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Inundation on the Po Plain caused by levee breaches

Mario Govi & Franca Maraga

Consiglio Nazionale delle Ricerche (Italian National Research Council)
Istituto di Ricerca per la Protezione Idrogeologica, Sezione di Torino (Research Institute for Geo-hydrological Protection, Section of Turin)

ABSTRACT. This paper presents cases of inundation on the largest alluvial plain in Italy, the Po Plain. Information about the past inundation and levee breaches dating from 11th century are a background as collected in Ministry Reports as well as in archive maps dating from the 18th century. Nearly 500 data have been referred to the current provinces and some of them have been geographically positioned to investigate the levee vulnerability situations. The 1982 and 1994 inundation are described following the field observations. The breach recurrence, as related to the levee alignment geometry, reveals a major frequency in concave sides, caused by levee overtopping, riverbank erosion or under levee siphoning. Concerning the relationship of floodwater spreading from the breach and abandoned channels, it is documented that the former river system can induce both levee breaches and flood waves onto the plain. These results supply suggestion to the inundation risk mapping.

Key terms: Floodplain, Flooding, Po River system, Northern Italy

Presentation

In Northern Italy the floodplain protection against river Po floods has been developed since Roman times (2000 years ago) by means of flood retaining levees. At present, the River Po watercourse is controlled by a flood corridor along 420 km starting from the river mouth on the Adriatic Sea. This flood corridor is characterized by irregular width between the two levee alignments, that were influenced by the topography of the riverain lands depending on the river Po system changes and the social development works.

Inundation caused by levee failures has been known for centuries as resulting in fast-flowing flood waters from the breaches onto protected territories and involving casualties and great damage to urbanized areas.

Reclamation of the plain for build-up area extension has led to the acquisition of floodplain and abandoned river channels. Over the years the genetically flood proneness of the plain outside the river corridor was gradually forgotten because of the safety provided by levees. Human works came more and more close to the levee alignments, the danger of losing property being unexpected by flooding. Therefore, assessment of the inundation risk caused by proneness to levee breaching regarded the vulnerability along the levee alignments and the flood hazard onto the plain provided by levee safety.

The aim of the survey was to collect data on flooding caused by levee breaches of the past and present, their geographic reconnaissance and topographic positioning, for recurrence studies of levee breaching related to the river plan form, the alluvial plain features and the sedimentary body conditions.

The purpose was to detect and map the levee breaching prone sites as well as the flooding prone areas outside the flood corridor.

Study area

The plain of the Po River system is the largest alluvial plain in Italy (nearly 30,000 km^2) degrading in elevation from about 550 m a.s.l. in the upper plain at the foot of the southwestern Alpine arc down to the Adriatic Sea, having a width of almost 100 km before the Po delta and lengthening of the Po watercourse by about 600 km.

The geographic position of the Po Plain with location of the provinces chief towns pertaining to the riverain territories of the River Po floodplain is shown in Fig. 1.

Physical characteristics

The Po River watercourse develops for about 650 km (MIN. LL. PP., 1996) from its source at about 2000 m a.s.l. to the mouth, including 92 km on the delta plain downstream from Pontelagoscuro hydrometric station near the city of Ferrara (FE). The channel width at the bankfull stage (CARONI & MARAGA, 1985) increases from about 100 m at the first hydrometric station of Moncalieri near Torino (TO), 546 km from the mouth and 214 m a.s.l., in the upper Po Plain, to 300 m at the last station of Pontelagoscuro near Ferrara (FE).

The main divides of the Po fluvial system are the Alpine mountain chain, defining the northern and western catchment system, and the Apennines mountain chain, defining the southern catchment system. Eastwards the main flow direction is generated in the Po River according nearly to the 45° north, between 7° 30' and 12° 30' east.

Gravel lithologies of the alluvial sediments are related to crystalline rocks (igneous and metamorphic rocks) from the Alps and to sedimentary rocks (calcareous and pelitic rocks) from the Apennines, respectively referred to the northern part and southern part of the plain.

Impressive fluvioglacial cones from the Alpine basin mouths were terraced in the northern plain during Holocene, while alluvial cones from the Apennines were aggraded in the southern plain, with northward shifts in the River Po watercourse (River Po channel changes are drawn on the geomorphological map of the Po Plain edited by CASTIGLIONI, 1997).

The drainage basin of the Po fluvial system is 70,091 km^2 where it is closed on its delta plain fanhead, at the last gauging station of Pontelagoscuro near Ferrara (FE).

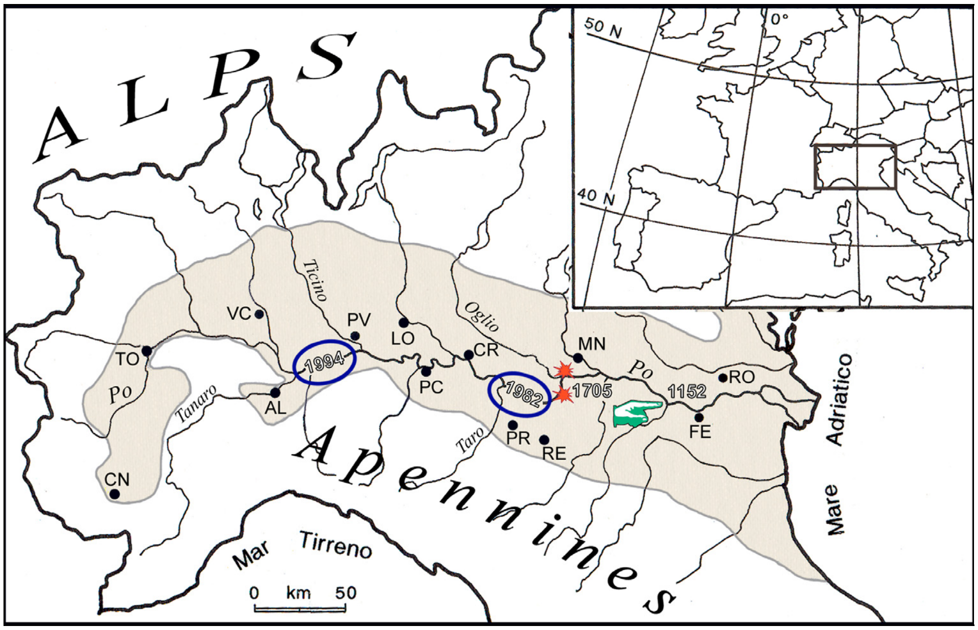

FIG. 1. Geographic localization of the Po Plain with location of its provincial capital towns that cover the river Po riverain territory. Downstream citation: CN (Cuneo), TO (Torino), VC (Vercelli), AL (Alessandria), PV (Pavia), LO (Lodi), PC (Piacenza), CR (Cremona), PR (Parma), RE (Reggio nell'Emilia), MN (Mantova), FE (Ferrara), RO (Rovigo). Study cases are indicated along the river Po watercourse by means of the years of levee breaching occurrence.

Floods and levee system

At the river Po basin closing station (FE), the mean annual discharge is 1510 m^3/s (1918-1985), the latest big flood was 9750 m^3/s in 2000, while the maximum flood was 10,300 m^3/s for November 14th 1951 (PRESIDENZA CONSIGLIO MINISTRI, 2002).

The present Po levee system defines a flood corridor completed during the 1960's for 420 km of the watercourse starting from the mouth up to the Pavia (PV) and Alessandria (AL) reaches, and also continuing for some ten kilometers along each tributary on the floodplain. We would like to mention the hierarchical system in the River Po levees on the middle Po Plain, where two or three levee alignments are constructed lower than main levee, proceeding towards the river channel. The main levee is locally 4.5 km from the channel, as in the Cremona (CR) plain, generating storage effects during the flood wave propagation (COMOY, 1860).

Beginning in the 17th century, the River Po levees were already continuous from the Adriatic Sea to the provinces of Cremona (CR) on the left riverside, and Parma (PR) on the right riverside, 265 km from the sea. At the end of the 18th century they were constructed up to the River Ticino confluence in Pavia province (PV), 374 km from the sea.

Up to today in the upper plain (provinces of CN, TO, VC and AL), the Po watercourse is controlled by discontinuous levees, that were constructed to protect some inhabited land or farming areas against floods.

Recurrence of inundation

Different flooding processes are associated with two models of evolutionary patterns that are recognized in the Po Plain downstream, as a result of dominant incision and straightening or deposition and lateral migration in the fluvial system (MARAGA, 1983, 1990):

- a model where terracing occurred on sandy-gravel sedimentary body, in the Po upper plain;
- a model where aggrading occurred on silty sand sedimentary body, in the Po lower plain.

With regard to the first model, river morphology includes braiding channels or wandering channels or irregular meandering channels that are controlled by discontinuous levee alignments and riverbank protection. Inundation caused by levee breaches is rapidly spreading. Flooded areas are circumscribed and connected with the irregular surface of the alluvial plain including sunken areas of abandoned channels. The floodplain reclaimed from the previous larger fluvial system is usually asymmetric with respect to the river channel, related to the river watercourse changes with a reduced number of channels or channel bend cut-off.

In the second model, the river morphology includes meandering or straight channels that are controlled by flood corridor and riverbank protection. Inundation caused by levee breaches is generally slow spreading and often dependent on infrastructures of the plain, the levee embankments themselves; therefore the flooding waters remain for several days. The sedimentation on the flood corridor plain has often created natural levee deposition bordering the river banks or sheet deposition, at times. So, the flood corridor plain is locally higher than the River Po plain outside the levee alignments, by up to a few meters.

History sources

A chronology from the year 1000 of inundation caused by levee breaches is collected in ministerial reports on River Po flood studies, reporting nearly 500 records.

Before 19th century, the references of 217 cases of flooding caused by levee breaches were located, relating to the presentday provincial territories on topographic maps (MARAGA *et al*., 2000). The territorial distribution (FIG. 2) indicates a dominant occurrence of inundation (80% of cases) in the lower Po plain, along the last 110 km of the watercourse on the right and left riversides before the mouth. Most breaches occurred in the Ferrara (FE) and Rovigo (RO) territories, where the levees were constructed next to the riverbank. In this fluvial reach the river Po is characterized by a narrow flood corridor having the must constricted floodway since the past. Some references refer to the ancient delta plain in the province of Ravenna, which is not at present connected to the River Po floodplain. The references location (MARAGA, 1996) follows the ancient Po river channels flowing to the sea on the southern part of the present mouth as floodways until the 1600.

However, before the 19th century nearly 50% of the inundation references occurred in the 16th century and 25% in the 18th century (FIG. 3). The highest number of references is reported in the 16th century, with higher and longer floods that are contemporary with climatic changes. A disastrous levee breach of 1152 that occurred in the Po delta lowlands near Ficarolo, 20 km upstream from Ferrara (‘1152’ in Fig. 1), created the present delta main channel of the River Po by a channel avulsion from its previous southeastern watercourse.

An extreme inundation in November 1705 was reported in numerous library records (GOVI & MARAGA, 1995) and was documented on the lower Po plain by a contemporary survey mapped in 1706. As reported on the map, the flooding spread along the plain over an area 20 km wide and 125 long to the Adriatic Sea.

From the territories of Mantova (MN) and Reggio nell’Emilia (RE) to the sea, the levees of the River Po and its tributaries were overtopped and breached in 48 sites in the plain, between November 4th and 16th. Of the breach sites which played a dominant role in the water flooding over such a vast surface, particular mention should be made of two levee breaches both on the right and the left bank (‘1705’ in Fig. 1), respectively 4.5 km upstream and 1.5 km downstream of the river Oglio confluence. On the right Po riverside, from a breach wider than 700 m and on the left bank from a 300 m breach, the flood waters flowed as impetuous streams, fed also by secondary levee breaches of the tributary rivers on the floodplain. They spread over the plain with a more rapid flow along a former fluvial system having parallel paths to the present Po watercourse. On

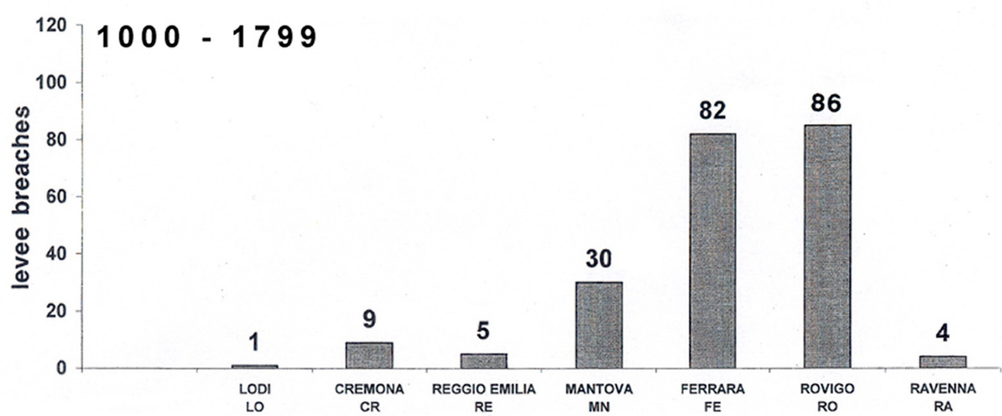

FIG. 2. Territorial distribution of inundation caused by levee breaches from the 11th to 18th century, as inferred from 217 historical references related to the floodplain provinces (see Fig. 1). The provinces are listed downstream from Lodi (LO) along the 320 km to the Adriatic Sea, corresponding to the River Po reach with levees at the end of the 18th century. The province of Ravenna is now outside the Po floodplain, because the River Po mouth changed after the 12th century.

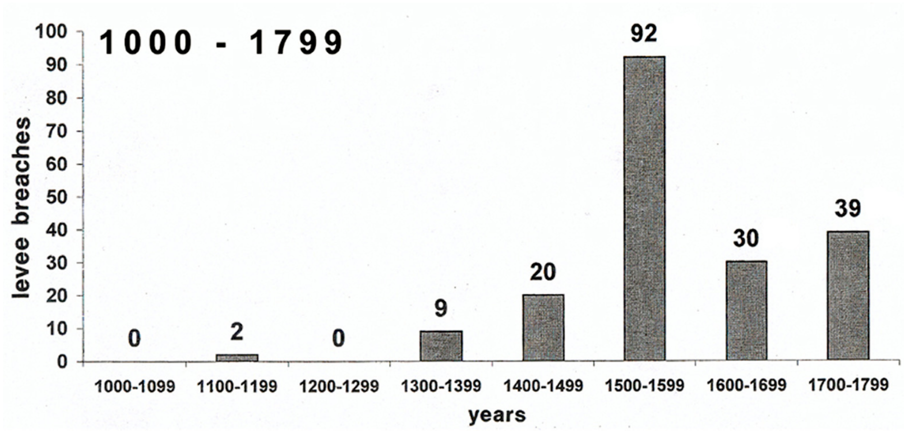

FIG. 3. Chronological distribution of inundation caused by levee breaches each century from the 11th to 18th, as inferred from 192 historical references.

these paths the floodwaters broke through the levees of its tributaries, determining the vast flooding that submerged the plain up to the sea.

During and after the 19th century, the inundation caused by levee breaches are reported by references that are supplied with some planimetric indications, which supported their hydrographic positioning along the River Po watercourse (GOVI, 1973). Breach locations downstream from the River Ticino confluence 274 km from the sea, are presented in Fig. 4 and cover inundation cases from 1801 to 1951.

In the 19th century the flooding by levee breaches in the lower Po Plain from Mantova (MN) to the sea covered areas of between 400 and 1650 km^2 and was often repeated in the same plain zones. Mention should be made of: the floods in November 1801 and December 1807 that concerned the left riverside of the Po River in the provinces of Mantova (MN) and Rovigo (RO); the floods in October 1812 and May 1872 on the territory of the right riverside in province of Ferrara (FE); the floods in November 1839, October 1872 and June 1879 over an extensive territory, with flooding continuity from Mantova (MN) to Ferrara (FE) on the right riverside (GOVI & TURITTO, 1997). This inundation that occurred on the right riverside plain developed on the parent fluvial system of the River Po from before the year 1000, when the plain was dominated by diffused swamps. Now the reclaimed low lands are urbanized beside the river watercourse. In this plain the flooded waters stagnated for times of between 2 and 5 months.

In the 20th century an inundation caused by the levee breaches with an extension that can be compared with the previously cited ones is referred to November 1951, covering about 1000 km^2. It was characterized by flooding on the right riverside of Parma (PR) province and left riverside of Rovigo (RO) province; in this lower land the flooding reached the sea as well as the plain 30 km upstream from the levee breach sites, because of backwater expansion. The floodwater lasted for 11 days on the plain (TURITTO 2004).

The most recent flood of the River Po occurred in October 2000 but remained in the flood corridor. Nevertheless attention was paid to levee failure hazard due to the riverbank erosion or piping phenomena that created danger of under-excavation or siphoning at the levee embankments.

November 1994 Flooding on the Pavia Po Plain

In November 1994, the levee breaches on the upper Po plain were documented in the provinces of Vercelli (VC), Alessandria (AL) and Pavia (PV), on continuous and discontinuous alignments with a great flooding impact along the ancient abandoned river channels (ARATTANO *et al.*, 1994; MARAGA, 1995). The inundation behavior was consistent with the terracing model of the Po Plain evolutionary pattern.

The Po flood corridor between Tanaro and Ticino tributaries (‘1994’ in Fig. 1) was completely occupied by the rush of the high waters, and the left levee was overtopped in numerous sites, with water level rising higher than those reached during the 20th century floods. The 1994 flood stage inside the flood corridor was measured + 8.60 m at the hydrometer of Chiavica Santa Chiara on the left Po levee 10 km upstream from the River Ticino confluence, while previous flood levels at the Chiavica were + 8.23 m in 1968, + 8.00 m in 1951, and + 7.60 m in 1926.

For the 1994 flood, the River Po discharge was measured at the Ticino confluence as 11500 m^3/s, in comparison with a mean discharge of 759 m^3/s in the period from 1948 to 1971. The plain had been flooded due to four breaches, two because of levee overtopping and two due to levee foot siphoning.

A common characteristic of the flooding caused by the levee breaches in the upper Po Plain is the impulsive action of the flooding waters, which are forced from the breach out off the flood corridor and create destruction along their flow paths marked by abandoned channels.

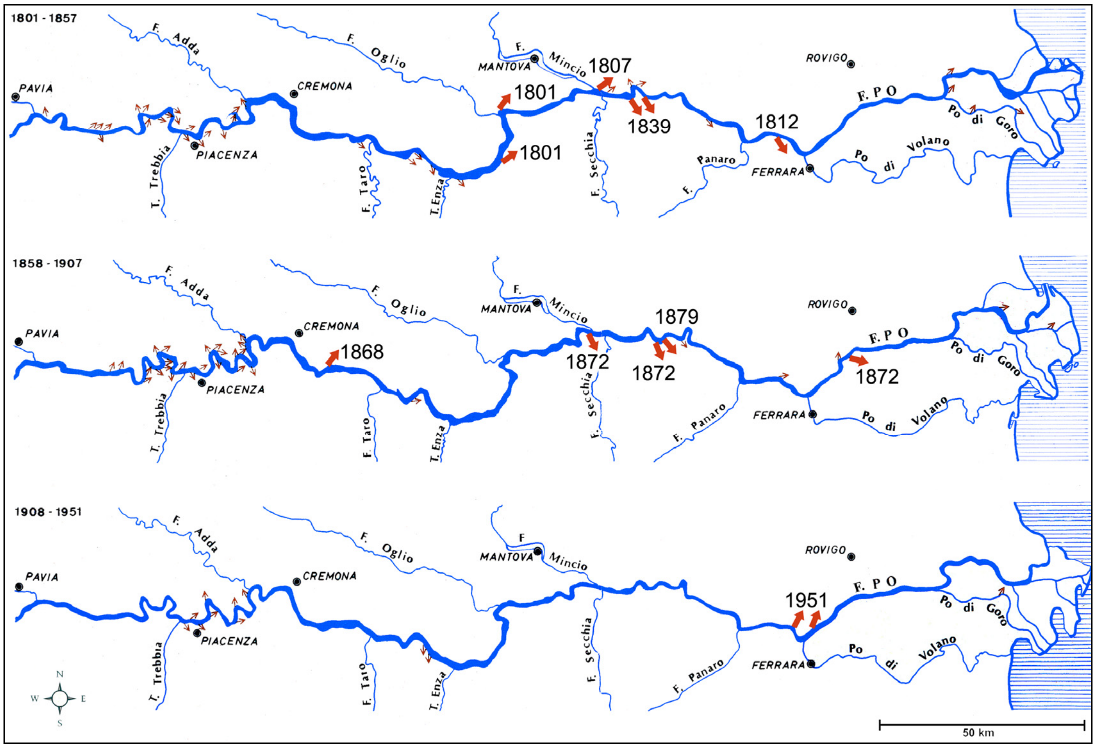

FIG. 4. Levee breach sites causing large inundation in the 19th and 20th centuries up to 1951, as located along the river Po watercourse on the basis of 255 historical references. The breach sites location is positioned on 1833, 1903, and 1966 planimetric maps, representing, respectively, the 1801-1857, 1858-1907, and 1908-1951 references. The large arrows and corresponding dates indicate the levee breach sites that generated flooding over an area of more than 300 km^2. In 1951, the last big inundation on the Po Plain occurred with flooded areas of nearly 1000 km^2 submerging the Polesine territory in the province of Rovigo (RO).

A terracing plain model of inundation

In the Po floodplain upstream of Ticino, the Po levee alignments have linked the stretches of the early defense works that were discontinuous, erected at the end of 1800 to locally defend the reclaimed lands against marshes and the large fluvial system on the plain, which was repeatedly flooded in the 19th century. The alignment was influenced by topographic configuration of the fluvial land and was sometimes placed to intersect abandoned channels or to border wide meander scars. Therefore the resulting geometry of the flood corridor is variable along the River Po here considered, both from the standpoint of corridor width (from 1.5 to 3 m) and height of the levee embankment (from 2 to 6 on the plain).

A floodplain study case in this area is 35 km long and about 10 km wide. The Po channel is 45 km long having a slope of 0.04% between 70 and 52 m a.s.l.

Channelling along the river Po since the 1950's (GOVI & TURITTO, 1993), already induced by artificial meander cuts during the 19th century, led the Po channel to develop irregular meanders of wandering type with low sinuosity, characterized by great instability of the river bank lines. The imposed limits of the flood corridor controlled the floodwater spreading on the plain and the flood activity was concentrated in the riverbed itself. During the period between 1954 and 1988, for example, a terrain loss due to bank erosion has been evaluated for a total surface of 3.6 km² measured on a channel reach 30 km long, due to lateral localized erosion on 19 sites of the left and right banks (DUTTO & MARAGA, 1991).

The Po floodplain presents on the right border an alluvial fan slope connecting the plain to the Apennine Mountains, while on the left border it presents a not submergible fluvial terrace at about 5 km from the river. The plain fluvial sediments are characterized by sandy grain sizes on the surface and sandy gravel grain sizes on the subsurface.

The fluvial territory outside the flood corridor is framed by traces of frequent abandoned channels beside the river watercourse up to 5 km both on the left and right side. The dating of the abandoned riverbeds gained from historic maps (DUTTO, 1989) allowed us to date the genesis of the terraced surfaces to the 17th century. They constitute the natural possible zones of spreading for the floodwaters.

The first inhabited centers on the plain have developed since the year 1000 together with the commercial organization of the fluvial navigation. The progressive acquisition of the floodplain with anthropic development towards the Po River has allowed the building of numerous villages near each other at a distance 2-4 km along the left and right Po riverside. At the moment there are 27 inhabited centers, the nearest to the river, 14 on the left bank and 13 on the right, with a few hundred resident inhabitants whose safeguard depends on the levee protection against flooding.

The Cambiò Nuovo village study case

The example regards the urban location of Cambiò Nuovo which has been directly involved, for more than one hundred years, in the flooding history of the River Po and represents the situation of potential risk of the built-up areas along the river, in the plain. Traces of ancient fluvial paths are present on degrading surfaces towards the Po by terracing scarps that are usually lower than 1 m (FIG. 5).

The configuration of the plain originated from the coalescence of the Po fluvial system and the Tanaro one, the first important tributary from the Apennines whose confluence has migrated 14 km upstream, during the last two centuries.

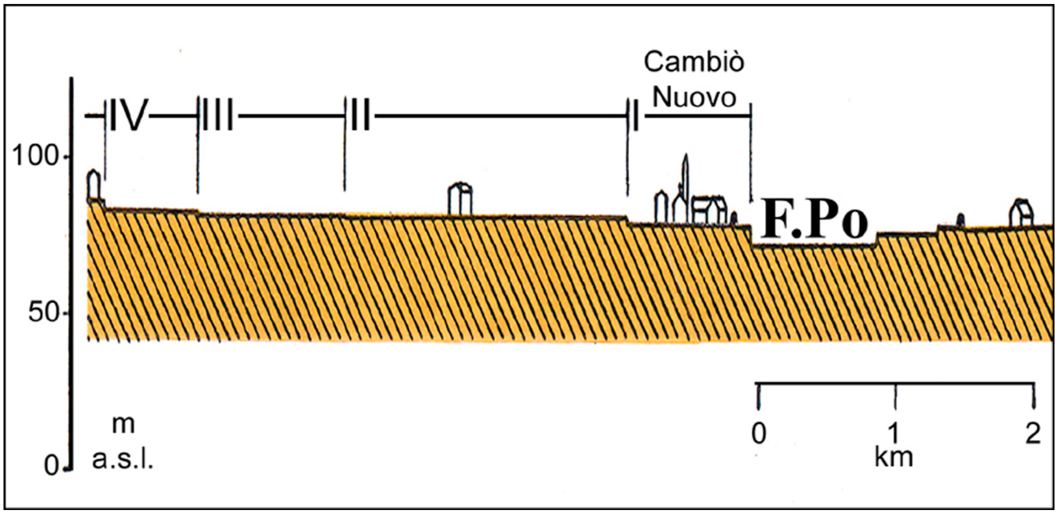

FIG. 5. Cross profile of the left floodplain in the province of Pavia (1994 study case in Fig 1), at Cambiò Nuovo village. The segments I, II, III, IV indicate terracing levels as stages relating to the hierarchy of natural proneness to flooding. The flood on November 1994 rushed the lower terrace protected by the levee and caused damage in the whole village by flooding across two levee breaches.

Cambiò Nuovo is a village on the left Po riverside downstream of the Tanaro confluence and was built at the end of the 19th century, in place of the village of Cambiò, which was destroyed by floodwater rushing. This previous village was just opposite the confluence on the left Po riverside and it was swept away by the impetuous water currents of the 1890 flood (PATTARO, 1894). In fact, the flood induced channel changes in the fluvial system with a wide shifting of the Po main channel towards the left riverside where the village was located.

As an effect of the November 1994 flood, two adjacent breaches was caused on the Po levee erected to defend the new village of Cambiò Nuovo and a fast water flooding was originated that spread over the plain and reached the second flood prone surface (II in Fig. 5). The entire village, that had previously been evacuated, was involved with floodwater heights of about 1m. Levee overtopping and failure caused the levee breaches on the evening of day 6, with a total breaching 200 m long (FIG. 6).

Some factors have to be referred for the levee breaching proneness. The levee top at the overtopping site had a lower level compared with the levee top downstream and upstream, so the floodwater overflowing was inevitable, given the water heights in November 1994. The two breaches were caused in a wide concave side of the levee alignment just upstream of a flood corridor reach having straightening constriction. This alignment configuration is a geometric frame that led to an anomalous increasing of the water levels inside the flood corridor caused by flood wave flow and backwater effects. Besides, in the concave side of

FIG. 6. Levee failure observed in November 1994 in the left floodplain, caused by flood waters overtopping the River Po embankment at the village of Cambiò Nuovo (1994 study case in Fig 1). (Photo taken three days after the levee breaching, viewed downstream.)

the levee alignment a wide abandoned channel is framed facing the levee: it constituted a path prone to the water flow and concentrated towards the levee both the flood wave waters and the backwaters from downstream.

November 1982 Flooding on the Parma Po Plain

The Italian National Group for the protection against floods and landslides (*Gruppo Nazionale per la Difesa dalle Catastrofi Idrogeologiche*, GNDCI) included in 1985 a special program, which was aimed to synthesize, test and standardize methodologies to be implemented for flood hazard mapping. A sample area was selected in the middle Po Plain, affected in November 1982 by extensive flooding in the right Po riverside, consequent to a big flood of the River Taro, a Po tributary from Apennines in the province of Parma (PR), 235 km from the sea. This area (‘1982’ in Fig. 1) underwent inundation of ca. 70 km^2 by flooding from eight levee breaches caused in the right levee of the River Taro and is presented as a consistent example of inundation related to the aggrading Po Plain evolutionary pattern.

A common characteristic of the flooding caused by the levee breaches in the lower Po Plain is the extension of flooded areas and their pond, that remain for a long time in the River Po floodplain.

An aggrading plain model of inundation

The case under study relates to the Po floodplain downstream from the Taro river tributary, a principal Apennine affluent of the Po. The November 1982 flood is considered the most severe for the River Taro in the last 100 years (LUNARDI, 1984). The peak discharge was determined at 3,200 m^3/s according to the stage-discharge relationship of the hydrometric station of Fornovo, at the outlet of the mountain catchment (1265 km^2) located about 50 km from the confluence. The 1982 flood magnitude is not expected to occur more often than once in 200 years.

The River Taro covers in the Po Plain a distance of 54 km flowing northward along its wide alluvial fan. The morphology of the plain is related to the evolution of the advancing alluvial fan of the River Taro onto the floodplain of the River Po (FIG. 7). The Taro alluvial fan is still in evolution having a frontal lobe advancing towards the Po floodplain of about 2 km during the last Holocene, due to accreting processes related to the fan radial line that is defined along the river channel.

It is likely that Taro River evolution was natural until the end of the 19th century. At that time the Taro watercourse had levees only in the Po floodplain reach (up to 20 km upstream from the confluence with the Po River) to protect the area against flooding caused by backwater of the Taro due to the confluence. At present, the Taro River watercourse is controlled within a flood corridor 31 km from the confluence, including the Taro reach in the distal and middle fan. This system of levees also controls the spreading of the accreting lobe by inducing accretion only within the flood corridor, somewhere found to be even 2-3 meters above the level of the plain. The right levee alignment continues along the river reach up to 5 km upstream, because of the right fan surface being lower than the left one.

The river morphology on the alluvial fan consists of a braiding channel in the upper fan, a wandering channel in the middle fan, and a meandering channel in the floodplain. The drop in elevation is one of about 115 m from the outlet of the mountain watershed to the confluence with the River Po (18.10 m a.s.l. at the thalweg elevation measured on the cross section as surveyed in 1973), generating a mean channel slope of about 0.2 %. Over the last 50 years, pattern variations occurred principally in the reaches of the alluvial fan connected to the river channeling.

The 1982 flooding processes are summarized as follows, related to the alluvial fan segments measured along its radial line in correspondence with the channel axis:- in the upper fan (Taro channel reach 18 km long), braided channel processes were generated with gravel sediment mobilization and remodeling of the overlapping medial bars into the width of the braiding system at the bankfull stage. Terrain loss occurred on the plain surface caused by lateral erosion at the river bank boundaries at the bankfull stage;

- in the middle fan (Taro channel reach 19 km long), wandering channel processes were generated with gravel bed forms remodeling in the channel. Lateral erosion produced bend increasing. Rapid over-bank flow and levee breaches occurred with the waters spreading into the plain and triggering soil erosion and alluvial deposition on it along the inundation water paths from the levee breaches, on the right river side, lower than the left one;

- in the Po floodplain (Taro channel reach 17 km long before the confluence in the river Po), the floodwaters were contained within the levees.

During the 1982 flood event, the Taro floodwaters and Po floodwaters interaction occurred as backwater effects in the Taro River flood corridor. A wave propagation model, tried out in 104 topographic river cross sections along the Taro River, points to the hydrodynamic behavior being due to backwater effect within the entire flood corridor up to 31 km from the confluence (CARONI *et al.* 1994).

The width of the corridor that controls the last 31 km of the Taro River varies from 109 to 1131 m along the distal reach of the alluvial fan with a wandering channel (average width 518 m) and from 187 to 1234 m along the floodplain with the meandering channel (average width of 507 m).

The Coltaro town study case

It is possible to identify geometric features that led to overtopping levee processes in the middle distal fan. This is particularly enhanced for the lower right riverside. On the left bank, flooding is limited to older river bends reclaimed for human settlements.

Due to the lowering of the alluvial fan, the right overflowing from breaches spread up to 10 km from the River Taro onto the Po floodplain, which acts as a flooding storage area generated by the dam effect of the Po River main levee. Inside this floodplain is located the little town of Coltaro, behind the Po levee (FIG. 8).

The flooding caused by breaches affected the distal alluvial fan, along the entire length of the crescentic lobe. The floodwaters completely invaded the flood corridor and overtopped the levees themselves in many sites of the left and right alignments starting from 22 km from the confluence with the Po River.

Eight levee breaches were activated on the right levee alignment, six of them along the river-wandering reach and two in the link reach between the wandering and meandering channels. Flooding waters flowed rapidly over 2.5 km of lobe of the alluvial fan and then caused inundation and water pond back to the levee of the Po in the floodplain, up to 9 km away. The waters, up to 2 m high, remained several days in the flooplain.

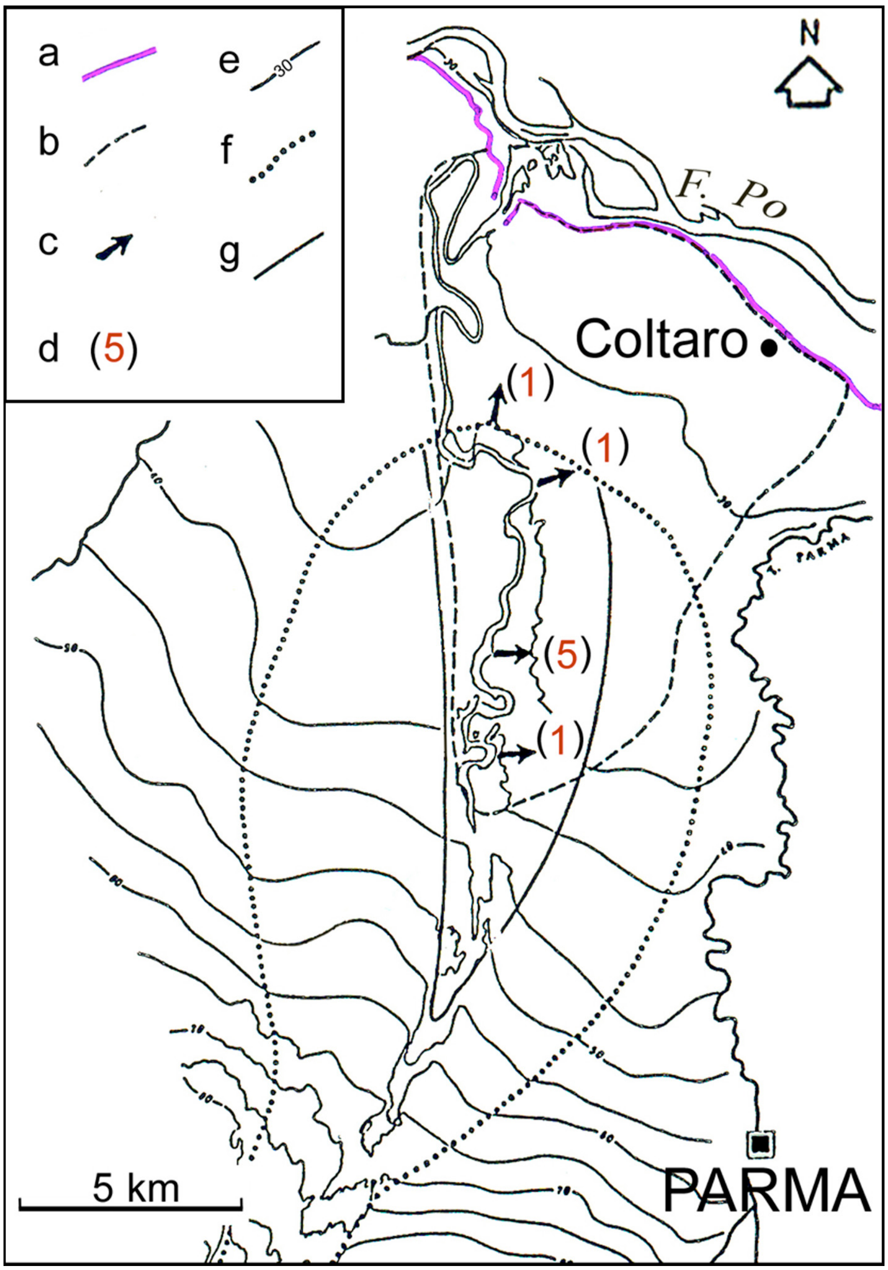

FIG. 7. Levee breaches of the River Taro presented in planimetric view relating to the November 1982 inundation on the right River Po floodplain in province of Parma (PR) (1982 study case in Fig 1). Key: a) right levee alignment of the Po; b) flooded area limit; c) River Taro levee breaching site; d) number of breaches at the site; e) 5 m contour lines; f) River Taro alluvial fan; g) accreting fan lobe.

FIG. 8. Inundation of the little town of Coltaro in the province of Parma (1982 study case in Fig 1) behind the main levee of the Po River. The flooding waters spread from eight breaches in the right levee of the Taro tributary into the Po floodplain 10 km downstream. The water pond was caused by a dam effect of the right levee alignment of the Po flood corridor. The River Po channel is seen in the left background. (Photo taken two days after the River Taro flooded onto the Po floodplain, viewed downstream.)

Proceeding on the right Po Plain riverside along the Taro alluvial fan towards the Po floodplain, starting from the first levee breach, the floodways are characterized as follows: across the upstream 15-m-wide levee breach the floodwaters spread up to the Po levee travelling a distance of 9 km. Subsequently the waters spread, across five breaches close to each other for a total 176 m in width, up to the Po levee 7.5 km away. A partial 8-m-wide failure originated the seventh floodway, with water spreading to the Po levee, 6.5 km away. Finally, again a 25-m-wide partial failure gave rise to the last floodway, with water spreading to the Po levee, 5 km away.

In-channel erosion effects were determined at the bank of the right riverside (a total length of about 1 km with a maximum width of erosion of about 80 m), while lateral bars were attached to the left bank, consistent with the evolutionary trend of the alluvial fan.

All levee breaches were determined by levee overtopping in concave side of the levee aligment.

Results

Recurrence investigations and field observations on the flooding caused by levee breaches have been applied to carry out predictive analyses on flooding areas and levee vulnerability sites in river Po flood. The aim of these studies is to recognize the flooding expansion ability in urbanized alluvial plains and map them on an operative basis in a topographic map, defining the flooding proneness in the protected areas as well as in those which have to be protected by new levee alignments.

As an example, in the Po plain located on the Po left riverside in the province of Pavia (PV in Fig. 1), six flood prone areas are recognized in accordance with levees as artificial flooding limits and the fluvial terrace scarps as natural limits. The flood prone zones are linked by a hierarchical proneness system to water expansion ability. Three of them are contained in the floodplain between the levee alignments, called "*golena*" in the Po Plain, corresponding to the flood corridor; the others can be found in the external plain of the corridor, on the urbanized plain.

Some abandoned riverbeds still maintain topographic evidence in the Po plain, creating a terracing system or lower zones, which could be connected to the flooding fluvial system. As an example, on the Po left riverside in the province of Lodi (LO in Fig. 1), a particularly representative flooding occurred in 1917 on the left Po riverside. The alluvial plain was embanked in the 19th

century and a large inundation caused by a levee breach submerged the lower zones on the plain up to 17 km from the Po left levee. The floodwater spread on the plain following the paths of the numerous abandoned channels that are composed by a mutual linking system of progressive lowering with respect to the Po River. Therefore, representation devices were inserted to mark the abandoned channels, with their lowering related to the riverbanks, and a suggested micro-zoning hazard was drawn on the flood prone maps in the plain outside the flood corridor.

Despite hydrographic variation over the past 1000 years, similarity between the modes of levee breaching and floodwater spreading can be noted. What this relationship reveals is that the geometry of levee alignments related to the channel morpho-dynamics and the abandoned channe system can provide vulnerability indications of the breaching prone sites. Levee breach proneness has been demonstrated to be higher in Po Plain where the following situations were observed:

- closeness of the levee embankment to the river bank, due to the danger of bank erosion;
- wideness variability of the flood corridor, due to the backwater dangerupstream narrowing;
- sedimentary changes in the alluvial deposits at the base of the levee structure, due to the danger of subsurface floodways, occurring in abandoned channels.

On the Po Plain other factors also have affected the flooding flows. Tributary levees and irrigation canals or road and rail embankments interact with the submersion wave, extending the floodwaters onto the areas not prone to direct submersion by flooding from the levee breach. Levees, dikes, and fills lying transversely to the flooding direction on the plain have often generated backwater expansion of the flooding, until the obstacle has been overtopped and destroyed. On that account the inundation risk mapping will have to adjust the flooding prone areas to the progressing infrastructure and the anthropogenic transformation of the floodplain.

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