attention. And it is of interest, in this respect, to note that possible effects downstream were not deemed so important at the time. Canfarini (1978) does mention this point: «[...] i danni che deriverebbero dalle maggiori portate in arrivo al tronco delle Cascine e ai tronchi a valle di Firenze, dai quali si sono prodotti nel novembre 1966 estesi allagamenti, non sono paragonabili a quelli risparmiati al cuore della città [...]» (“[...] damage caused by the increased discharge reaching the Cascine reach and areas further downstream, where extensive flooding was experienced in 1966, cannot be compared with the reduction of damage achieved in the heart of the city [...]”). This important statement represents a ‘qualitative’ primitive version of a cost-benefit analysis that maintains its validity nowadays.

#### Mobile bed model tests (Cocchi, 1975; Canfarini, 1978)

In 1975 a second sequence of tests was performed. Their aim was to investigate variations of the local scour at bridge structures and bank protections resulting from the lowering of the aprons of the two bridges.

These tests suffered from modeling problems justified by the insufficient knowledge on sediment transport and morphodynamics available at the time.



**Fig. D-2.** The picture shows the river bed between Ponte Vecchio and Ponte a S. Trinita after a 3 450 m<sup>3</sup>/s ‘flood’. Note the presence of nearly 2-D dunes covering the bottom.

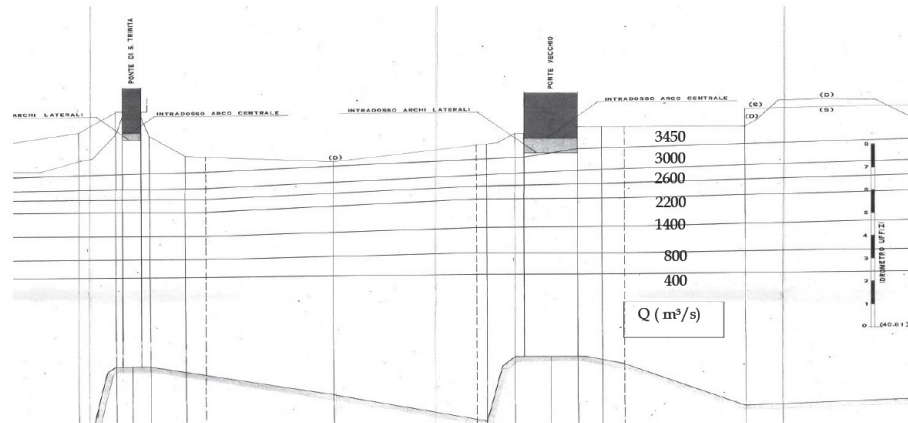
The main problem derived from the assumption that, using in the model a grain size distribution obtained reducing the original sizes according to the spatial scale of the model (1:60), would enable a correct similitude of sediment transport and, consequently, morphodynamics. This is unfortunately not true as the sediment size of the model was fine enough for dunes to develop. On the contrary, dunes cannot be extensively present in the prototype (except locally where fine sand may accumulate) as the sediment size exceeds 20 mm. This alters the similitude as it is well known that the presence of dunes affects both the hydrodynamics (increasing flow resistance significantly) and sediment transport.

The extensive formation of dunes in the model is explicitly mentioned and documented by Cocchi (1975). See figure D-2, reproduced from the latter report.

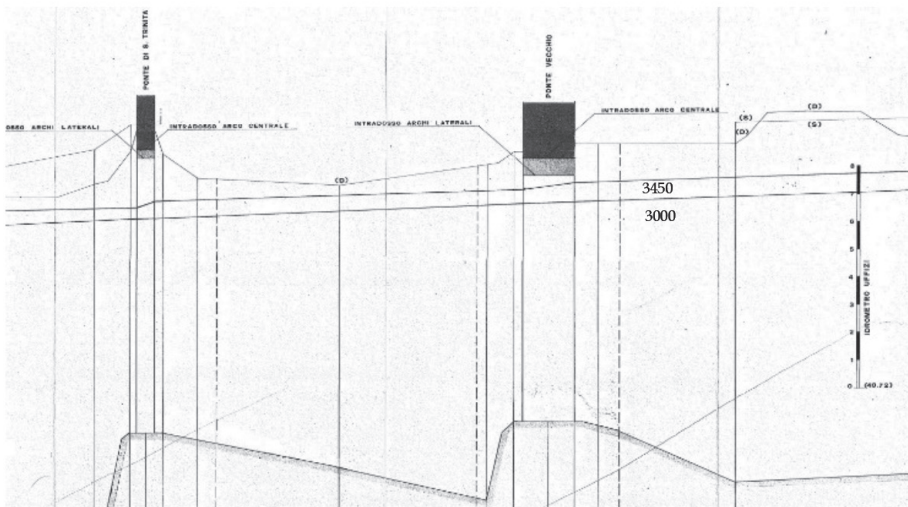
The presence of dunes and ripples in the physical model implies that form drag has to be taken into account besides grain and skin friction induced by the sediment used in the model. Form drag due to the presence of dunes will increase head losses and result in higher water levels for a given flow discharge. On the other hand, grain-induced skin friction contributes to flow resistance but its main role has to do with sediment transport. In a movable-bed model study the resulting flow stage is a function of both skin friction as well as form drag. Unfortunately, in the fixed-model study the value of skin friction was large due to the sediment material used (8 mm pea-size gravel) and therefore it seems that there were no ripples or dunes mentioned in the Report, either because the sediment might have been glued to the model boundary or the flow could not entrain and transport the gravel downstream.

In the case of the movable-bed tests, the scaling of the model sediment was not done with what are today commonly accepted similarity criteria for physical sedimentation modeling. Therefore, the fine sediment used in the movable-bed testing, resulted in the development of dunes which bring along with them flow resistance associated with form drag that is not expected to happen in the prototype. One might conclude then that in fixed-bed model tests hydraulic resistance induced by the size of the model material was exaggerated while in the case of the movable bed material the presence of dunes was responsible for most of the flow resistance and skin friction played a secondary role.

A second problem is related to sediment supply. In the Report, it is stated that sediment was fed 'as required', presumably in open loop, but no quantitative information is given. It is then unclear whether the sediment supply was initially calibrated to be 'in equilibrium' with the average bed slope and the given liquid discharge. Note that the test did not reproduce an actual flood; rather, it maintained a constant discharge for a time equivalent to 16 hours in the prototype. Hence, the sediment discharge was presumably held constant throughout the test. Another factor worth mentioning relates to the fact that sediment transport upstream of Ponte alle Grazie can be expected to be controlled by the Pescaia di San Niccolò, which was not included in the model study. At the very least the Pescaia di San Niccolò will limit the amount of bedload transport reaching Ponte alle Grazie, except when floods take place and sediment will bypass the crest of the hydraulic structure and continue downstream. Only fine suspended sediment will be transported downstream under normal flow conditions. This would suggest that supplying sediment to the model 'as required' might have been far removed from the sediment transport conditions one could expect to see in the Arno River at Florence.



(a)



(b)

**Fig. D-3.** The free surface profiles in the fixed (a) and mobile (b) bed tests for various values of the liquid discharge. The lines denoted (s) and (d) represent the elevations of the left and right banks respectively.

Hence, the physical model may not have reproduced adequately the main features of the hydrodynamics and sediment transport. The possibility of bed armoring was not mentioned even though the boring done for the lowering of the aprons indicates the existence of a substrate (see Table D-1) having a grain size distribution typical of rivers that have developed a pavement or armor layer along their surface. It is then hard to interpret the experimental observations. In particular, to mention a feature that is not explicitly noted in the Report, but would be worth investigating, **the free surface profile associated with the highest discharge ( $3\,450\text{ m}^3/\text{s}$ ) in the mobile bed tests was lower than in the fixed bed case** (see Fig. D-3). One might speculate that in the fixed-bed model tests, the hydraulic resistance induced solely by skin friction (with no bed deformation) due to the size of the model roughness was larger than the flow resistance induced by the dunes and the fine-grain roughness present in the movable-bed tests. But the bed deformation in the course of the mobile bed experiments could also have affected the observed free

surface profiles. This would not be surprising, but it would merit substantiation by a better founded, physical and numerical model.

This notwithstanding, the conclusion of the Report was that lowering the aprons of the two bridges did not lead to significant worsening of local scours observed at those structures, the more so if adequate protection of the aprons was implemented. However, missing from the Report is the impact that debris accumulation could have had in reducing the discharge capacity of the different bridges during floods as well as the impact that debris would have on exacerbating local scour around bridge abutments.

It is also worth observing that the Arno River undergoes a lateral contraction as it flows towards the Ponte Vecchio, where the channel experiences its narrowest width and this would imply that the potential for sediment erosion and transport would increase close to the bridge as the flow accelerates during a flood. While it was not the aim of the experiments to investigate long term effects of structural modifications of bridges (and Pescaie) on the bed profile, this is a major issue that would also deserve attention in the future.

To summarize, the physical model study conducted at the University of Bologna is without doubt of great historical value and represented the state-of-the-art at the time. Given the morphological changes experienced by the Arno River since the seventies, when the model study was done, it is clear that the channel characteristics today are very different from those observed at the time of the model construction. Sedimentation in the form of alternate bars, uncontrolled vegetation growth as well as an increase in recreational use of the Arno River would all indicate that resistance to flow will increase and the conveyance capacity of the river has most likely decreased in the last few decades.

The challenge ahead consists in incorporating all these changes into computational and physical models coupled with field measurements that make use of the latest knowledge about laterally-confined rivers transporting sediment and debris in the presence of hydraulic structures such as bridges and Pescaie.

The implementation of the works to lower the aprons of Ponte a S. Trinita and Ponte Vecchio (Canfarini, 1984).

The construction of the new aprons, begun on June 1977 was completed by November 1980. An interesting account of the design criteria and construction procedures is given in Canfarini (1984). It falls outside the scopes of the present Report to discuss the content of this paper in detail. However, it is worth pointing out few interesting features.

- The feasibility study performed before the design and execution of the works was based on an accurate knowledge of the history of those structures, including results of old borings and information on previous consolidation works. Moreover, a new field campaign of borings of the structures and the soil was performed in 1975. Results of the latter campaign revealed, in particular, that the soil below the aprons consisted of an alluvial layer of maximum thickness around 9 m, lying on the top of a rock substrate consisting of Pietraforte (a kind of sandstone). The grain size distribution of the alluvial substrate at various depths is given in Table D-1. This would suggest that the river bed has most likely experienced armoring where the finer material is removed and the coarser material is left behind forming an armor layer or pavement which determines the roughness of the river bed. The substrate material is



representative of the sediment the river can transport under high flow conditions and should be used in the design of future movable-bed, numerical and physical model.

**Table D-1.** Grain size distribution of the alluvial substrate at various depths (from Canfarini, 1984).

Depth (m)	Pebbles (%)	Gravel (%)	Sand (%)	Silt and clay (%)
2-4.5	6.7	45.6	31.1	16.6
4.5-7	12	45.5	28	14.5
7-9	24.5	41.8	16.3	17.4

- Demolition of the existing aprons allowed submerged ruins of previous structures to come to light: accurate dating of those ruins was possible through radiocarbon techniques. The detailed description reported in the paper enlightens the construction techniques employed for the original bridge and the later reconstructions following floods that led to bridge failure or the more recent destructions of the German Army at the end of the Second World War.

### D.3 Construction of the Bilancino dam

The Sieve River joins the Arno River at Pontassieve, about 18 km upstream Florence. The contributing catchment of the Arno upstream the confluence is about 3 238 km<sup>2</sup>. With a catchment area of about 840 km<sup>2</sup> at the confluence, the Sieve is one of the most important tributaries of the Arno upstream Florence. In fact, an ancient local proverb says that “Arno non cresce se Sieve non mesce” (Arno flow does not increase if the Sieve does not contribute), therefore witnessing that people well knew the important role played by the Sieve to form the Arno floods. In particular, previous studies (Uzzani, 1996) determined that the peak flow of the Arno and Sieve rivers are likely to occur at the same time at Pontassieve, therefore summing up each other, for rainfall events longer than 18-20 hours.

Actually, the conditions which determine the synchronicity of the peaks for the Sieve and Arno hydrographs are determined by the interaction of the meteorological and hydrological processes of runoff formation for the two catchments and cannot be summarized by a simple rule. Meteorological processes in the Arno River basin are impacted by climate change (Burlando and Rosso, 2002; Castelli, 2016, personal communication) and land use change and are therefore not stationary. Thus, synchronicity of the Arno and Sieve flows may happen under slightly different situations with respect to the past and with non-stationary frequency. An updated analysis, taking into account the actual geometry of the river network and land use, and validated against updated climate change scenarios, would provide a refined perspective of what is stated by the above ancient proverb.

After the 1966 flood in Florence, the Commission nominated by the Italian Government to identify solutions for mitigating the Arno floods recognized the important role played by the Sieve and suggested to control its flow by building a dam at Dicomano, where the catchment of the Sieve is about 577 km<sup>2</sup>. After long discussions and evaluation of alternative solutions, it was decided to build the Bilancino reservoir, which is however located about 47 km upstream Pontassieve and therefore

much upstream Dicomano. In fact, the area of the contributing catchment to the Bilancino reservoir is only 149 km<sup>2</sup>.

The Bilancino (Figure D-4) is a multipurpose reservoir mainly designed for water supply to solve the problems of water demand for the city of Florence and provide the minimum “ecological” water discharge needed by the Arno River in the dry period (June to September) for environmental purposes. The latter was estimated at the time of the Plan around 8 m<sup>3</sup>/s, taking account of the fact that 2.5 m<sup>3</sup>/s are withdrawn by the aqueduct. Note that the natural flow in the dry season does not exceed an average of about 3.5 m<sup>3</sup>/s. The reservoir is also equipped with a hydropower plant. Also, a plan was developed to reserve part of the storage for mitigating the downstream peak flow.

The earth fill dam is 42.07 meters high (from the lower level of the base to its top elevation) and the maximum water depth behind the dam is 37.5 meters. The maximum elevation of the water surface in the reservoir is 254.50 m a.s.l. The maximum and minimum storage are 84 Mm<sup>3</sup> and 6.5 Mm<sup>3</sup>, respectively.

According to the Plan, out of the total storage of 84 Mm<sup>3</sup> generated by the earthfill dam, 69 Mm<sup>3</sup> are used for regulation and 15 Mm<sup>3</sup> are employed to reduce the peak discharge of the Sieve tributary which affects significantly the flood propagation in the Arno river.

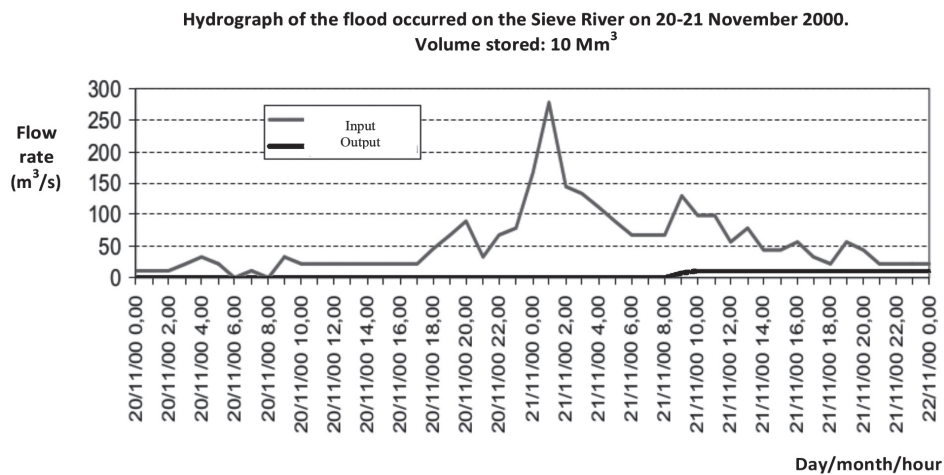
**Fig. D-4.** The Bilancino earthfill dam at the maximum storage (Courtesy by Dott. Grossi and Publiacqua).



The peak reduction effect of the Bilancino dam was studied by Brath et al. (1998). Later on, the public institution that manages the dam (Publiacqua) reported that the dam can effectively mitigate severe flood events that may occur along the Sieve River. In particular, during the high flow event that occurred on November 20-21, 2000, with a peak river inflow into the dam of about 280 m<sup>3</sup>/s, the dam stored about 10 Mm<sup>3</sup> of water therefore reducing the downstream peak flow to a negligible amount (see Fig. D-5).

According to information provided by the Arno River Basin Authority, the lamination effect of the Arno River was studied through the application of a hydraulic model by the Province of Florence (the former local administration). The results of the analysis are not published but are available to public administrations and river basin authorities. Their results were taken into account by the Arno River Basin Authority when developing the Flood Risk Management Plan (PGRA) that was set out according to the European Flood Directive 2007/60.

***The Arno River Authority reports that the peak reduction effect induced by the Bilancino Dam on the peak flows in Florence is small but not negligible.***



**Fig. D-5.** Mitigation of flow hydrograph downstream the Bilancino Dam for the event occurred on November 20-21, 2000 (courtesy of Dott. Grossi and Publiacqua).

It is not clear what the effect would be for the flood of November 4, 1966, when the discharge of the Sieve River at the confluence with the Arno was estimated to be about 1340 m<sup>3</sup>/s. However, by taking into account the results presented in Fig. D-5 and considering that the contributing catchment to the Bilancino Reservoir covers about 3.5% of the catchment of the Arno River at Florence, the mitigation effect of the Bilancino Dam over a flood hydrograph like the one that occurred in 1966 may be empirically estimated in about 100-200 m<sup>3</sup>/s. Therefore, one may agree with the Arno River Basin authority that the effect is small but not negligible. The reader must be aware, though, that the latter effect would not add to the lamination effect of the flood detention areas in the upper Valdarno: as discussed in the next section, the lamination effect of the latter for a 1966 event is practically negligible. In other words, until the Levane dam will be heightened, the peak discharge in Florence for a 1966 event will not be smaller than 3 900 m<sup>3</sup>/s.

Moreover, it is well known that the lamination effect actually achieved depends on how the reservoir is managed. Therefore, the availability of a detailed report of the hydraulic model results for the Sieve River, for different meteorological scenarios and different scenarios of reservoir management, would be an extremely useful piece of information to promote a better understanding of the inherent hydrological and hydraulic conditions. Improving such a knowledge would be beneficial to plan updated and sce-

nario-dependent management policies, and would allow to improve our knowledge of how retention areas and basins may contribute to mitigating the flood risk in Florence.

Finally, at this stage it is important to mention that, as pointed out by Uzzani (1996) the construction of the Bilancino dam was strongly supported by a part of Florentine politicians, who overemphasized its possible effect on the lamination of floods of the Arno River in order to achieve consensus. For the same reason, the proposed construction of a reservoir in Dicomano was abandoned, in spite of the fact that, as already pointed out, the area of the Sieve watershed drained in Dicomano is much larger than at Bilancino. We think that the latter decision was unfortunate and new consideration should be given to that proposal. Indeed, the estimate of Todini and Buffoni (1976) suggests that a 20 Mm<sup>3</sup> reservoir in Dicomano would have reduced the discharge of the first peak of the 1966 event by 190 m<sup>3</sup>/s and the second peak by 411 m<sup>3</sup>/s.

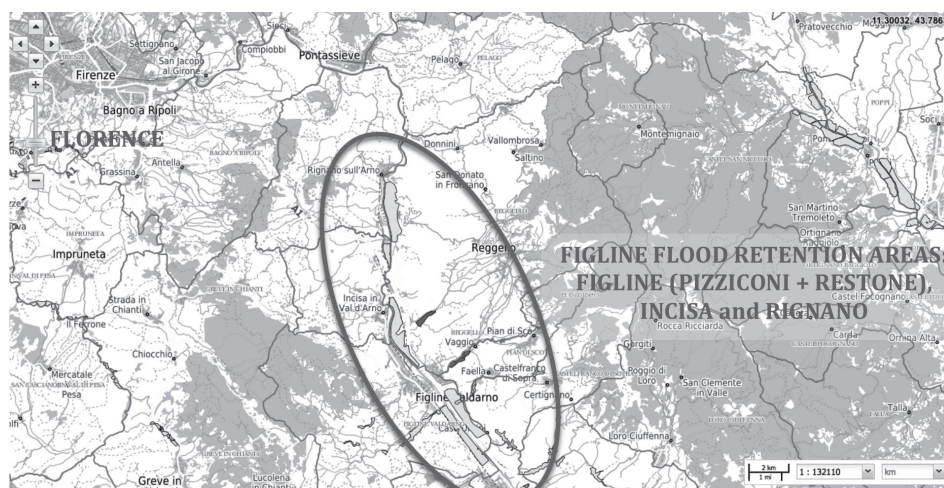
#### D.4 Design and construction of Figline flood retention areas

As discussed in Chapter 3, the flood retention areas in the Figline region are part of the set of structural measures that were envisaged by the original 1996 *Hydraulic Risk Plan* (Figure D-6). These retention areas are denominated *Figline*, *Incisa*, and *Rignano*.

The *Figline* retention area is located in the municipality of Figline Valdarno, and it is divided into two parts by the Arno River. The part located on the right riverbank is denominated *Pizziconi*, whereas that on the left bank *Restone*. *Incisa* and *Rignano* are mainly located in the municipality of Reggello.

These areas are located about 22 km upstream of Florence; the surface of the river basin upstream of these areas is about 2 730 km<sup>2</sup>.

**Fig. D-6.** The Figline flood retention areas as from the original Hydraulic Risk Plan (from web-gis of Arno River Basin Authority).



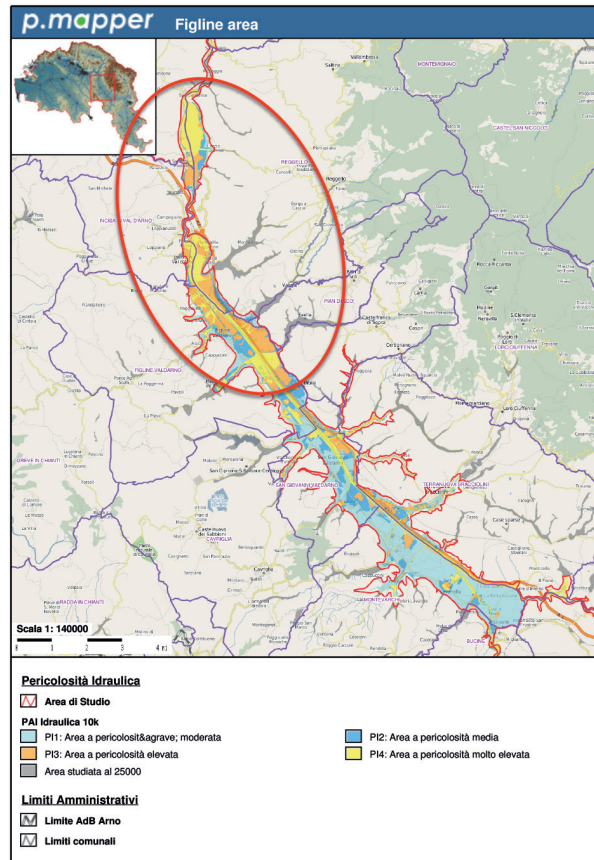
The total storage capacity of these retention areas foreseen by the *Plan* was 35.5 Mm<sup>3</sup>, with 16.59 Mm<sup>3</sup> for *Figline*, 6.53 Mm<sup>3</sup> for *Incisa* and 12.38 Mm<sup>3</sup> for *Rignano*.



According to the 2005 *Hydro-Geological Plan* (PAI) these retention areas are located in a portion of the river basin subject to a relevant degree of hydraulic hazard, classified either as high (PI3 level) or very high (PI4 level); see Figure D-7.

Later, with the 2009 preliminary design, the storage capacity was modified (reduced) as compared with the estimation foreseen by the *Plan*.

**The actual total storage volume is estimated as 22 Mm<sup>3</sup>, thus about 62% of the volume originally accounted for in the *Plan*;** the areas occupy an overall surface of about 493 hectares (Table D.2). The total estimated cost is about 48 million € (Table D.3).



**Fig. D-7.** Hydraulic hazard in the Figline area according to the Hydro-Geological Plan. The flood retention areas fall either in the high PI3 (orange) or very high PI4 (yellow) hazard level.

**Table D-2.** Storage capacity of Figline flood retention areas according to the original *Plan*, and to the 2009 preliminary design (area is also shown).

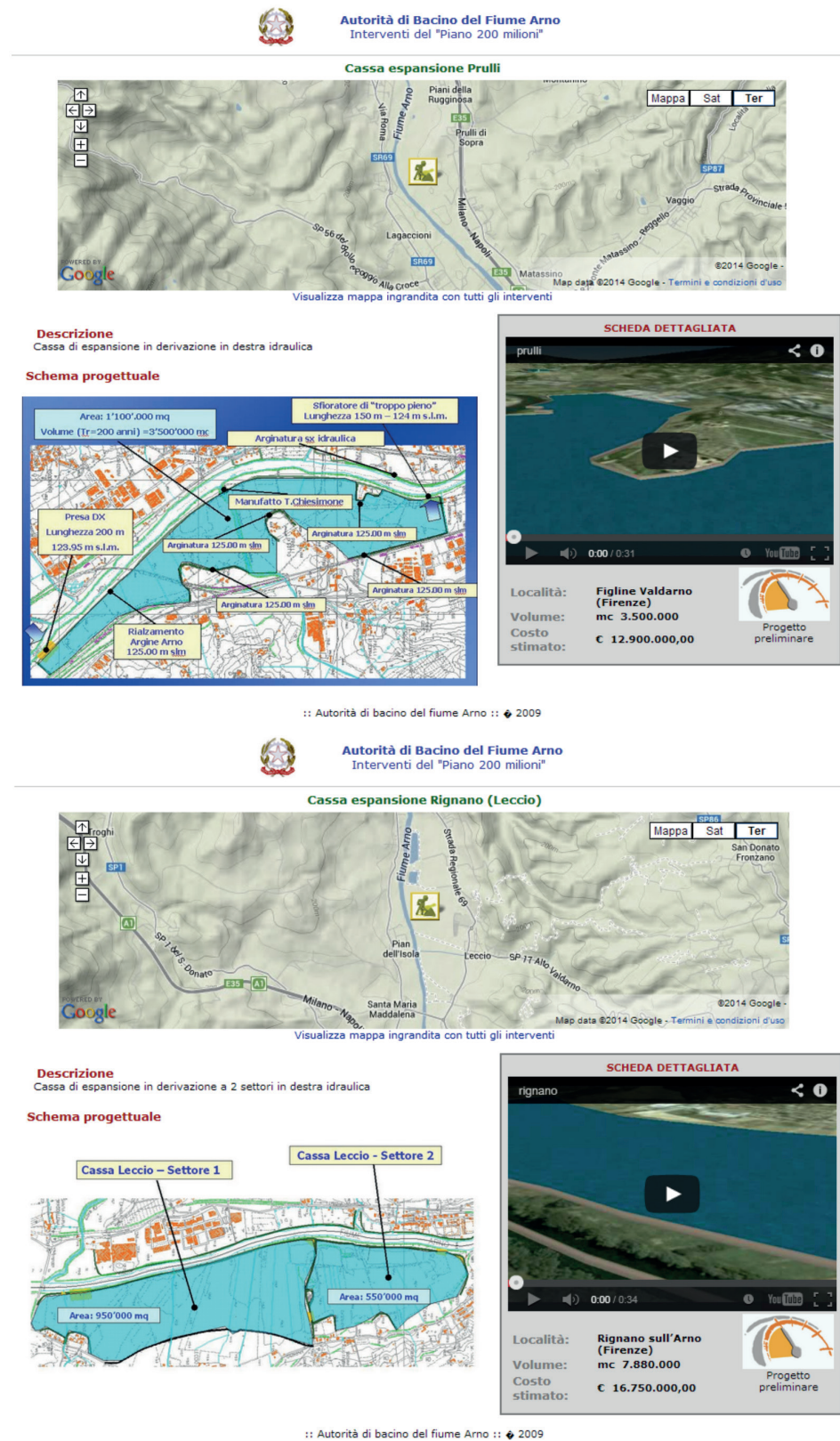
Flood retention area	Storage capacity according to the <i>Plan</i> [Mm <sup>3</sup> ]	Storage capacity in the preliminary design [Mm <sup>3</sup> ]	Surface in the preliminary design [ha]
Figline (Pizziconi + Restone)	16.59	10.62	233
Incisa	6.53	3.50	110
Rignano	12.38	7.88	150
<i>total</i>	35.50	22.00	493

**Table D-3.** Estimated costs.

Flood retention area	Estimated cost [M€]
Pizziconi	11.80
Restone	6.50
Incisa	12.90
Rignano	16.75
<i>total</i>	47.95

Sketches of the flood retention areas with some relevant information (storage capacity, cost, and work progress update) are illustrated in Figures D-8, D-9, D-10 and D-11 (from the former Arno River Basin Authority, <[https://www.google.com/maps/d/viewer?mid=1M7hM0CVdQ6D\\_b38UdefwIAiHo0k&chl=it](https://www.google.com/maps/d/viewer?mid=1M7hM0CVdQ6D_b38UdefwIAiHo0k&chl=it)>).



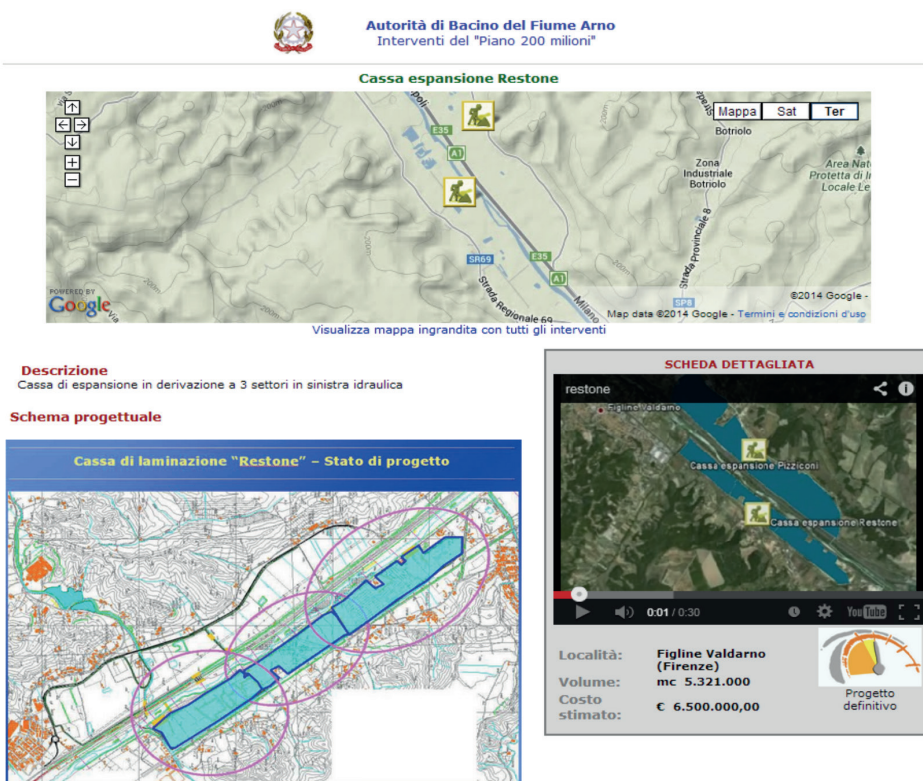


**Fig. D-8:** Pizziconi flood retention area (Brugioni, Arno River Basin Authority, I meeting of ITSC, 2014).

**Fig. D-9.** Restone flood retention area (Brugioni, Arno River Basin Authority, I meeting of ITSC, 2014).



**Fig. D-10.** Incisa (or 'Prulli') flood retention area (Brugioni, Arno River Basin Authority, ITSC meeting, 2014).



**Fig. D-11.** Rignano (or 'Leccio') flood retention area (Brugioni, Arno River Basin Authority, ITSC meeting 2014).

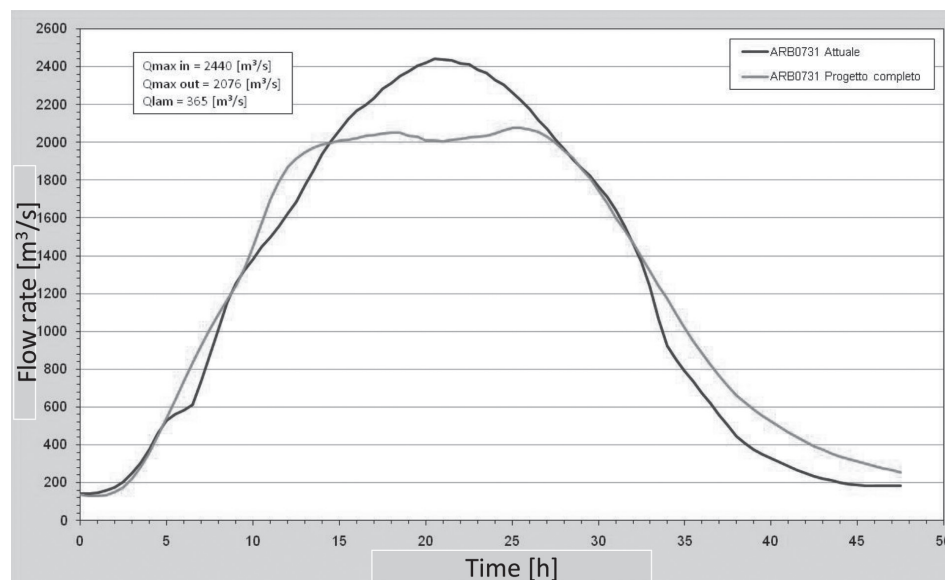
## Hydraulic modeling

The preliminary design of these works was based on the same hydraulic model developed for the original *Hydraulic Risk Plan* and used in the *Hydro-Geological Plan*. Later, the Arno River Basin Authority and the Department of Civil Engineering of the Tuscany Region implemented the current hydraulic model of these retention areas. The model is basically the same employed to study the hydraulics of the Arno River in Florence, consisting of a 1D scheme inside the river and a quasi-2D scheme for the flooded areas. The software used is the unsteady flow version of HEC-RAS 4.1.0.

The hydraulic effects of the retention areas were evaluated both at a *local scale*, to evaluate their local impact on the Figline area, and at a *large scale*, focusing on their impact on the city of Florence.

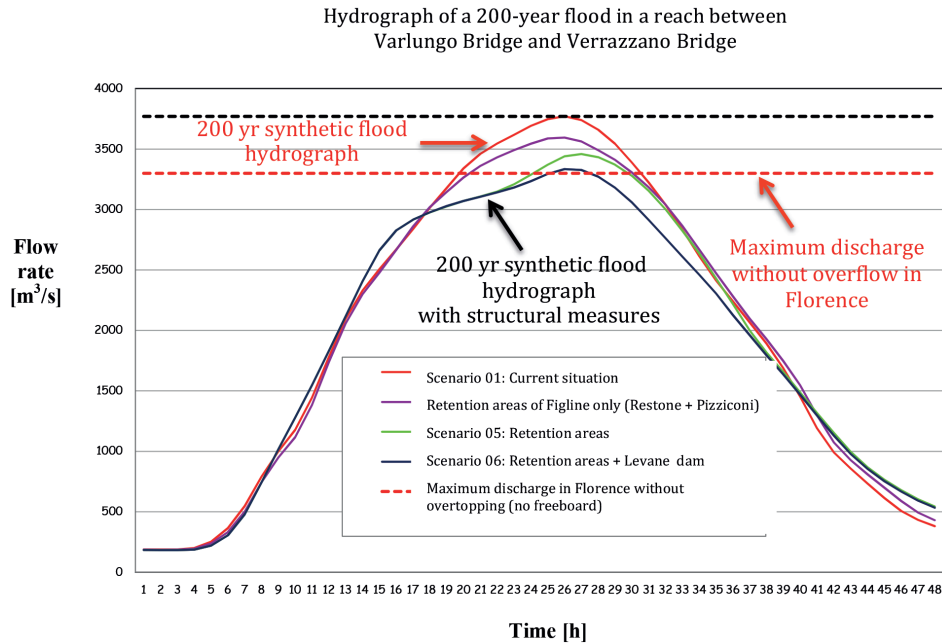
Simulations were run for various flood events with return periods of 30, 100, 200 and 500 years and rainfall durations of 12, 18, 24 and 36 hours, as well as for the significant flood events of 1966 and 1992. The Figure D-12 illustrates results at the *local scale* considering a 200-year synthetic flood event. It appears that the retention areas produce a significant reduction of the peak discharge; the ratio between the downstream peak discharges with and without these structures is about 85%.

**Fig. D-12.** Comparison between the hydrographs just downstream of the flood retention areas with and without these structures. The peak is reduced by 365 m<sup>3</sup>/s.



With regard to effects produced at the *large scale*, results in Figure D-13 show that the planned structural measures operate a reduction of the 200 yr. synthetic flood hydrograph peak from 3 792 m<sup>3</sup>/s to 3 459 m<sup>3</sup>/s (see green hydrograph), which becomes 3 401 m<sup>3</sup>/s (black hydrograph) if the raising of the spillway of the Levane dam is included. While this reduced discharge can be contained within the banks (with no free board) in the historical part of Florence, some overflow might be expected to occur in the downstream area of Florence in the Cascine park.





**Fig. D-13.** 200-year synthetic flood hydrographs just upstream of Florence with and without the planned structural measures (courtesy of Eng. Massini, Tuscany Region, I meeting of ITSC, 2014).

However, when we come to the effects of the planned structural measures on a 1966 type of event, unfortunately their benefit turns out to be negligible.

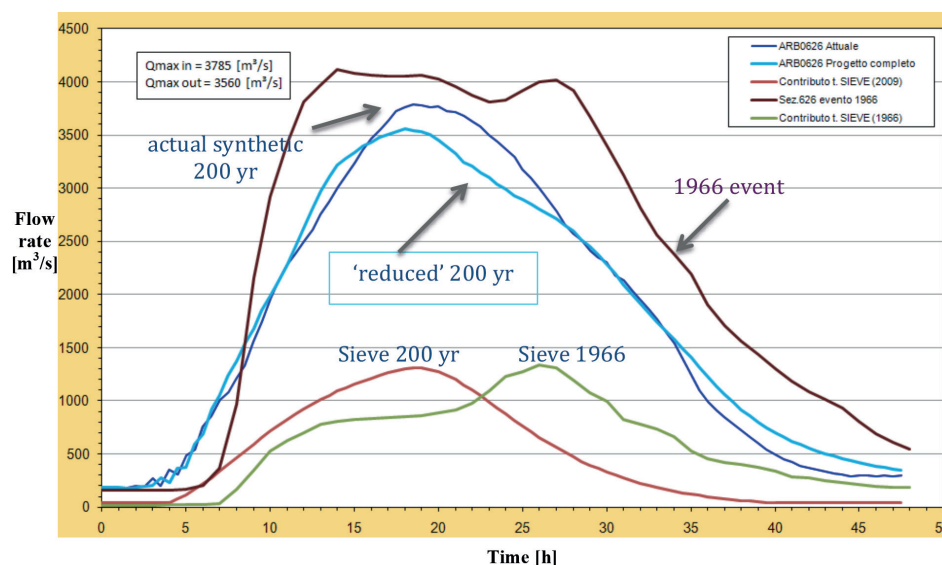
In particular, the peak of the 1966 hydrograph is reduced from 4 139 m<sup>3</sup>/s to 4 036 m<sup>3</sup>/s (Table D-4). The reason for this behavior is due to the large difference between the *shapes* of the synthetic 200 yr. and of the 1966 hydrographs: even though they have similar return periods (200 and about 230 yr., respectively), the duration of the peaks and therefore the associated water volumes are very much different. This comparison can be seen in Figure D-14. Also, note that the peak of the 200 yr. hydrograph from the Sieve tributary is in phase (no lag) with the hydrograph in the Arno. On the contrary, in 1966, the peak of the Sieve showed a considerable delay with respect to the first flood peak in the Arno river.

**Table D-4.** The peak discharges of synthetic hydrographs just upstream of Florence for recurrence intervals ranging from 30 to 500-year. The 1966 and 1992 real events are also included. Scenario 01 depicts the current situation (no structural measures); Scenario 05 considers only the effect of the flood retention areas, while Scenario 06 considers both flood retention areas and raising of the spillway of Levane dam (from 'Construction of the backwater retention areas to mitigate the hydraulic risk in Valdarno Fiorentino. Backwater retention areas of Leccio and Prulli. Preliminary design', Tuscany Region, 2009).

Recurrence interval [yr]	Peak discharges		
	Scenario 01 [m <sup>3</sup> /s]	Scenario 05 [m <sup>3</sup> /s]	Scenario 06 [m <sup>3</sup> /s]
30	2 505	2 662	2 614
100	3 338	3 086	3 086
200	3 792	3 459	3 401
500	4 643	4 653	4 549
1966	4 139	4 116	4 036
1992	2 128	2 197	2 173

From the various hydraulic simulations that were carried out, it turned out that the timing of Sieve floods has a great impact on the intensity and duration of the flood peak reaching Florence. Therefore, in order to take full advantage of the storage capacity of these flood retention areas, their side weirs will be equipped with mobile gates. The gates are supposed to be operated taking into consideration the time-lag between the flood hydrographs in the Arno River and in the Sieve Tributary.

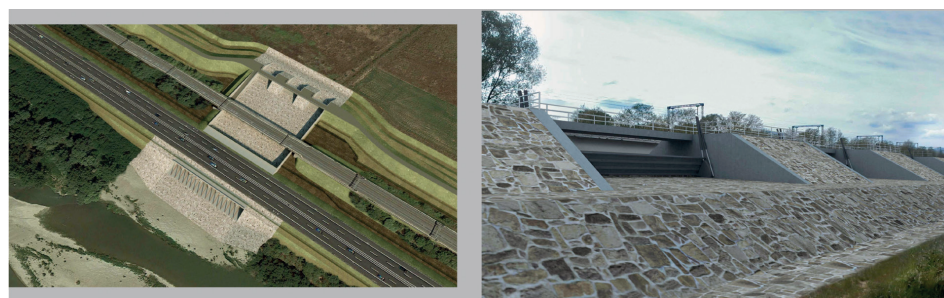
**Fig. D-14.** Comparison between different hydrographs in Rovezzano (just upstream of Florence): 1966 event, 200 yr. synthetic event without and with the structural measures. Hydrographs from Sieve tributary (1966 event and 200 yr. synthetic event) are added for comparison. The 'reduced' hydrograph is obtained considering the 2009 preliminary design of the flood retention areas.



### Structural specifications

The embankments of the flood retention areas have a maximum height of approximately 8.0 m, with a top width of 4.0 m and 1:2 slope of the retaining walls. The side weirs are equipped with mobile gates; this is to obtain maximum flexibility in the usage of the given storage capacity.

The movable parts consist of flap gates (Figure D-15). The increased flexibility may be guaranteed both in relation to the variability of the floods in the Arno and the Sieve, as well as in relation to the progressive variations of the discharges resulting from the structural measures planned upstream.



**Fig. D-15.** Side weir of the Pizziconi flood retention area (from [www.gruppoeurostudio.it](http://www.gruppoeurostudio.it)).



The mobile gates will generally be governed by the levels of the Arno River at the weir and will in any case have to ensure the possibility of regulation by means of a remote control system. This could be operated using data originating from the flood warning and control system from the River Arno's basin upstream from Florence.

The use of mobile gates will furthermore permit the optimization of the various retention areas operation during the period in which they are being constructed.



## Appendix E

### Sources of Photos

Fig. C-3. Different views of the Pescaia di Nave di Rovezzano. (a) Google Map. (b) Reproduced from <http://www.panoramio.com/photo/4707697>

Fig. C-4. The S. Niccolò mill (a) and the S. Niccolò weir with the S. Niccolò gate (b) (Drawing of E. Burci, Museum 'Firenze com'era')

Fig. C-5. Two different pictures of the S. Niccolò weir today. (<http://www.teladoiofirenze.it/arte-cultura/la-pescaia-di-san-niccolo-e-il-passaggio-segreto-sotto-larno/>)

Fig. C-6. Cross section of the Pescaia di S. Niccolò (<http://www.teladoiofirenze.it/arte-cultura/la-pescaia-di-san-niccolo-e-il-passaggio-segreto-sotto-larno/>)

Fig. C-7 (a) View of the Pescaia di S. Niccolò (Google Maps); (b) The Arno 'beach' (Courtesy of G. Federici)

Fig. C-8. Stanislao Pointeau, *I renaioli d'Arno*, 1861, Private Collection ([http://document.library.istella.it/user/516e6e1b237819e55100009a/documents/f48c3f55/cover\\_740\\_w\\_5228a32e49cd409e5900004c.jpg](http://document.library.istella.it/user/516e6e1b237819e55100009a/documents/f48c3f55/cover_740_w_5228a32e49cd409e5900004c.jpg))

Fig. C-9. The Arno Port in 1700. Anonymous painter. (<http://spazioinwind.libero.it/circolo16firenze/pignone/porto.htm>)

Fig. C-10. The Pescaia di S. Rosa in a painting of 1744 ([https://commons.wikimedia.org/wiki/File:Zocchi,\\_ville\\_09\\_pescaia\\_di\\_santa\\_rosa.jpg](https://commons.wikimedia.org/wiki/File:Zocchi,_ville_09_pescaia_di_santa_rosa.jpg))

Fig. C-11. The Pescaia di S. Rosa today (left [https://upload.wikimedia.org/wikipedia/commons/8/87/Pescaia\\_di\\_santa\\_rosa.JPG](https://upload.wikimedia.org/wikipedia/commons/8/87/Pescaia_di_santa_rosa.JPG)); right: Google Map)

Fig. C-12. The Isolotto weir and counter-weir (<http://www.comune.fi.it/materiali/Arno/Project.pdf>)

Fig. C-13. The Arno river and its Florentine bridges: photo taken by Bob Tubbs from Piazzale Michelangelo ([https://it.wikipedia.org/wiki/Ponti\\_di\\_Firenze#/media/File:Florence\\_bridges.jpg](https://it.wikipedia.org/wiki/Ponti_di_Firenze#/media/File:Florence_bridges.jpg))

Fig. C-14. The Varlungo bridge (left, <[https://upload.wikimedia.org/wikipedia/commons/5/56/Ponte\\_di\\_varlungo\\_12.JPG](https://upload.wikimedia.org/wikipedia/commons/5/56/Ponte_di_varlungo_12.JPG)>) and the Giovanni da Verrazzano bridge (right, <<http://www.artearti.net/magazine/articolo/anni-settanta-fra-inutili-concorsi-e-sprazzi-di-novita/>>)

Fig. C-15. The Arno River and the S. Ferdinando bridge (the old S. Niccolò suspended bridge) in a painting of the XIX century (<[http://www.turismo.intoscana.it/allthingstuscany/tuscanyarts/files/2011/01/Pittore\\_ottocentesco\\_veduta\\_dellarno\\_col\\_vecchio\\_Ponte\\_di\\_San\\_Niccolò.jpg](http://www.turismo.intoscana.it/allthingstuscany/tuscanyarts/files/2011/01/Pittore_ottocentesco_veduta_dellarno_col_vecchio_Ponte_di_San_Niccolò.jpg)>)

Fig. C-16. The San Niccolò bridge today (<[https://upload.wikimedia.org/wikipedia/commons/thumb/2/25/Ponte\\_san\\_niccolò\\_11.JPG/520px-Ponte\\_san\\_niccolò\\_11.JPG](https://upload.wikimedia.org/wikipedia/commons/thumb/2/25/Ponte_san_niccolò_11.JPG/520px-Ponte_san_niccolò_11.JPG)>)

Fig. C-17. Ponte a Rubaconte (upper; XVII century <<http://www.teladoiofirenze.it/storie-firenze-2/quant-sono-i-ponti-di-firenze/>>; lower: XIX century, photo Alinari)

Fig. C-18. The modern Ponte alle Grazie (<[https://newtonexcelbach.files.wordpress.com/2012/06/img\\_4996.jpg?w=1866&h=1245](https://newtonexcelbach.files.wordpress.com/2012/06/img_4996.jpg?w=1866&h=1245)>)

Fig. C-20. Vasari Corridor (<[https://en.wikipedia.org/wiki/Ponte\\_Vecchio#/media/File:Vasari\\_Corridor\\_1.JPG](https://en.wikipedia.org/wiki/Ponte_Vecchio#/media/File:Vasari_Corridor_1.JPG)>)

Fig C-21. View of damage to the Ponte Vecchio from the east. (Source: Tanner (Capt), War Office official photographer —<<http://media.iwm.org.uk/iwm/mediaLib//32/media-32455/large.jpg>>. This is photograph TR 2286 from the collections of the Imperial War Museums)

Fig. C-22. The Ponte Vecchio today, photo taken from S. Trinita Bridge. (<[https://upload.wikimedia.org/wikipedia/commons/thumb/7/77/Panorama\\_of\\_the\\_Ponte\\_Vecchio\\_in\\_Florence%2C\\_Italy.jpg/2880px-Panorama\\_of\\_the\\_Ponte\\_Vecchio\\_in\\_Florence%2C\\_Italy.jpg](https://upload.wikimedia.org/wikipedia/commons/thumb/7/77/Panorama_of_the_Ponte_Vecchio_in_Florence%2C_Italy.jpg/2880px-Panorama_of_the_Ponte_Vecchio_in_Florence%2C_Italy.jpg)>)

Fig. C-25. Santa Trinita bridge today. View from Palazzo Bardi Guicciardini's terrace (<[https://en.wikipedia.org/wiki/Ponte\\_Santa\\_Trinita#/media/File:Ponte\\_santa\\_trinita\\_view.JPG](https://en.wikipedia.org/wiki/Ponte_Santa_Trinita#/media/File:Ponte_santa_trinita_view.JPG)>).

Fig. C-26. Ponte alla Carraia today (<[https://en.wikipedia.org/wiki/Ponte\\_alla\\_Carraia](https://en.wikipedia.org/wiki/Ponte_alla_Carraia)>)

Fig. C-27. The Amerigo Vespucci bridge (<[https://en.wikipedia.org/wiki/Ponte\\_Amerigo\\_Vespucci#/media/File:Ponte\\_amerigo\\_vespucci.JPG](https://en.wikipedia.org/wiki/Ponte_Amerigo_Vespucci#/media/File:Ponte_amerigo_vespucci.JPG)>)

Fig. C-28. This 1932 photo shows both the Ponte alla Vittoria, just completed, and the Ponte Sospeso, shortly before it was dismantled (<[http://spazioinwind.libero.it/circolo16firenze/pignone/p\\_sospes.htm](http://spazioinwind.libero.it/circolo16firenze/pignone/p_sospes.htm)>)

Fig. C-29. The Ponte alla Vittoria in its present shape (<[https://it.wikipedia.org/wiki/Ponte\\_alla\\_Vittoria](https://it.wikipedia.org/wiki/Ponte_alla_Vittoria)>)

Fig. C-48. The floodway Firenze-Prato-Pistoia-Serravalle-Padule di Fucecchio proposed by Leonardo, as sketched in one of his famous drawings (<<http://www.mentelocale.it/images/articoli/full/67351-1.jpg>>)







