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Historic fluvial development of the Alpine-foreland Tagliamento River, Italy, and consequences for floodplain management

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Abstract

The fluvial geomorphological development of the Tagliamento River and its flooding history is analysed using historical documents and maps, remote-sensed data and hydrological information. The river has been building a complex alluvial fan starting from the middle part of its alluvial course in the Venetia–Friuli alluvial plain. The riverbed is aggrading over its entire braided length. The transition from braiding to meandering near Madrisio has shifted downstream where the river width determined by the dikes becomes narrower, causing major problems. The flood hazard concentrates at those places and zones where flooding occurred during historical times. Prior to the agrarian and industrial revolution, land use was adjusted to the flooding regime of the river. Subsequent land-use pressure led to a confinement of the river by dikes to such an extent that the flood risk in the floodplain downstream of Madrisio has increased consistently, and represents nowadays a major territorial planning issue. The planned retention basins upstream of the middle Tagliamento will alleviate the problem, but not solve it in the medium and long term. Therefore, fluvial corridors in the lower-middle parts (from Pinzano to the sea) have been identified on the basis of the flooding history in relation to fluvial development during historical times. The result should be used for hydraulic simulation studies and land-use planning.

Keywords: Flood events; Historical analysis; Fluvial dynamics; Fluvial corridors

1. Introduction

Flooding damage caused by the Tagliamento River has been reported since historical times. Meteorology, a large area of the upper catchment and steep slopes confer to the river a torrential regime that generates flash flood events of considerable size in the alluvial plain. Alluvial fan deposition by braided rivers takes place due to large sediment loads entering the foreland. This situation is typical of the Po foreland, but a parallel situation is found, for example, in the Himalayan range and the Gangetic foreland. Furthermore, the anthropogenic interventions of the last centuries, such as the construction of dikes and draining of existing wetlands in the lower lands, have severely reduced the river's space, causing highly critical hydraulic conditions in the lower part of the floodplain where the river changes from braiding to meandering (Fig. 1).

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Fig. 1. The Tagliamento catchment. Source: Basin Authority for the North Adriatic Rivers.

In this context, a number of questions arise. First, how does the geomorphological setting influence the overall hydraulic morphology of the river? Second, what evidence is available to analyse and map changes of the river since historical times? Third, what has been the role of human activity on the river? Finally, can likely near future developments of the river be described and taken into account to work out measures for flood control?

To understand the existing flood hazard, it is useful to study the behaviour of the river in the past. For this purpose, different approaches were adopted that produced new findings concerning the dynamics of the Tagliamento River. Historical descriptions of flooding were positioned on a map base. A land-use map of 1833, which forms the first reliable cartographic data, was compared with topographic maps of 1899, 1925 and other recent maps to relate land-use changes with channel changes. Aerial photos from different periods (1953–1955, 1966 and 1997) as well as recent satellite images were interpreted to retrieve geomorphological observations concerning the river's evolution, which were then related to existing hydrological data.

2. Description of the present situation

The Tagliamento River originates from Mauria Mountain at 1195 m and is 175 km long. It has a catchment area of 2871 km^2 (Basin Authority for the North Adriatic Rivers, 1997), which shows a funnel shape with a wide and mountainous upper part, a smaller and hilly central part and a long and narrow band in the floodplain (Fig. 1). The catchment includes 60 towns with a total population of approximately 180,000 inhabitants.

The principal tributaries of the upper catchment, the Lumiei, the Degano, the But and the Fella, converge and join the Tagliamento River forming a palmate pattern. Their basins are characterised by steep slopes and lie in one of the wettest regions of Italy, where annual precipitation can reach 3000 mm (Fig. 2). Rainfall is concentrated mainly in heavy and erosive showers determining the torrential regime of the river. Furthermore, the mountain basin is seismically active and has a dense distribution of landslides, resulting in much bed load and a braided nature of the river downstream.

Although this paper focuses on the relation between historic fluvial changes and flooding risk, it is valuable to provide the main hydrological data. The rainfall characteristics cause high peak flows in the central

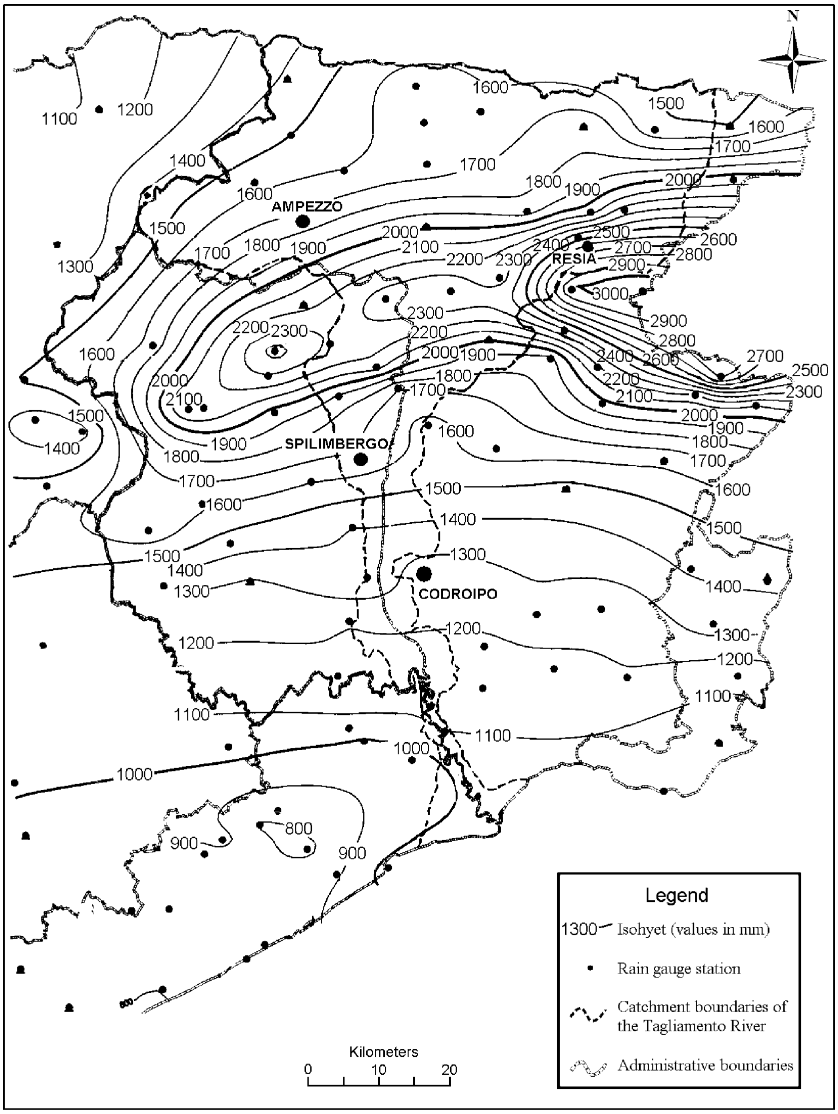

Fig. 2. Average annual precipitation for the period 1961–1990. Source: Basin Authority for the North Adriatic Rivers.

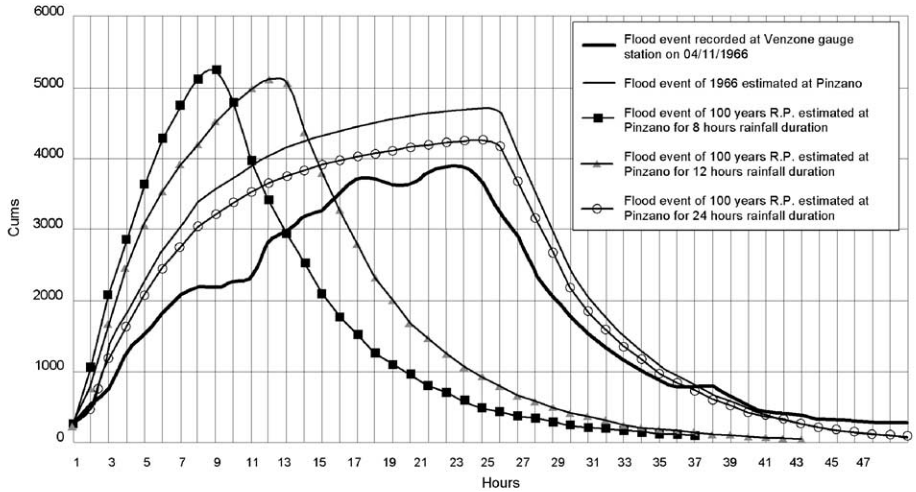

Fig. 3. Recorded and estimated hydrographs of major flood events of the Tagliamento River. Source: Basin Authority for the North Adriatic Rivers.

and lower part of the basin. The crest of the peak flow propagates rapidly downstream. The difference in arrival times of the peak between the upstream Venzone gauging station and the downstream Latisana gauging station (Fig. 1) is generally 12–16 h. Since the distance between the two gauging stations is 75 km, the crest propagates with a speed of 1.75 m/s. The annual average discharge is approximately 100 m^3/s, while the 50-year return-period (RP) peak discharge is 3500 m^3/s. For 100 years RP, 4300 m^3/s, and for 500 years RP, over 6000 m^3/s (Maione and Machne, 1982). Fig. 3 reports the hydrograph of the exceptional 1966 flood

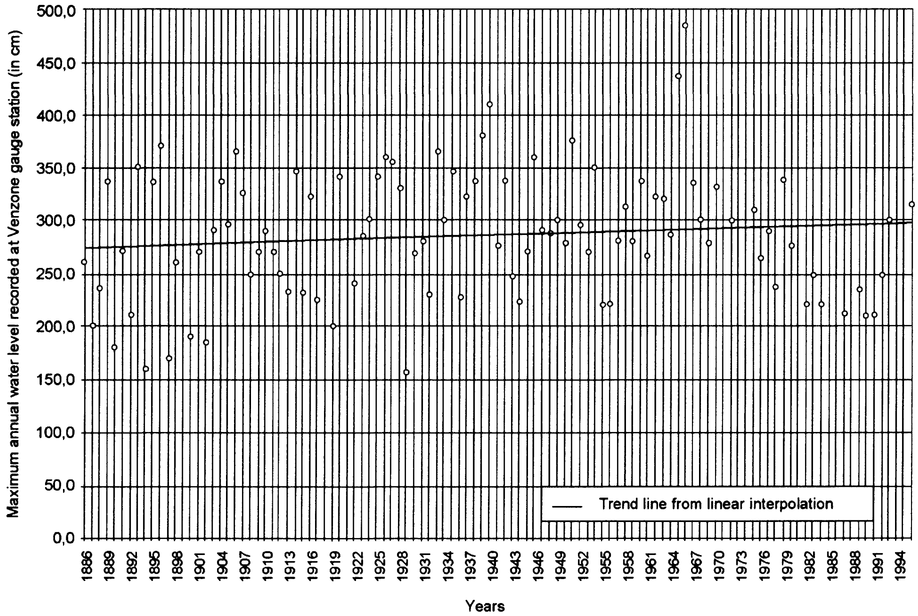

Fig. 4. Maximum annual water levels recorded at Venzone gauge station for the period 1886–1996. Source: Basin Authority for the North Adriatic Rivers.

recorded at Venzone and the estimated hydrographs at Venzone and Pinzano of flood events of 100 years RP for different rainfall durations, according to the Basin Authority for the North Adriatic Rivers (1997). A linear trend line fitted on a plot with the annual maximum water levels recorded at Venzone gauging station between 1886 and 1996 shows a slight long-term increase (Fig. 4). It is difficult to identify how much this increase is due to aggradation of the riverbed or to the increases of discharge; furthermore, in the latter

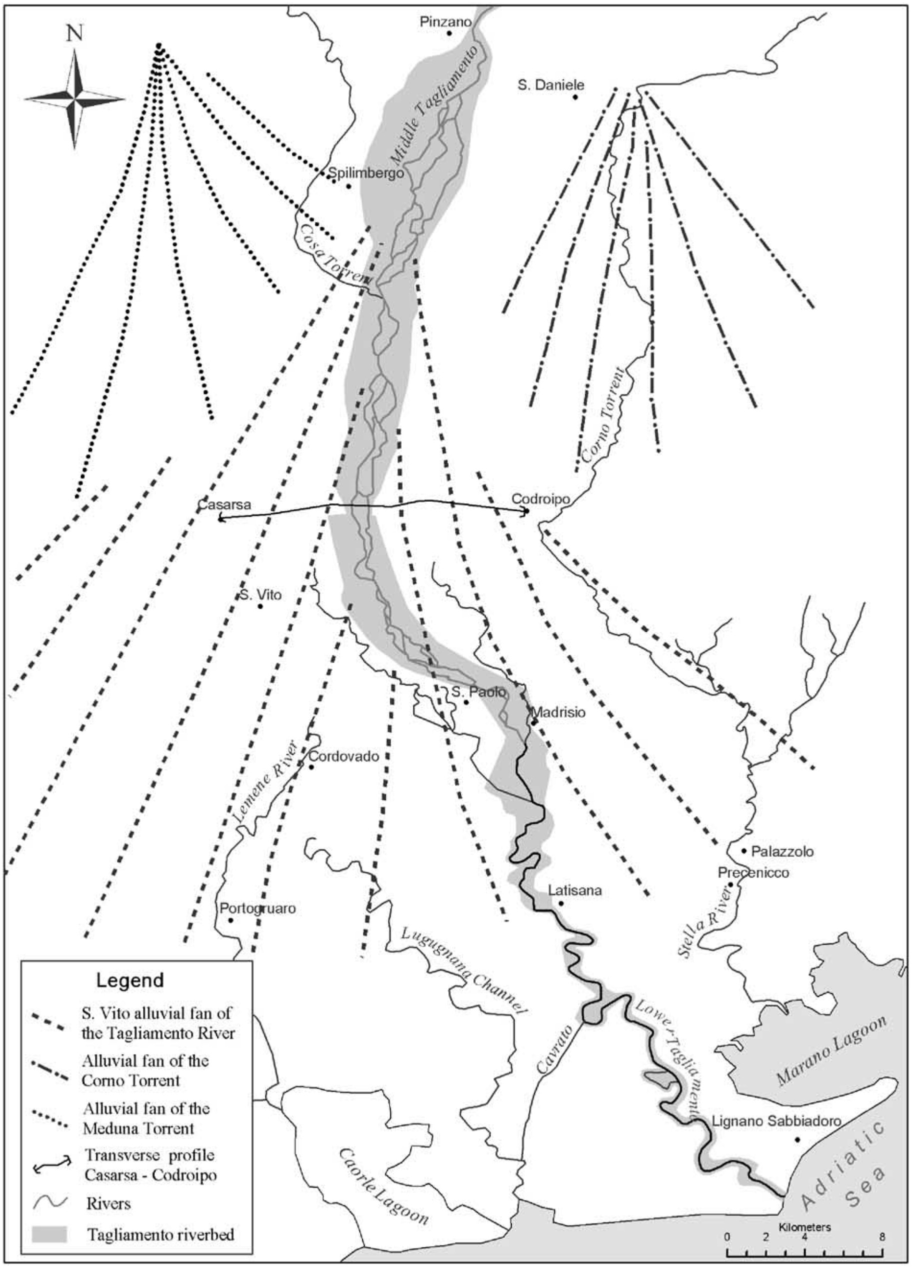

Fig. 5. Alluvial fans of the rivers Tagliamento, Corno and Meduna.

case, it has to be considered that flood discharges are based on extrapolation of rating curves and not on direct measurements.

The study area, which starts from Pinzano and reaches the outlet in the Adriatic Sea, is represented by the middle and lower Tagliamento (Fig. 1). From the Pinzano gorge to the confluence with the Cosa tributary, the river is confined between two high Quaternary terraces and can reach a maximum width of 3 km near Spilimbergo during periods of high water. There starts the large S. Vito alluvial fan of the river (Figs. 5 and 7), which has an area of 500 km^2.

The riverbed in the middle part is fully braided, as would be expected under conditions of irregular discharge, high bed load and associated relatively steep gradient of the alluvial fan. Because the braided reach is wide and shallow and the channel banks are unstable, the rate of sediment transport per unit width of channel may be relatively low (Leopold et al., 1964). In this river stretch, the average width of the active riverbed is about 1 km and is aggrading, as discussed below. The cross-section in Fig. 6 shows the riverbed at the highest position on the San Vito cone. Dry season flows infiltrate fully.

The lower Tagliamento starts near Madrisio, where the river changes to a single channel showing a semi-meandering pattern. This change is accompanied by a less steep gradient and finer grained sediments in the riverbed. The river width reduces drastically and measures 175 m at Latisana. At this location, as an average, the river bottom is 14 m deeper than the immediate surroundings, while the dikes are on average 6 m higher. Latisana, located 25 km from the coast, was an estuarine settlement in the past; at this distance, the river is under a tidal backwater effect. This factor caused overflow in front of the town during the last major flood event, in 1966, when a peak discharge greater than 4000 m^3/s was estimated at Latisana gauging station. During the second half of the 19th century, the Cavrato channel was built 10 km downstream of Latisana to dissipate the high water. Its capacity has been recently enlarged to 2500 m^3/s and it starts to function once the Tagliamento reaches a discharge of 2000 m^3/s (Foramitti, 1990).

3. Historical evolution of the fluvial dynamics

Historical documents were used to reconstruct and map the evolution of the Tagliamento during the past centuries. Of particular interest is to analyse the location and area of the floodplain, the flood and sediment regime and to define fluvial corridors.

The overall setting of the lower and middle Tagliamento catchment is shown on Landsat TM false colour composite of Fig. 7. The band combination used for the false colour image is a result of experimentation to obtain an image with most hydrological and geomorphological information. The older Quaternary deposits can be recognized by the large alluvial fan of the ancestors of the Tagliamento River: the Udine fan. It stretches from the city of Udine in the east to Pordenone in the west, where the wide Meduna and Cellina braided riverbeds are deflected along the

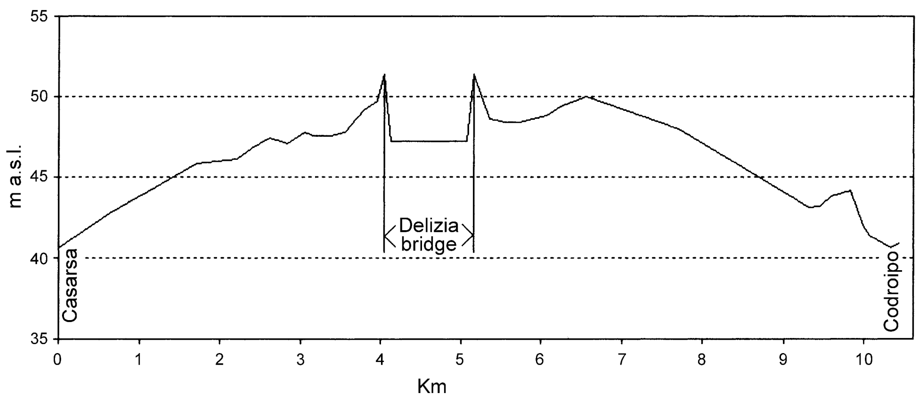

Fig. 6. Transversel profile Casarsa–Codroipo extracted from topographic map 1:10,000.

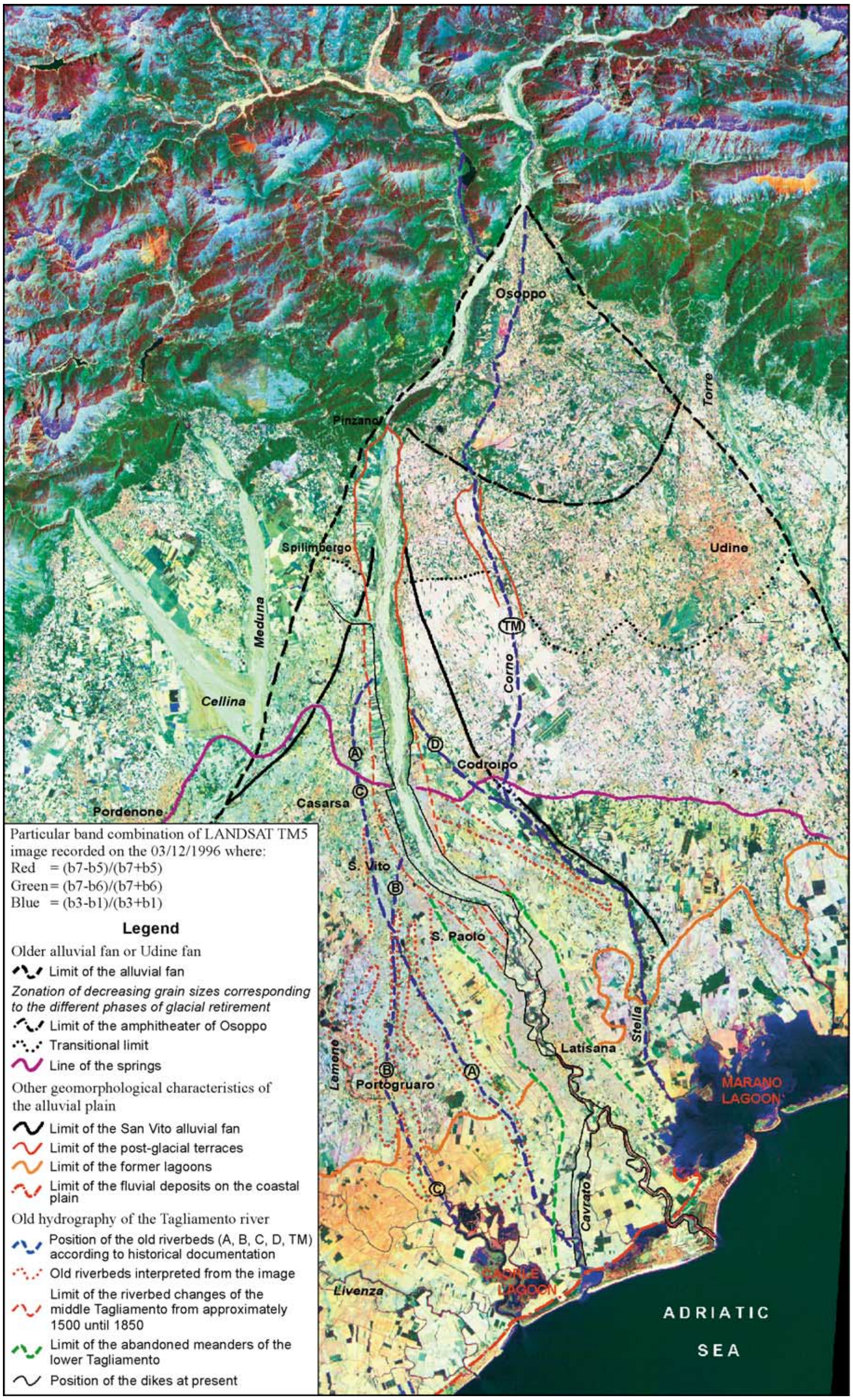

Fig. 7. Interpretation of the study area using a LANDSAT TM5 image.

old fan to the southwest. As mentioned, the upstream part of the middle Tagliamento River is incised in the older fan deposits. The zonation of decreasing grain sizes of the Udine fan is reflected in the land use pattern, as indicated by four zones in the image. At the start of the Holocene, the Tagliamento River occupied the western part of the old fan and formed during the period 18 000–6000 BP the San Vito alluvial fan (Fantin, 1990), shown also in Fig. 5. The western position is probably due to the complex configuration of the glacial deposits within the Osoppo amphitheatre that obliged the river to pass through the Pinzano gorge. It is also possible to delineate the fluvial deposits from the coastal plain sediments on the image, as shown. The partial on-lap of the Tagliamento fluvial deposits on the coastal plain sediments south of Latisana can be noted, as well as the redistribution of the sands by long shore transport in the small and young delta, which has grown beyond the coastal plain. Before the 10th century, there was an uninterrupted lagoon between Ravenna in the south and Grado in the north (Fantin, 1990). This important water body was divided in the lagoons of Comacchio, Venice, Caorle, Marano and Grado between the 10th and the 14th centuries by intense alluvial depositions of the north Adriatic rivers, in particular the Tagliamento River, due to deforestation in the Alpine region (Fantin, 1990).

During the Roman Empire, the Tagliamento River flowed in two main branches: *Tiliaventum Maius*, which had approximately the present position, and *Tiliaventum Minus* (TM in Fig. 7) that most probably was more in the east, where the rivers Corno and Stella are located (Averone, 1911). The rivers Lèmene and Stella and the Lugugnana channel were all Tagliamento's riverbeds (A, B, C and D in Fig. 7) during the past centuries (Averone, 1911); at present, only groundwater is discharged in these beds (Stefanini and Cucchi, 1977, 1978). In fact, the diverging branches mark active fan formation downstream of the incised part of the Tagliamento River. These ancient branches were often reused during the main flood events (Scimone, 1927; Ciconi, 1855; Rinaldi, 1870; Castellarin, 1990) and urban settlements like Portogruaro, Palazzolo or Precenicco, which are located relatively far from the Tagliamento, were flooded repeatedly (Figs. 8 and 9) until the dikes for the middle Tagliamento were completed, after 1850 (Fig. 10).

During the period 1400–1599 (Fig. 8), the middle Tagliamento flowed more to the west compared to its present position (Rinaldi, 1870), i.e., in alignment with its ancient riverbeds A, B and C (Fig. 7). Therefore, the towns of Cordovado and Portogruaro were flooded several times.

From 1600 to 1799 (Fig. 9), an eastwards migration took place and, consequently, the ancient riverbed D was reoccupied several times during the inundations (Castellarin, 1990). Even the Tiliaventum Minus was used twice (Fig. 10).

In particular, from 1596 to 1692, the river bifurcated at the transition between the medium and the lower Tagliamento, forming an island where the settlements of San Paolo, Bolzano and Mussons were located (Castellarin, 1990). After an important flood in 1692, the river occupied the eastern branch, its present position. However, since that time, the abandoned western branch was used several times during the flood events (even during the last one in 1966), causing important damage in particular to the city of San Paolo (Fig. 10).

During the flood events of the first half of the 19th century, when the middle Tagliamento was still free to migrate eastwards or westwards at the top of its alluvial fan, the old riverbeds of both sides were reused. With the growth of the population after the industrial and agrarian revolution, the pressure on the riparian lands increased and agricultural practices changed. The information reproduced in Fig. 11 was derived from the land-use map of 1833 made by official surveyors of the Austrian Empire, which shows the situation before the major pressure developed. Areas prone to inundation were grasslands, wetlands or were used for pastures. In the middle Tagliamento, these uncultivated areas clearly indicate that the old river courses (A, B, C and D) and the bifurcation close to San Paolo were left as they were for centuries; however, patches of cultivated areas along the edges of the floodplain witness the attempt to occupy what was fluvial space in favour of agriculture. The town of Latisana, being a major stakeholder and at the most vulnerable position, played a role in maintaining the status quo flood protection in a natural manner. The uncultivated lands of the lower Tagliamento served as overflows during major flood events through openings in the dikes. These areas were part of a large lagoon (Fig. 7). This technique of dissipation was applied to protect the important settle-

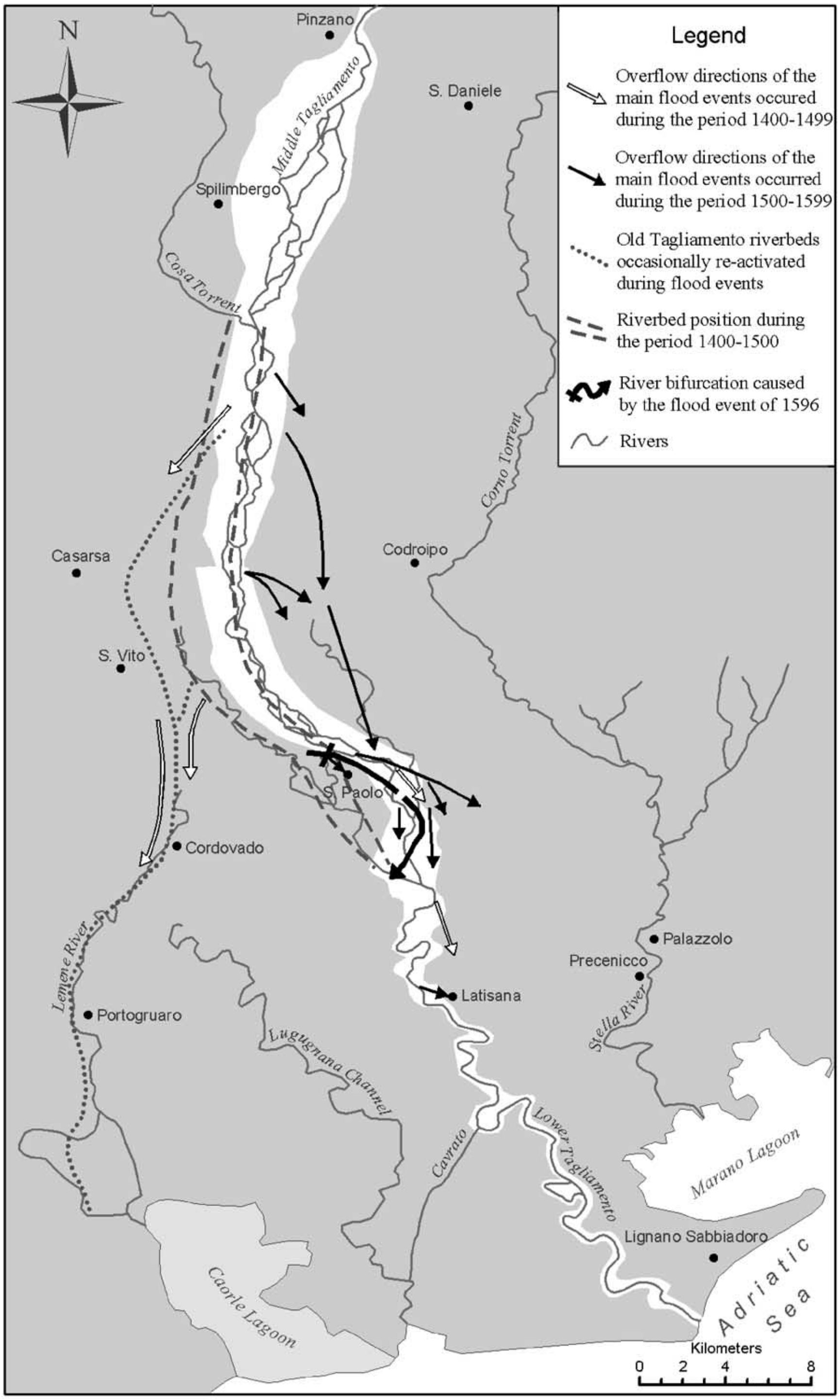

Fig. 8. Fluvial dynamics for the period 1400 – 1599.

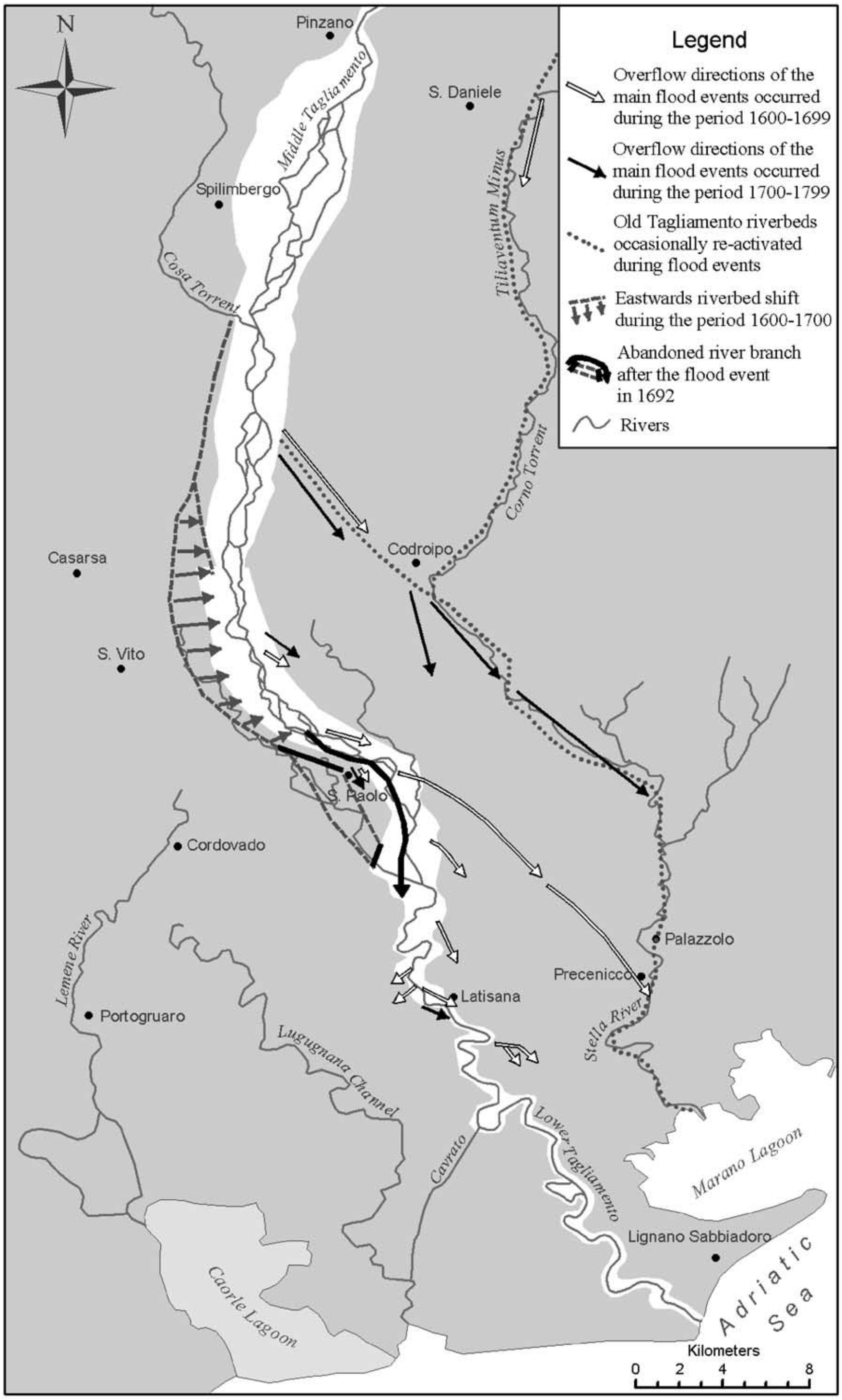

Fig. 9. Fluvial dynamics for the period 1600–1799.

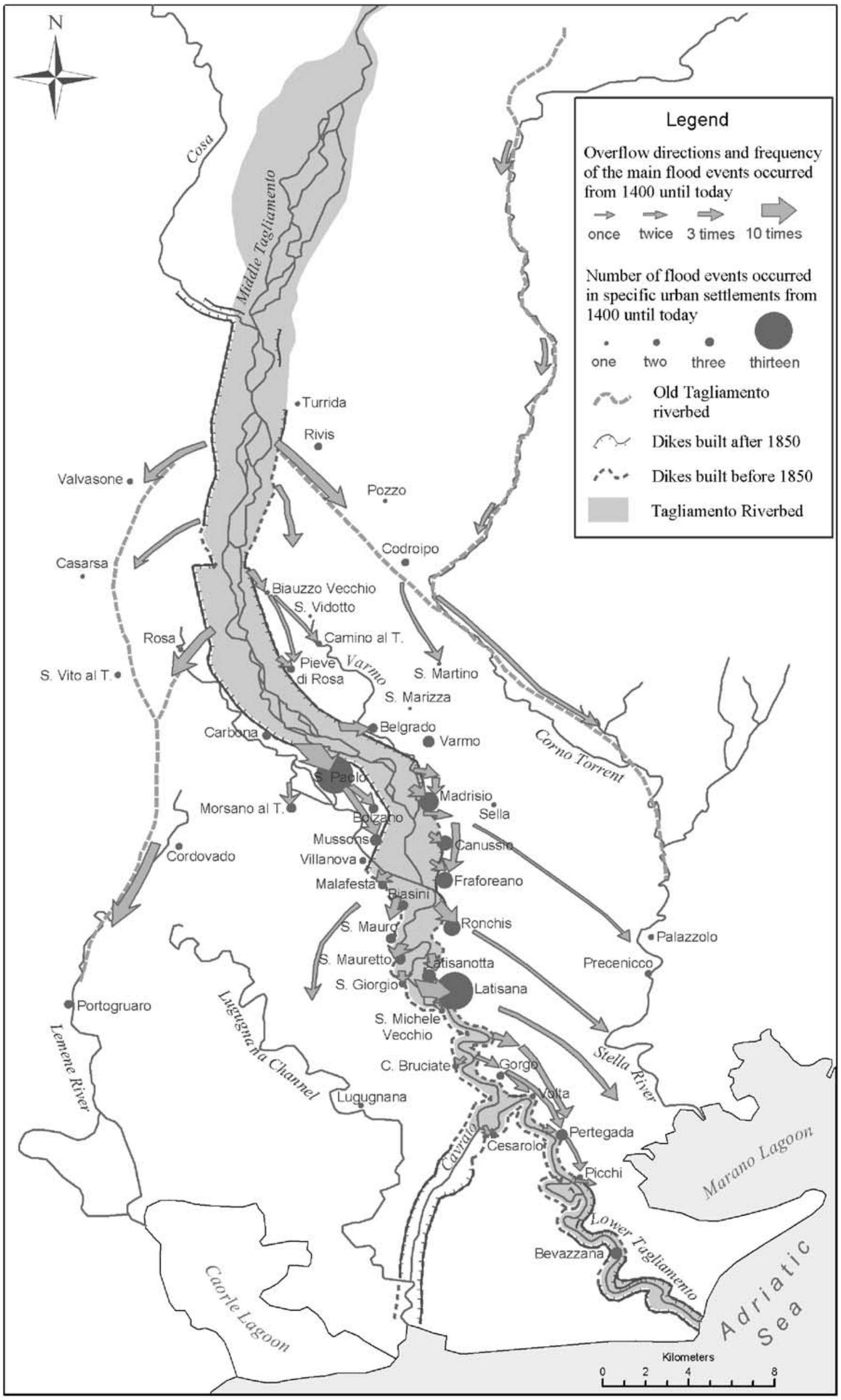

Fig. 10. Synthesis of the historical dynamics of the Tagliamento River.

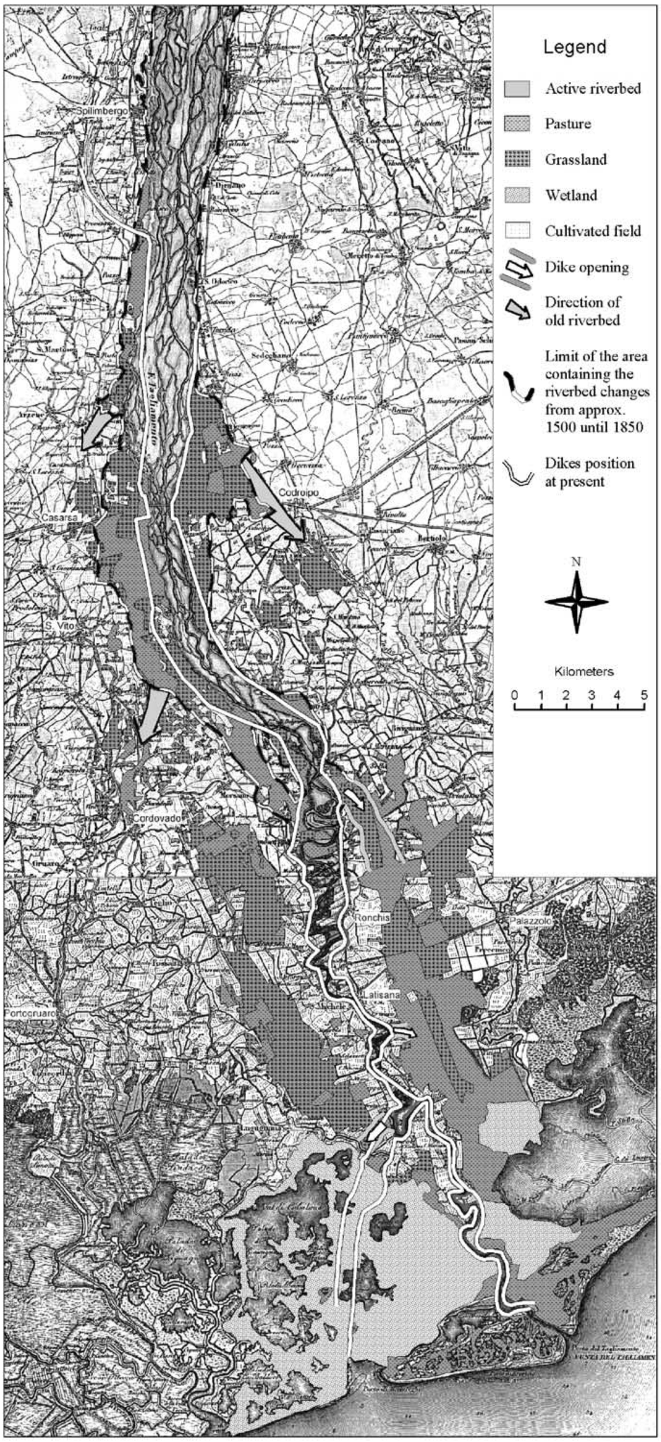

Fig. 11. Interpretation of the land cover map of 1833. Source: land-use map made by the official surveyors of the Austrian Empire, 1833.

ments and the cultivated fields located in the riparian zones of the lower floodplain (Scimone, 1927; Castellarin, 1990).

After 1850, dikes were completed for both the middle and the lower parts of the river (Fig. 10). Meanwhile, the openings in the dikes were closed (Croci, 1899), the wetlands adjacent to the lower Tagliamento were drained for cultivation purposes, as well as significant parts of the lagoons of Marano and Caorle, and the grasslands and pastures were progressively converted into cultivated fields. Thus, during the second half of the 19th century, the hydraulic regime of the Tagliamento River was drastically modified by man. Instead of the former situation where the floodwaters had space to spread out over a wide floodplain and over several branches and overflows, they were now contained by dikes in a narrowed floodplain. Consequently the frequency and the magnitude of overflows increased in the lower Tagliamento and, in particular, in the stretch where the river changes from braiding to meandering, upstream of Latisana town (Fig. 10). Even if the reliability of historical records depends on the potential for channel changes that could alter stage-discharge relations at the site (Cook, 1987), Table 1 seems to confirm that in Latisana, significantly higher water levels were recorded after 1850. It can be expected that the situation will get worse, since the downstream part is the narrowest, as it is still adjusted to the earlier conditions where the flood peaks were attenuated by upstream storage over a wide floodplain and branches, and the coarse bed load was laid down in the upstream parts. The channel patterns of the area upstream Latisana were interpreted using aerial photos of 1953 and 1997, and it was found that traces of meanders are present in stretches where the river is now braiding. Therefore, we can conclude that sediment wedge associated with the aggradation of the middle section was curtailed by the dikes and has moved downstream; this process may have contributed to the trend shown in Table 1.

Table 1
High water levels recorded since 1800 in Venzone gauging station and in Latisana gauging station during the major flood events

Major flood events after 1800	High water level in Venzone (m)	High water level in Latisana (m)
15/10/1823		8.1
02/11/1851		8.2
28/10/1882	3.9	8.76
21/10/1896	3.7	9.88
02/09/1965	4.37	10.5
04/11/1966	4.85	10.88

There is no reason to expect that either the flood-producing rainfall or the sediment yield of the upper mountain catchment will reduce in the near future, so the sediment wedge will continue to migrate downstream. From a geomorphological point of view, the river will tend to maintain a steep gradient as an adjustment to the high sediment load and irregular discharges (Schumm et al., 1987), which it can achieve by extending the braided course ultimately to the sea. Similar narrowing of braided rivers (e.g. the Agri River in South Italy) by dikes has led to substantial increases of the absolute level of the bed, with the consequence that flood discharges cannot be contained by the cross-sectional area between the dikes (Meijerink, 1984). Breakthrough of the dikes can then be expected and in the worst case, the river finds a new course in the adjoining, topographically lower areas.

The map in Fig. 10, which synthesizes the fluvial dynamics resulting from the historical analysis, confirms this tendency. It can be observed that the river overflowed mainly at the same locations, in particular, close to San Paolo where, as mentioned above, the river bifurcated for almost one century, and downstream where the transition from braided streams to a single meandering channel engenders a much narrower river section.

This paper does not provide a full understanding of the fluvial dynamics, which would require further investigations. Other natural factors could be considered, such as tectonic movements determining uplift or subsidence processes, changes in sea level and changes in rainfall regime. For example, the possible effects of the little Ice Age on the bed load are unknown. Little information exists on the frequency of landslide contribution to the sediment load, a part from some reports by Ciconi (1855) concerning the flood events of 1851, which caused the bifurcation near San Paolo as did that of 1962. Detailed topographic surveys, such as longitudinal profile and cross-sections, would be needed to document the process of river aggradation since the 19th century.

4. Planned measures for flood mitigation

The only remediation so far for the problems created by the interventions of the 19th century was to increase the height of the dikes and to maintain the Cavrato channel as the only diversion for floodwaters.

At present, a plan to construct three interlinked retention basins between Pinzano and Spilimbergo is under discussion for approval. The attenuation of the flood peaks by channel, floodplain storage and transmission losses in the middle Tagliamento would be modified by the basins; they are designed for a capacity of 30 million m^3 that should reduce the peak discharge from 4600–5000 to 4000 m^3/s at Latisana (Foramitti, 1990). It is planned to construct the basins in the western part of the post-glacial valley, nowadays intensely cultivated. Their construction would cause severe reduction of the riverbed width with consequences for the erosion–sedimentation regime of the river, as well as rapid groundwater seepage because of the coarse gravels below the retention basins, with dikes of 10-m height (Foramitti, 1990). Furthermore, in light of this research, that project does not solve the risk of aggradation in the downstream stretch between San Paolo and Latisana in the medium to long term.

Concerning the area where it is planned to construct the basins, a progressive expansion of Spilimbergo City close to the western terrace of the post-glacial valley has occurred since the beginning of the 20th century, while the Tagliamento River was shifting eastwards. New settlements were built in an area that had been actively occupied by the riverbed a few decades earlier. Even if at present the river is flowing more than 2 km away from these settlements, close to the eastern terrace, the valley was entirely occupied by the riverbed less than two centuries ago and has been regularly flooded during important flood events (the last time was in 1998).

5. The option of fluvial corridors

The medium to long term prospects necessitate to develop options other than solely retention basins. First of all, floods larger than the 1966 event may be expected, not only on statistical grounds, but also because most climatic change models agree that rainfall extremes will increase. Even with an attenuation of the flood peak by the planned retention basins by some 15–20%, the effects of the moving sediment wedge towards Latisana will still cause a dangerous situation.

One option was building a dam in the narrow gorge of Pinzano in order to create a reservoir upstream of 50 million m^3, but it met strong opposition from the local communities (Foramitti, 1990).

Another option left is to consider fluvial corridors (Gardiner, 1990; Govi and Turitto, 1994) in the middle to lower Tagliamento. The corridors should reflect the historical fluvial geomorphological developments and the areas where floodwaters found their way. In that perspective, a fluvial corridor is described here as a zone that belonged in historical times to the active part of the fluvial ecosystem and that appears to be still under the rivers' influence when analysing flood dynamics. The map of Fig. 12 shows fluvial corridors by taking into account the past dynamics of river shifts and locations of frequent overflows. The map provides the background information as a starting point for further working out expansion of the present Tagliamento corridor, which has too limited capacity. Widening the river by shifting the dikes downstream of the transition between middle and lower Tagliamento would provide an obvious corridor, but the presence of significant urban settlements at both river edges, such as Latisana and S. Michele, causes problems. In this sense, the map can be used for the planning of urban expansion and infrastructure to avoid developments that may form additional burdens in the near future.

The middle Tagliamento has two categories of corridors corresponding to different stages of the river's evolution. The *fluvial corridor A1* includes more recent changes in the riverbed width, approximately between 1700 and 1850. During flood events, the dikes are subject to the lateral erosion of the river trying to reoccupy its former corridor. Particularly dangerous is the section narrowed by the dikes of the two Delizia bridges. The *fluvial corridor A2* contains the riverbed migrations approximately during the period 1500–1700. Since the construction of the dikes, this area has been relatively stable, except at places of the former courses indicated by arrows in Fig. 12. During the last major flood event of 1966, near San Paolo, the right bank dike was overtopped and damaged.

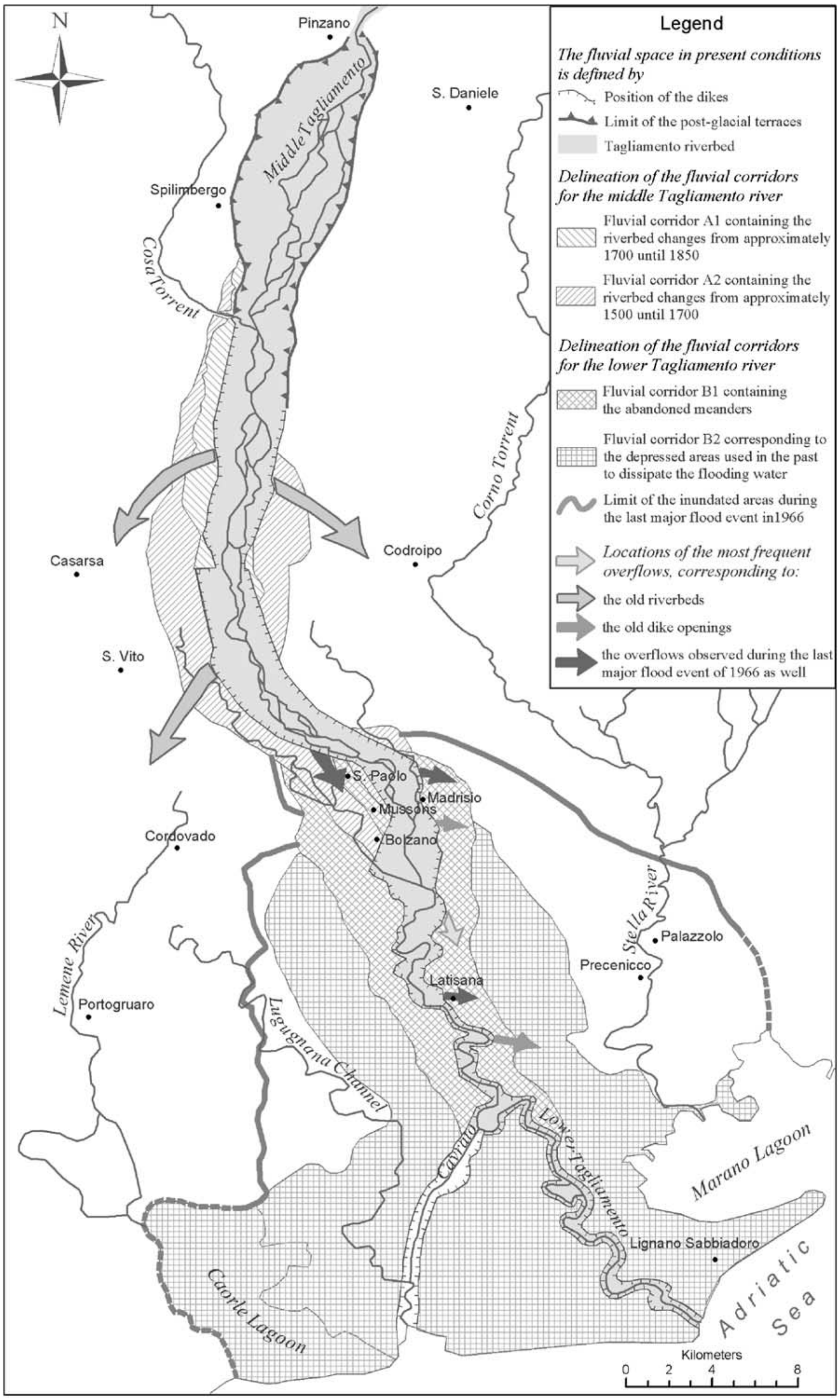

Fig. 12. Definition of the fluvial corridors.

The abandoned meanders of the lower Tagliamento were detected by aerial photo interpretation. Their spatial pattern and distribution density allowed the definition of the *fluvial corridor B1*. It is interesting to notice that the old meanders are more concentrated where the river overflowed frequently in the past, e.g. in front of Latisana. Several abandoned meanders were found upstream of the place where the river starts to meander nowadays. Thus, as mentioned above, the sediment wedge associated with the braiding–meandering transition has moved downstream, but the floodplain confined by the dikes is narrowing, which creates hydraulic instability.

For the zone B2, the limit of the depressed areas used in the past for the dissipation of the flood is taken as corridor receiving the floodwaters from zone B1. Because of the downstream shift of the braiding–meandering transition and the confined narrow width of the lower Tagliamento, this zone will remain a vulnerable zone in the medium to long term. The map shows also the limit of the inundation of 1966, when the river overflowed at the same locations as the historical events.

The number, trace and dimensions of the corridor(s) should be based on hydraulic modelling, assuming a further rise of the braided riverbed, detailed topography and by the land use and land ownership within potential traces.

Finally, concerning the future evolution of the riverbed's position, it seems that the lower Tagliamento tends to shift eastwards since a greater frequency of damage was suffered by the eastern riparian territories during the last major inundations. On the other hand, the middle Tagliamento pushes westwards to reoccupy its former riverbeds A, B and C (see Fig. 7).

6. Conclusion

The fluvial geomorphological development of the Tagliamento River and flooding history is described and analysed using historical documents and interpretation of satellite images and aerial photographs. The geologic and climatic conditions of the upper catchment determine a hydraulic regime with high sediment load and irregular discharges, which led to the formation of a complex geomorphology of the alluvial plain. The riverbed of the middle course is aggrading and the transition from braiding to meandering is shifting downstream. These natural processes favour the flood risk, which was increased by the confinement of the river by dikes after 1850. The historical analysis confirmed that the flood hazards tend to concentrate in the same locations where historic fluvial changes occurred, allowing the delineation of the areas under major risk. Therefore, since the planned retention basins will not solve the problem in the medium-long term, fluvial corridors were defined. The results of the approach adopted in this study could be integrated with hydraulic studies that are commonly carried out, in order to obtain more information on the complexity of fluvial dynamics. For example, modelling the propagation of flash floods should be extended to include the use of corridors, to develop a plan for flood containment. The effects of further aggradation of the riverbed should be included in the modelling. It will be wise policy to start considering restrictions on land use and infrastructural development in the zones of anticipated future fluvial corridors.

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