GEOMORPHOLOGICAL ASPECTS OF THE FLOOD HAZARD IN THE AREA BETWEEN THE RIVERS PO, SECCHIA AND PANARO (PO PLAIN, NORTHERN ITALY)

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ABSTRACT – Geomorphological aspects of the flood hazard in the area between the rivers Po, Secchia and Panaro (Po Plain, Northern Italy). This paper examins the geomorphological aspects of the flood hazard in the area between the rivers Po, Secchia and Panaro. The River Po, which flows in the northern part of the study area, and the Rivers Secchia and Panaro, which flowing northwards cross the study area, have periodically caused flooding in their territory. The flood hazard, related to morphological factors, is much higher in the sector north of Modena (where the rivers flow elevated over the surrounding plain between high banks) than in the sector south of the town (where the watercourses run deep in the alluvial plain). North of Modena. in order to defend the territory from the flood hazard the systematic practice to build, strengthen and increase in height artificial banks was adopted. Moreover several meander cuts were carried out along the Rivers Secchia and Panaro (the length reductions correspond to about 11÷12% of their overall length in the plain). As these interventions resulted to be ineffective, flow-regulation systems were constructed in the area of Modena along both rivers. They consists of a regulating dam built across the riverbed and a storage basin bordered by embankments. The historical flood events show that the banks breaches often occured near to paleochannels and that the flooded waters were collected in the lower areas and had as boundaries the embankements and/or the fluvial ridges flanks; sometimes the flooded waters remained for long periods in the areas where mainly clay superficial deposits crop out. Therefore, an important contribution to assess the flood hazard can be given by the geomorphological investigation through the implementation of GIS georeferenced thematic documents (Digital Elevation Model, microrelief, surface deposits and geomorphological maps) and related Data Base.

1. Introduction

This paper examins the geomorphological aspects of the flood hazard in the area between the rivers Po, Secchia and Panaro (located in the southern central sector of the Po Plain) (Fig.1).

According to Panizza (1996), the hazard of watercourses is mainly connected with occasional and exceptional changes of their water stages occurring during extra-bank flow rather than with the changes periodically generated by ordinary flow (the latter being more frequent but less noticeable). Usually the river

hazard is recognized when flooding events take place in populated areas, since the in-channel flooding, although more frequent, is also more limited and therefore more easily controllable and manageable.

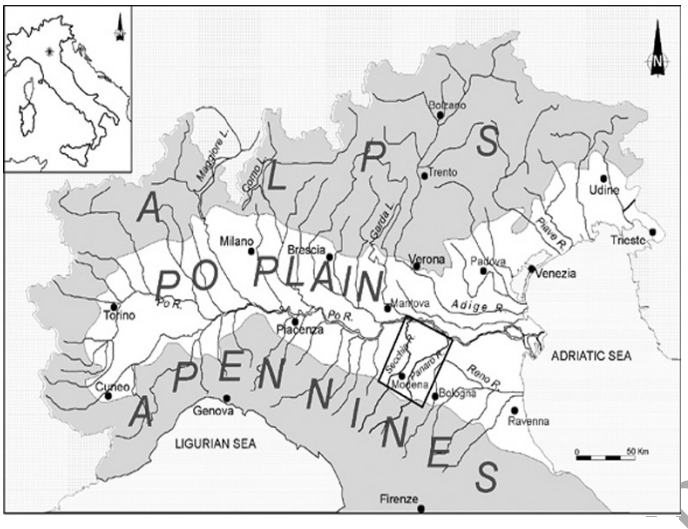

Fig. l. Location of the study area in the Po Plain (see inset)

The whole Po Plain itself was costructed by repeated episodes of flooding and sedimentation (Castiglioni & Pellegrini G.B., 2001). In particular, the River Po, which flows in the northern part of the study area and the rivers Secchia and Panaro, which flowing from south towards north cross the study area, have periodically caused flooding in their territory. As the southern central sector of the Po Plain is a quite populated area, the flood hazard is a very important problem.

2. Geographical, geomorphological and geological outline

The study area is located in the southern central sector of the Po Plain which is the most extensive plain in Italy (approximately 46,000 km^2, corresponding to 71% of all the plain areas and 15% of Italy). This sector of the Po Plain is situated in a temperate climate zone (Type Cfa of Koppen's classification). From the pluviometric viewpoint the study area corresponds to one of the least rainy sectors of the Po basin, with an annual average rainfall of about 600 to 800 mm, with seasonal peaks concentrated in the fall and spring (about 250 mm), and minimum values in the summer (about 150 mm)(Cati, 1981).

The central-southern sector of the Po Plain develops from the foot of the Apennine chain (where altitude goes from 110÷100 m a.s.l.) till to the River Po which flows through the middle of the plain from the west towards the east (altitude to 15÷10 m a.s.l.).

The plain/Apennines boundary is purely morphological as the Apennine structures continue towards NNE as far as the River Po buried under the Quaternary continental sediments; fault or fold deformations also involve these deposits (Pieri & Groppi, 1981).

The superficial alluvial deposits in the study area are Holocene in age; their particle-size distribution ranges from mainly gravel, in the sector south of Modena, to mainly clay in the northern sector. Their thickness is variable from hundreds of metres to one thousand metres in relation with the depth of the buried apenninic structures. (Castiglioni et al., 1997; Castiglioni & Pellegrini, 2001).

The geomorphological characteristics of the plain are mainly the result of the evolution of rivers Po, Secchia and Panaro and, in the last centuries, of the human activity. The natural landscape is characterised by alluvial fans, fluvial scarps, traces of abandoned river bed (at plain level as well as ridges), depressed areas and resourgences (Castiglioni *et al*., 1997; Castiglioni & Pellegrini G.B., 2001). In detail, at the Apennine margin the water–courses reaching the plain have built up alluvial fans which extend to the north near Modena town. Many ridges caused by the local evolution of ancient watercourses depart from the foot of the fans and continue till to the River Po; their patterns revealing the recent migration of these rivers. North of Modena town, depressed areas are located in between the fluvial ridges (Gasperi *et al*., 1989; Giusti, 2001; Castaldini, 2001; Panizza et al., 2004; Castaldini & Balocchi, 2006).

Two rivers flowing northward cross the study area: the River Secchia along the western sector and the River Panaro along the eastern one. The rivers Panaro and Secchia have total lengths of 148 km and 172 km, respectively, and catchment basins of 1784 km^2 and 2174 km^2, respectively. These two rivers collect waters from the central portion of the Northern Apennines and, after a course across the Po Plain (about 85 km and 90 km long, respectively), they flow into the River Po as the two lowermost right-hand tributaries (Monti & Moratti, 1997). The hydrological regime of the rivers Secchia and Panaro is characterised by two very similar peaks in the spring (March–April) and in the fall (November), and a minimum in the summer (August).

3. Flood hazard in the study area

The morphological features are one of the main factors which condition the flood hazard. In fact, according to Panizza (1996) and Maraga & Turitto (1998), in an alluvial plain with river terracing, the currents transfer down stream according to the system's dominant flow direction. The presence of embankments on the alluvial plain, confines the highwater flows within artificial levees whose breaking can cause vast floods. In particular, the flood determined by the breach of the embankments is transversally propagated according to the gradient of the plain along directions with no possibilities of return within the former river course and the flooding currents go out of their original system.

One of the most striking features in the study area is the morphological changes of the watercourses: south of Modena. upper part of the plain, they run deep in the alluvial plain whereas north of the town (mid-lower part of the plain)

they flow elevated over the surrounding areas within artificial embankments (Fig. 2). Therefore, because of these aspects, the flood hazard, related to morphological factors, is much higher in the mid-lower part of the plain (north of Modena) than in the upper part of the plain (south of the town).

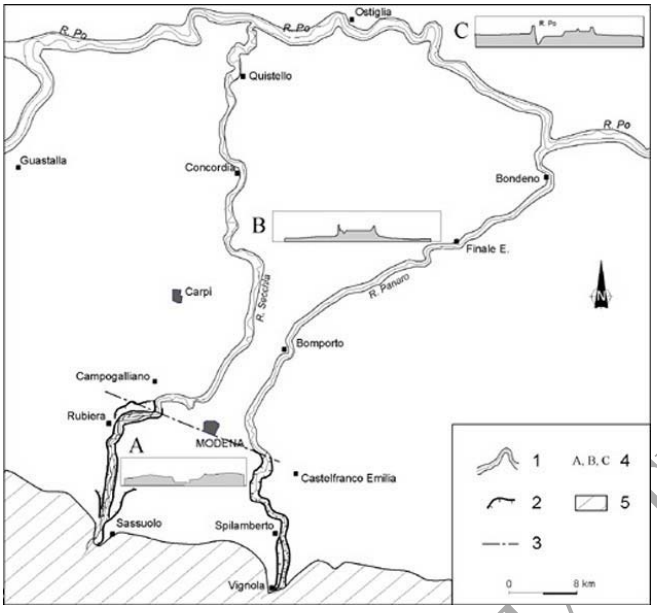

Fig. 2. Geomorphological sketch of the rivers Po, Panaro and Secchia in the study area. Legend: (1) hanging river, within artificial embankments; (2) fluvial scarp; (3) boundary between the upper and the mid-lower part of the plain; (4) schematic topographic profiles of the riverbeds: A, the rivers Panaro and Secchia in the upper part of the plain; B the rivers Panaro and Secchia in the mid-lower part of the plain, C, River Po in the study area; (5) Apennine margin.

A long recurrence of inundations concerns the Po Plain with historical records quoted in chronological lists and in official articles of the Italian Ministry for Public Works: the event listed started from the 11th century (Govi & Turrito, 1993). The most extensive informations on floods events become from the period after 1918 (Castiglioni & Pellegrini G.B., 2001).

In the Po Plain, the first man's interventions along the rivers (building of artificial banks), although to a minor extent, go back to Etruscan and Roman times (Ferrari & Gambi, 2000); these works were carried out in order to defend from flooding and turn surrounding areas into farming land. In the following centuries, the works involving the fluvial systems become systematic: beside walls, groynes, check dams, and canalizations, embankemets along 400 km course from the mouth of the River Po. were built. Since then the rivers' impediment to flooding has caused an increase of riverbed sedimentation with consequent over-elevation of the artificial embankments thus accentuating the hanging conditions of the watercourse over the surrounding plain

The building of artificial banks system was strucyured in external "master levees", with the essential defensive function for the surrounding areas (especially during most important floods events) (Fig. 3), and "secondary lower

embankements", located inside the high water river bed, to provide protected spaces with a lower margin of safety.

Fig. 3. River Po in the study area, October 2000. Floodwater confined within"the master levees"; note the waterflood level estendine over the surrounding plain (Photo by Bertolini G.)

In spite of the sistematic practice of building artificial banks, breaches due to overflow, siphoning, erosion or collapse of levees were frequent along all the rivers and expecially along the River Po. (Govi & Maraga, 1995; Govi & Turitto, 1996, 1998 and 2000; Cardinali et al., 1998; Guzzetti et al., 1998; Castiglioni & Pellegrini G.B., 2001). The banks breaches inundated enormous areas and floodwaters sometimes remained for long periods (from a few weeks to several months) in low-lying parts difficult to drain.

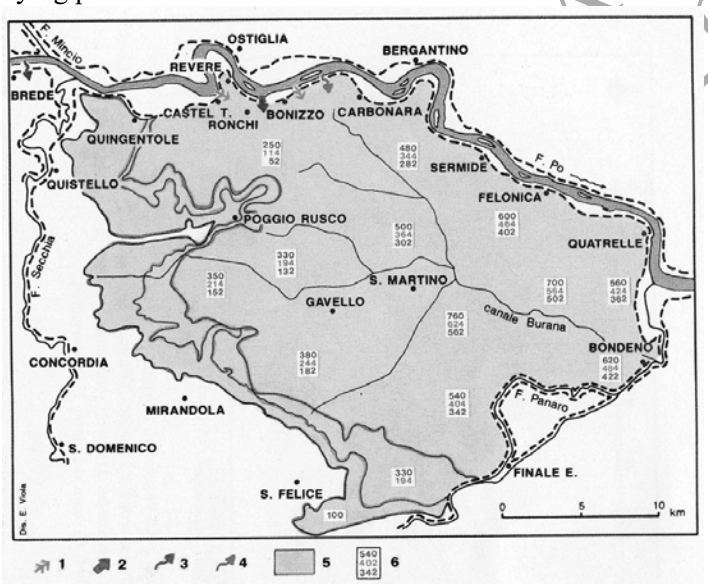

Fig. 4. Boundaries of the areas flooded by river Po in the northern sector of the study area in the 19th century. 1, 2, 3, 4) crevasse or overflow points; 5) flooded areas which occured on 1839, 1872, 1879; 6); height (in cm) of the floodwater on the soil level in occasion of the floods which occured on 1839, 1872, 1879 (from Govi & Turitto, 2000)

In the northern sector of the study area, the most recent inundations due to the River Po occured in 19th century on november 1839 (flooded area (f.a.): 47,000 ha), october 1872 (f.a.: 58,834. ha and june 1879 (f.a. :40,511 ha**)** (Consorzio

Fig. 5. Effects of flooding by the River Secchia in the early 1930s (from Consorzio di Gestione Parco Fluviale del Secchia, 2006)

Interprovinciale per la Bonifica di Burana, 1987; Consorzio della Bonifica Burana – Leo – Scoltenna - Panaro, 1999; Govi & Turitto, 2000) (Fig. 4). The floodwater reached the maximum height of 7,60 m in the depressed areas to south-east of S.Martino village in occasion of the october 1872 inundation. The level reached by the floodwater is still artificially marked on the walls of some houses of S. Martino village.

In the 20th, the demographic espansion required a greater availability of food resources which could be faced thanks to the estension of farming areas. This was acquired by means of land reclamation practices in the areas which were frequently inundated**.** In order to defend these territories from floods events, the embankments were strengthened and increased in height several times (Consorzio della Bonifica Burana-Leo-Scoltenna-Panaro, 1999).

The Rivers Secchia and Panaro flow through the outskirts of Modena, (Secchia to the East, and the Panaro to the West) and after forming a scissors-like course around the city, they flow tortuously to the NE between high banks until their confluence with the River Po. The waters of these rivers have periodically caused flooding in the area of Modena. The flood events of the last centuries are described in several papers (e.g. Moratti & Pellegrini M., 1977; Consorzio Interprovinciale per la Bonifica di Burana, 1987; Consorzio della Bonifica Burana-Leo-Scoltenna-Panaro, 1999; Idroser 1988; Moratti, 1988; Provincia di Modena; 1996; Panizza et al., 2004; Consorzio di Gestione Parco Fluviale del Secchia, 2006).

In the 19th century the R. Secchia flooded four times (November 1862, January 1863, October 1869, October 1889) whilst the River Panaro flooded five times (November 1812, September 1813, November 1887, October 1889, October 1897). In the 20th century rivers Secchia and/or Panaro flooded in 1928, 1932, 1939, 1944, 1949**.** 1956 and 1960 (Fig. 5). The more recent floods of the R. Secchia occured in April 1960 (flooded area (f.a.): 8,900 ha), November 1966 (f.a.: 7,000 ha), and September 1972 (f.a.: 1,320 ha). Those of the R. Panaro occurred in November 1952 (f.a.: 3,000 ha) November 1966 (f.a.: 9,400 ha), September 1972

(f.a.: 2,540 ha) and September 1973 (f.a.: 5,700 ha) (Fig. 6). In the 19th and 20th centuries, several other floods occurred in the lowermost tract of the R. Panaro.

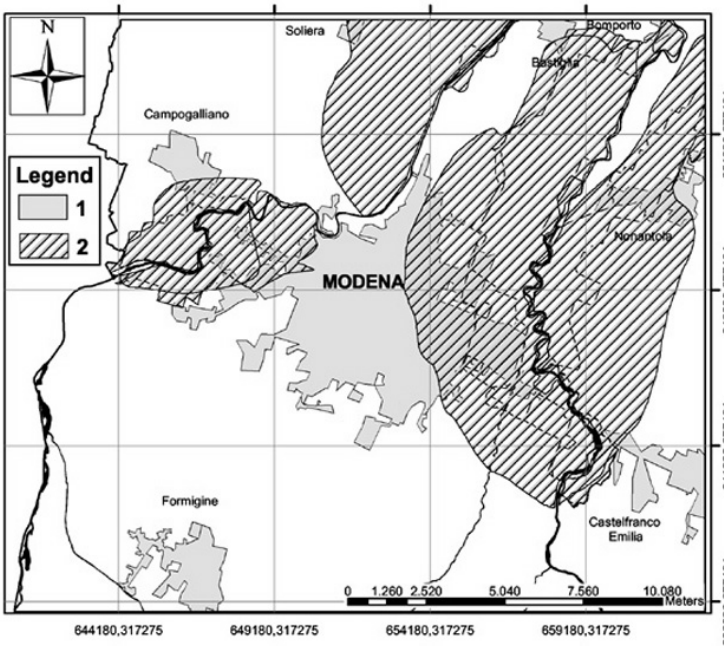

Fig. 6. Areas near Modena inundated by the rivers Secchia and Panaro in the more recent floods: 1) Present day built-up areas; 2) flooded area which occurred in autumn 1966, 1972, 1973 (from Panizza et al., 2004 redrawn)

In order to reduce the flood hazard making the flood peaks discharge faster, several river cut-offs were carried out**.** These kind of river works are described since the second half of the 17th century on the R. Secchia downstream of Modena; they caused a reduction of the river length of about 1.5 km (Lombardini, 1865; Manicardi, 1985). The latest cut-off was made in the early 1970s when the R. Panaro was, once more, shortened in length by man's intervention (about 3 km): in this case four meanders were cut east of Modena (Fig. 7). But also this work resulted to be ineffective, as testified by the flood which struck the territory

Fig. 7. River Panaro east of Modena that flows from the left (south) to theright (north). The meander cut-offs carried out in the early 1970s are evident

near the lowermost tract of the river in November 1982 (f.a,: 2,300 ha)(Consorzio Interprovinciale per la Bonifica di Burana, 1987; Consorzio della Bonifica Burana-Leo-Scoltenna-Panaro, 1999).

Therefore, two "flow-regulation systems" were planned and constructed in depressed areas, bounded by fluvial scarps, adjacent to the courses of the two rivers in order to better control flood hazard (Castaldini & Pellegrini M., 1989).

The flow regulation systems are both located near Modena, where the rivers Panaro and Secchia flow inside natural riverbed depressions, that are approximately 2 km wide, previously used as quarrying areas. These structures have been operating since 1979 for the R. Secchia and since 1985 for the R. Panaro. Each structure consists principally of a regulating dam built across the riverbed and a storage basin which allows the store of about 16 million m^3 of water. The basins are almost completely confined by embankments about 6 km long and 4 to 5 m high that were constructed to increase the capacity of the storage basin. During low-water periods, the water is discharged through mouths located in the regulating dam at the same level as the riverbed. In the event of high water, no more than a limited amount could be discharged through the dam's mouths. Excess water is stored upstream of the regulating dam, producing an increase in water level and regulating the flow downstream.

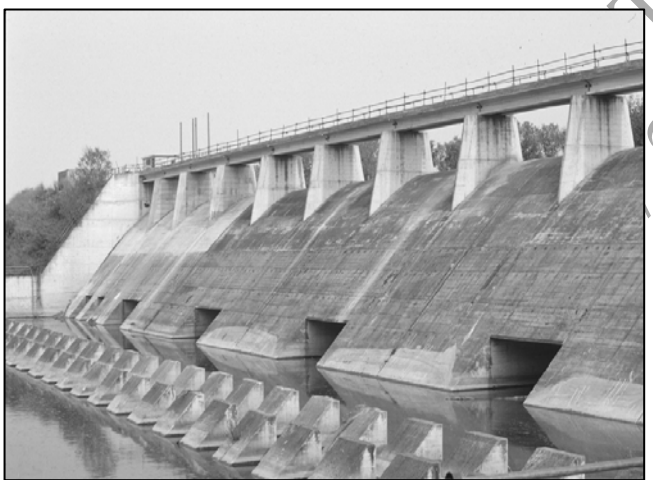

Fig. 8. Regulating dam of the "flow regulation system" of the River Panaro

The R. Panaro flow regulation system was completed in November 1999 after a rising of the embankments and adjustment of the dam (Fig. 8) carried out in order to increase the capacity of the storage area from 16 to 24 million m^3.

The most important function of these large hydraulic works is to reduce flood peaks; that is, they intervene on a very limited water capacity but with a high hydrometric level. The efficiency of these flow regulation systems has not yet been properly tested under the actual flood conditions; in any case, no inundation has occurred since they have been in operation. Similar structures were also built on other watercourses of the Emilia-Romagna Region.

Conclusions

In the study area, the flood hazard, related to morphological factors, is much higher in the sector north of Modena (where the rivers flow elevated over the surrounding plain between artificial levees) than in the sector south of the town (where the watercourses run deep in the alluvial plain). An incorrect perception of river instability phenomena can lead to erroneous assessments of hazard conditions. In particular, with embanked rivers in a large natural flood plain, man forgets the tendency of a protected area to be submerged by flood waters and the possible breaking of an embankment causes disastrous floods (Govi & Maraga, 1995).

A long recurrence of inundations concerns the northern sector of the study area as testified in many historical records starting from 11th century. In order to defend the territory from floods events, the embankments were strengthened and increased in height several times.

Moreover, several meander cut-offs were carried out along the rivers Secchia and Panaro since the second half of the 17th century. In detail, the R. Secchia assumed its present course essentially in the mid-19th century, following the artificial meander cut-offs which reduced its length by about 12÷13 km. The present course of the R. Panaro was conditioned by the meander cut-offs carried out in the late 19th century, in the lowermost tract and just upstream of its outlet, and at the beginning of the 1970s east of Modena, which reduced its length by about 10÷11 km. These length reductions of the R. Panaro and R. Secchia correspond to about 11÷12% of their overall length in the plain before the cut-offs (Tab. 1).

Table 1. Length reduction (in km) of the rivers Panaro and Secchia following meander cut-offs

Age of cutoffs	**Length reductions owing to meander cutoffs**	
	River Panaro	**River Secchia**
17th century	No data	1.5 km
18th century	No data	No data
19th century	7.5 km	10 km
20th century	3 km	1 km
Total reduction	10.5 km	12.5 km
Present-day length	85 km	90 km
Length before cutoffs	95.5 km	102.5 km
Reduction (%)	11%	12%

Since these cut-offs did not reduce flood hazard adequately, which was the primary goal of man's interventions (the meander cut-offs did not eliminate the flood hazard, of course, but they only transferred the problem to the river stretch downstream of the cut-offs), "flow regulation systems" were constructed in the area of Modena along both rivers.

The historical flood events show that: i) the banks breaches often occured near to paleochannels; ii) the flooded waters were collected in the lower areas and had as boundaries the embankements and/or the fluvial ridges flanks; iii) sometimes the flooded waters remained for long periods in the areas where mainly clay superficial deposits crop out.

Because of these aspects, the geomorphological features of an alluvial plain have a great importance to assess the flood hazard and the flood propagation. Therefore, an important contribution to the study of this matter can be given by geomorphological investigations. The studies can be carried out according to the traditional methods (bibliographic research, research on historical documents and maps, morphological analysis by means of interpretation of remote sensed images taken in various periods and different scales, field-survey, etc..) as well as with methods concerning the digital treatment carried out on maps and aerial photographs. The final goal is the implementation of GIS georeferenced thematic documents (Digital Elevation Model, microrelief maps, surface deposits maps and geomorphological maps) and related Data Base (for example see Bertens et al., 2000).

Acknowledgments

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