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MASTER'S THESIS IN WATER AND GEOLOGICAL RISK ENGINEERING

"INCORPORATING GEOMORPHOLOGICAL ANALYSES TO IDENTIFY POTENTIAL CRITICALITIES FOR FLOOD SUSCEPTIBILITY IN ROMAGNA PLAIN"

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ABSTRACT

Emilia-Romagna, Italy, suffered significant floods in May 2023 consequently, of torrential rains following a protracted drought. Levees, major flood defense infrastructure, were damaged yet played an important role throughout the event, illustrating the critical necessity for effective flood risk management techniques and emphasizing the essentials of comprehensive flood susceptibility assessment in the area. While flood susceptibility mapping takes into account a variety of factors such as land use, rainfall, and hydrological variables, the role of geomorphological features is yet underexplored. This thesis seeks to address this gap by incorporating geomorphological analyses into flood susceptibility assessments, by systematically defining geomorphological indicators and their relationship to flood processes. The methodology involves a multi-step approach, including the synthesis of data analysis, GIS integration, and the development of potential indicators for flood susceptibility, particularly for the Sillaro and Senio Rivers in the region. Historical topographic maps, Geomorphological maps, Digital Terrain Models and several other data were acquired from the online sources and regional authorities of Emilia Romagna. Using Geographic Information System (GIS), this work aims to leverage historical and geomorphological data to pinpoint areas susceptible to future flooding, by analyzing river channel shifts, sinuosity patterns, meander migration, potential cutoff locations and post-event criticalities. The insights of this study reveal a strong link between historical geomorphological evidences, current sinuosity patterns, and flood susceptibility. The identified critical locations from the post-event orthophoto aligns with the area highlighted in the geomorphological analyses, suggesting significant correlation of geomorphological aspects to flood susceptibility, especially for the Senio River. The patterns of riverbank expansion and contraction further emphasizes the dynamic nature of the river system in the plain. These insights underscore the essentials of incorporating geomorphological analyses into flood susceptibility mapping to enhance flood risk management in the region.

1 INTRODUCTION

GENERAL

Flood risk management is a complex, interdisciplinary field that necessitates the integration of diverse components to mitigate the adverse impacts of flooding on human settlements, infrastructure, and ecosystems. Central to this domain are several key elements: hazard assessment, vulnerability analysis, risk mitigation, emergency preparedness, and post-event recovery. A critical aspect of hazard assessment, which forms the foundation of flood risk management, is the identification and mapping of areas susceptible to flooding, which traditionally incorporate a thorough analysis of environmental and climatic factors. However, the critical role of geomorphological and historical analyses has increasingly been recognized as indispensable in the comprehensive understanding of flood dynamics.

Italy's geological, geomorphological, and hydrographic characteristics inherently predispose the country to considerable hydrogeological instability, manifesting in recurrent flood risks. A nationwide study conducted by ISPRA in 2015 revealed the extent of hydraulic risk across the country, identifying 12,218 km² of high hydraulic risk areas, 24,411 km² of medium risk, and 32,150 km² of low-risk zones. Emilia-Romagna is among the regions with the highest surface areas of medium hydraulic risk, a region that has suffered multiple severe flood events in recent years, including fluvial flooding in January 2014, flash floods in mountainous areas in September 2015, and pluvial flooding in urban areas in June 2013 [1]. According to ISPRA, approximately 63% of the population in Emilia-Romagna are potentially vulnerable to floods with a medium probability (likely return period greater than 100 years) [1]. This statistic highlights the region's significant risk of flooding. The catastrophic flood event in May 2023, which caused significant infrastructural and economic damage, underscored the pressing need for more effective flood risk management strategies, particularly in light of the failure and subsequent reconstruction of levees, which were crucial in mitigating flood impacts [2].

The event of May 2023, exacerbated by intense rainfall following an extended period of drought, highlighted the necessity of an integrated approach to flood risk management, emphasizing the importance of comprehensive flood susceptibility assessments. While conventional methodologies have typically prioritized hydrological and hydraulic variables, the influence of geomorphological characteristics remains underexplored. Yet, geomorphological processes such as river channel shifts, sinuosity patterns, meander migration, and sediment dynamics are pivotal in shaping flood behavior and identifying potential criticalities within flood prone regions.

This thesis aims to address this gap by incorporating geomorphological analyses into flood susceptibility assessments for the Emilia-Romagna region, with a specific focus on the Sillaro and Senio Rivers. By systematically delineating and analyzing geomorphological indicators, this research seeks to elucidate the correlations between geomorphological processes and flood susceptibility. The integration of Geographic Information System (GIS) allows for the spatial analysis of geomorphological and historical data, enabling the identification of areas that are particularly susceptible to future flood events. Hence, this study seeks to enhance flood susceptibility assessment practices by emphasizing the role of geomorphological and historical analyses as fundamental components in the broader context of flood risk reduction and resilience building.

BACKGROUND AND RATIONALE

With the advancement of spatial data collection techniques, including remote sensing (RS) and processing techniques, such as geographic information system (GIS), the development of a reliable decision-making tool for food risk management has become more feasible. The integration of RS and GIS techniques, along with morphometric analysis of flood susceptibility, has led to noteworthy contributions [4].

However, forecasting the occurrence of flash floods and predicting their impacts on the fluvial system are challenging. The accuracy of forecasting is still insufficient to allow reliable prediction of the amount, timing, and basin-specific locations of the meteorological event and of the morphological responses in the river system [5]. The combined use of geomorphological, sedimentological and hydraulic data and evidence can greatly contribute to the identification of the most critical reaches. [5].

Identifying morphometric parameters, assigning scores to produce the final flood hazard potentiality map, and then validating, which includes the use of available data, e.g. past floods and rainfall, to verify the results. This approach has been used by many researchers to evaluate the impacts of the morphometric characteristics of the drainage basin on flood susceptibility [4].

Determining the geomorphic effectiveness of extreme flooding caused by a breach mechanism provides insight into the role of flood scale on the resulting processes and landforms [6]. Extreme floods are relevant in fluvial morphology but their geomorphic consequences differ depending upon peak discharge, duration, and river channel pattern. The relationship between the flow hydraulics and resulting geomorphic effectiveness remains complex and non-deterministic [6].

Since, flood events are complex phenomena influenced by a combination of factors, including geomorphological features, which play a crucial role in determining flood behavior. However, the integration of geomorphological analyses into flood susceptibility assessment has been limited in the Emilia-Romagna region. Understanding the geomorphological characteristics of the area is essential for identifying areas prone to flooding and implementing effective mitigation measures. Therefore, this project aims to systematically develop geomorphological framework and analyze geomorphological indicators and their significance in flood susceptibility mapping to improve flood risk management strategies in the region.

OBJECTIVES

This thesis project aims to contribute to flood risk management by analyzing the geomorphological and historical factors that influenced the floods of May 2023 in the Sillaro and Senio Rivers of Emilia-Romagna. The emphasis is on elucidating how the historical evolution and geomorphological dynamics of these rivers impact flood processes and contribute to the development of a flood susceptibility map informed by geomorphological aspects.

The specific objectives of this research entails:

1. **Historical Analysis of River:** The initial step implicates a comprehensive historical analysis of the rivers, emphasizing their evolution over time. This process includes an extensive review of historical maps and literature.
2. **Identify and Analyze Geomorphological Indicators**: Building on historical analysis, the following objective involves systematically identifying key geomorphological indicators and elucidating their relationship with flood processes. A thorough assessment of the region's geomorphology, including the analysis of river sinuosity and other relevant factors, will be conducted to understand the physical processes that contributes to susceptibility assessments.
3. **GIS-Based Analytical Framework**: The project will then establish a Geographic Information System (GIS)-based framework to analyze historical and geomorphological data. This framework will aid in identifying potential criticalities corresponding to flood susceptibility, particularly focusing on the integrity and functionality of levees.
4. **Identification of Criticalities**: The framework will integrate various datasets, including historical maps, geomorphological maps, and spatial data obtained before and post the flood events. This integrated approach will provide a comprehensive understanding of the geomorphological factors at play and enable spatial analyses to identify indicators of potential flood-related criticalities.

By achieving these objectives, the thesis seeks to develop flood susceptibility maps while enhancing the understanding of how geomorphological and historical analyses, which are fundamental for flood risk management, can be effectively applied, thereby contributing valuable insights for future flood prevention and mitigation strategies.

2 LITERATURE REVIEW

The Romagna plain has experienced recurrent flooding, prompting a need for improved flood risk management. Geomorphological analyses provide useful insights into flood susceptibility by examining historical river behavior, geomorphological features, and anthropogenic impacts on river systems. This literature review synthesizes key studies that highlight the role of geomorphology in flood susceptibility assessment, tracing the evolution of methodologies and their relevance to the Romagna Plain context.

2.1 GEOMORPHOLOGY AND FLOOD SUSCEPTIBILITY: AN EVOLVING APPROACH

Flood susceptibility mapping has evolved significantly, with an increasing emphasis on geomorphological factors. Early research in this area primarily focused on understanding the physical characteristics of landscapes and their influence on flood behavior. Over time, the integration of Geographic Information Systems (GIS) and remote sensing techniques has enhanced the ability to assess and predict flood risks, considering the dynamic interactions between geomorphology and hydrology.

Early researches such as (Leopold, 1964) [25] and (Wolman et al., 1978) [26] highlighted the critical role of historical river dynamics and geomorphological features in assessing flood hazards. These studies explored how natural river behaviors, such as meandering and sediment deposition, influence flood risks in various regions. The findings emphasized that both natural and human-induced geomorphological changes significantly impact flood patterns. This foundational understanding underscored the importance of incorporating geomorphological data into flood risk models to enhance the accuracy of flood susceptibility mapping.

Subsequent studies continued to build on this approach, integrating more sophisticated methodologies. For instance, the work by (D. Castaldini, 2006) [16] focused on the southern central sector of the Po Plain, analyzing the geomorphological changes between the rivers Po, Secchia, and Panaro. This study used GIS and digital elevation models to demonstrate how historical modifications, such as river course elevation and the construction of artificial embankments have exacerbated flood risks. The research provided crucial insights into the interplay between human interventions and natural geomorphological processes, emphasizing the need for comprehensive flood hazard assessments that consider both factors.

As technology advanced, researchers increasingly utilized GIS and remote sensing tools to enhance geomorphological analyses in flood susceptibility studies. (Saadi and Adda, 2013) [17], for example, introduced a GIS-enabled approach that assessed the damage potential of levee systems by analyzing the underlying geology and river morphology. The study employed geostatistical methods, such as ordinary kriging, to estimate soil properties along levees, focusing on under seepage and soil liquefaction as key damage indices. This approach demonstrated the value of spatially continuous data in improving the reliability of flood risk assessments, particularly in regions with complex geomorphological settings.

In a parallel development, (Ahmed et al., 2021) [4] explored flood susceptibility using a geomorphometric approach, which combined historical flood records, geomorphological mapping, and hydrological modeling. This study highlighted the critical role of geomorphological parameters, such as river channel shifts and sediment deposition patterns, in understanding flood dynamics. By integrating these parameters into flood models, the research provided a more nuanced understanding of flood susceptibility, paving the way for more targeted flood management strategies.

The study by (Santos-González et al. 2020) [6] examined the geomorphological and hydraulic impacts of the 1959 Vega de Tera dam failure in Northwest Spain, a catastrophic event that triggered significant flooding and extensive geomorphic changes. The research analyzed the released flow's hydraulic properties, sediment transport, and geomorphic effects, highlighting the spatial variation of erosional and depositional features along the river. The study also investigated sediment connectivity between the watershed and the lake, considering the event's long-term implications for landscape evolution. This study illustrates how extreme flood events can drastically alter geomorphological features and emphasizes the importance of considering such impacts in flood risk assessments.

More recent studies have further refined the integration of geospatial data and hydro-geomorphic assessments in flood susceptibility research. (Hasan et al, 2023) [18] examined the flood vulnerability of Nijhum Dwip Island using remote sensing techniques, analyzing spatiotemporal changes in the island's morphology. By leveraging Landsat satellite data and digital elevation models, the study identified significant morphological changes due to erosion and accretion processes. The research demonstrated the potential of remote sensing for monitoring coastal and river dynamics, providing valuable insights into the geomorphological factors contributing to flood vulnerability.

2.2 SYNTHESIS AND RELEVANCE TO THE ROMAGNA PLAIN

The evolution of flood susceptibility mapping methodologies reflects a growing recognition of the importance of geomorphological factors in flood risk assessment. Early studies laid the groundwork by emphasizing the role of natural and anthropogenic geomorphological changes, while later research leveraged GIS and remote sensing technologies to refine these assessments.

For the Romagna Plain, these insights are crucial. The region's flood risk is intricately linked to its geomorphological characteristics, including historical river dynamics and human modifications. By leveraging data availability and incorporating the advanced methodologies highlighted in this review, especially those utilizing GIS and remote sensing, this study seeks to create a comprehensive framework for identifying potential flood susceptibility criticalities. This approach not only deepens our understanding of flood dynamics in the Plain but also offers a strong foundation for developing effective flood risk management strategies

2.3 MAJOR TAKE AWAY FROM LITERATURE REVIEW

The following table 2.1 below shows the major outcomes obtained from the literature review.

Table 2.1: Major take away from literature review

S.no	Study	Major Takeaways
1	Leopold, 1964 [25] and Wolman et al., 1978 [26]	• Highlights the critical role of historical river dynamics and geomorphological features in assessing flood hazards. • Explored how natural river behaviors, such as meandering and sediment deposition, influence flood risks. • Emphasized that both natural and human-induced geomorphological changes significantly impact flood patterns.
2	D. Castaldini, 2006 [16]	• Geomorphological investigations are key aspect in flood hazard assessment. • GIS-based thematic maps are crucial for hazard analysis.
3	Mustafa Saadi and Adda Athanasopoulos-Zekkos, 2013 [17]	• GIS and geostatistical methods are effective for assessing levee system damage potential. • Regional variable such as river meandering and sinuosity index are essential in effective susceptibility mapping. • Spatial variability in soil properties is critical for accurate risk assessment • Underlying seepage and soil liquefaction are key damage indices in the considered region
4	Ahmed et al, 2021 [4]	• Geomorphological data is essential for flood hazard and susceptibility assessment. • Historical flood records and geomorphological mapping improve flood risk understanding. • Identifying river channel shifts and sediment patterns is crucial for flood management.
5	Gonzalez et al, 2021 [6]	• Dam failure floods can cause peak discharges significantly higher than meteorological floods, leading to notable geomorphic changes. • Erosional and depositional features vary along the river based on local hydraulic conditions, with steep sectors showing deep bedrock erosion and low-gradient sectors showing extensive deposition. • Historical flood layers in lake sediments offer insights into past extreme flood events and their impact on sediment connectivity and landscape evolution

		• Emphasizes the importance of understanding sediment connectivity in fluvial systems, especially during extreme events.
6	Hasan et al, 2023 [18]	• Dynamic erosion and accretion is primarily influenced by fluvial sediments and tides in the coastal areas. • Highlights the effectiveness of remote sensing and GIS in evaluating coastal changes and planning mitigation strategies.

2.4 GEOMORPHLOGICAL PROCESSES AND FLOOD SUSCEPTIBILITY

Geomorphological processes play a crucial role in influencing flood susceptibility, particularly in areas with active fluvial dynamics. Aforementioned studies have highlighted how channel morphology and processes, e.g. River meandering and sinuosity indices can serve as key indicators for assessing flood risks and levee stability [4] [25] [26]. The following subsections further review literature and explains on the relationship between these geomorphological features and flood susceptibility in details.

2.4.1 River Meandering /Sinuosity: Indicators of Flood Susceptibility

The sinuosity of a river, which refers to the degree of meandering or curvature of the river's path, has been widely studied as a predictor of flood risk. A river's sinuosity index (SI) is a commonly used quantitative measure, calculated as the ratio of the actual length of the river channel to the straight-line distance between two points. Researchers have shown that increased sinuosity leads to complex erosion and deposition dynamics along the riverbanks, particularly in areas with high curvature, which can contribute to localized flooding [25] [26].

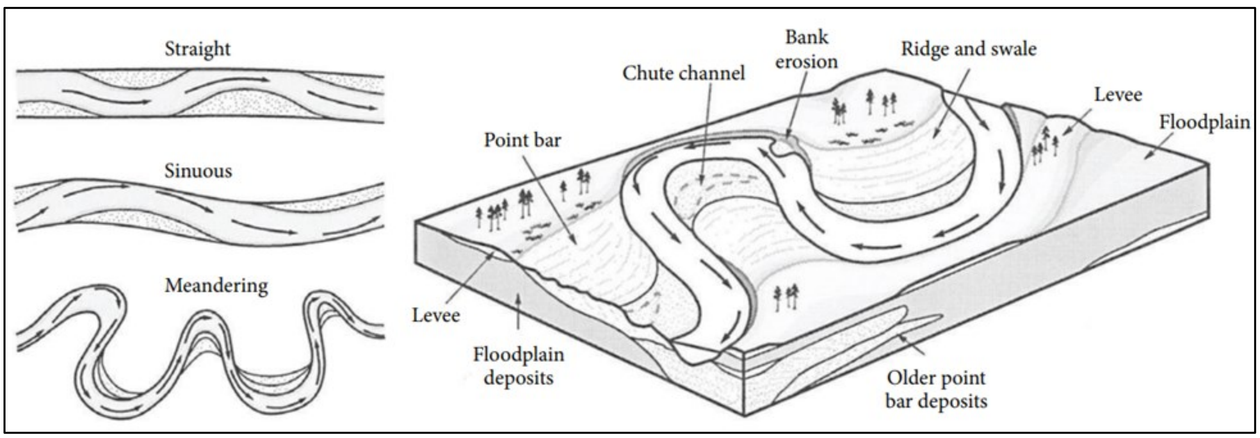

Figure 2.1: Schematic diagram of river meandering/sinuosity [17]

In straight river segments, where the SI approaches 1.0, there is less variability in the sediment deposition along the banks. Conversely, highly sinuous rivers (SI > 4.0) are associated with significant outer bank erosion and deposition of material in the inner bank, creating alternating point bars along the river's length. The literature suggests that such rivers pose a higher flood risk due to the increased potential for channel migration and lateral shifts, which can affect levee stability [4].

High sinuosity has been linked to increased flood susceptibility, as rivers with intricate meanders tend to have longer pathways and more frequent interactions with floodplains. Studies indicate that these rivers are more prone to overbank flooding during high flow events [17]. Floodplain connectivity is particularly critical in regions with high sinuosity, as the meandering river often spills over its banks, inundating adjacent lands. This highlights the importance of accounting for river sinuosity in flood risk assessments and the design of flood defenses.

Figure 2.2: Highly sinuous section of Senio River

2.4.2 Meander Cutoff and Floodplain Dynamics

Meander cutoffs, a key feature of dynamic fluvial systems, are another geomorphological process closely associated with flood risk. The formation of cutoffs, which occurs when the river creates a new, straighter channel, isolating a meander into an oxbow lake, has been discussed extensively in the geomorphological literature [27] [17]. These cutoffs indicate past river migration and are often found in flood-prone areas. During periods of high flow, such cutoffs can reconnect with the main river channel, expanding the floodplain area susceptible to inundation [27].

The presence of multiple meander cutoffs along a river's course has been interpreted as evidence of a historically dynamic system, with implications for future flood risks. This underscores the need to integrate geomorphological analyses into flood susceptibility models, particularly in regions like the Romagna Plain, where past river behavior can provide critical insights into future flood hazards [28].

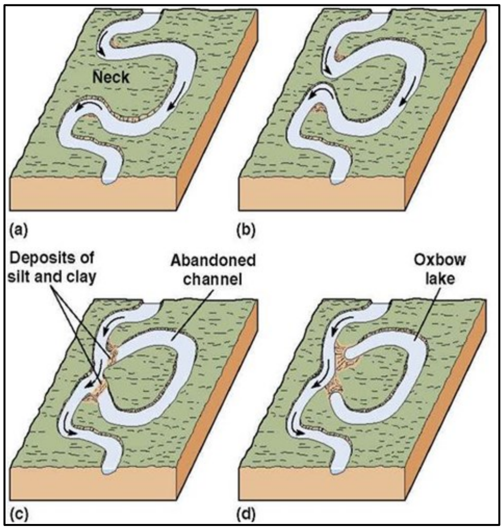

Figure 2.3: Schematic diagram of meander cutoff [17]

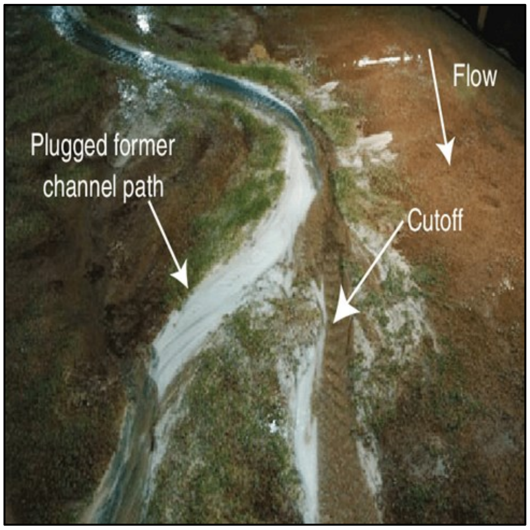

Figure 2.4: Meander cutoff example [17]

2.4.3 Meander Migration and Levee Vulnerability

Meander migration, the lateral movement of river bends, poses a significant threat to levee systems. Scholarly work has emphasized that high-flow events in meandering rivers can result in severe bank erosion, particularly along the outer banks, which weakens levees and increases the likelihood of failure [29]. Meander migration has been shown to cause toe erosion at the base of levees, thereby compromising their structural integrity.

High sinuosity, in particular, is associated with increased meander migration rates, which can exacerbate these risks. Researchers have also noted that the continuous movement of meanders can lead to changes in flow patterns, increasing hydraulic pressure on levees and concentrating erosive forces on specific sections of the riverbank [29]. This not only raises the risk of breaches during flood events but also underscores the need for flood risk management strategies that account for geomorphological processes.

Figure 2.5 shows an example of meander migration in the highly sinuous section of Senio River and observed bank erosion. Green color highlight the banks digitalized from 2008 orthophoto while red color represents banks digitalized from 2020 orthophoto.

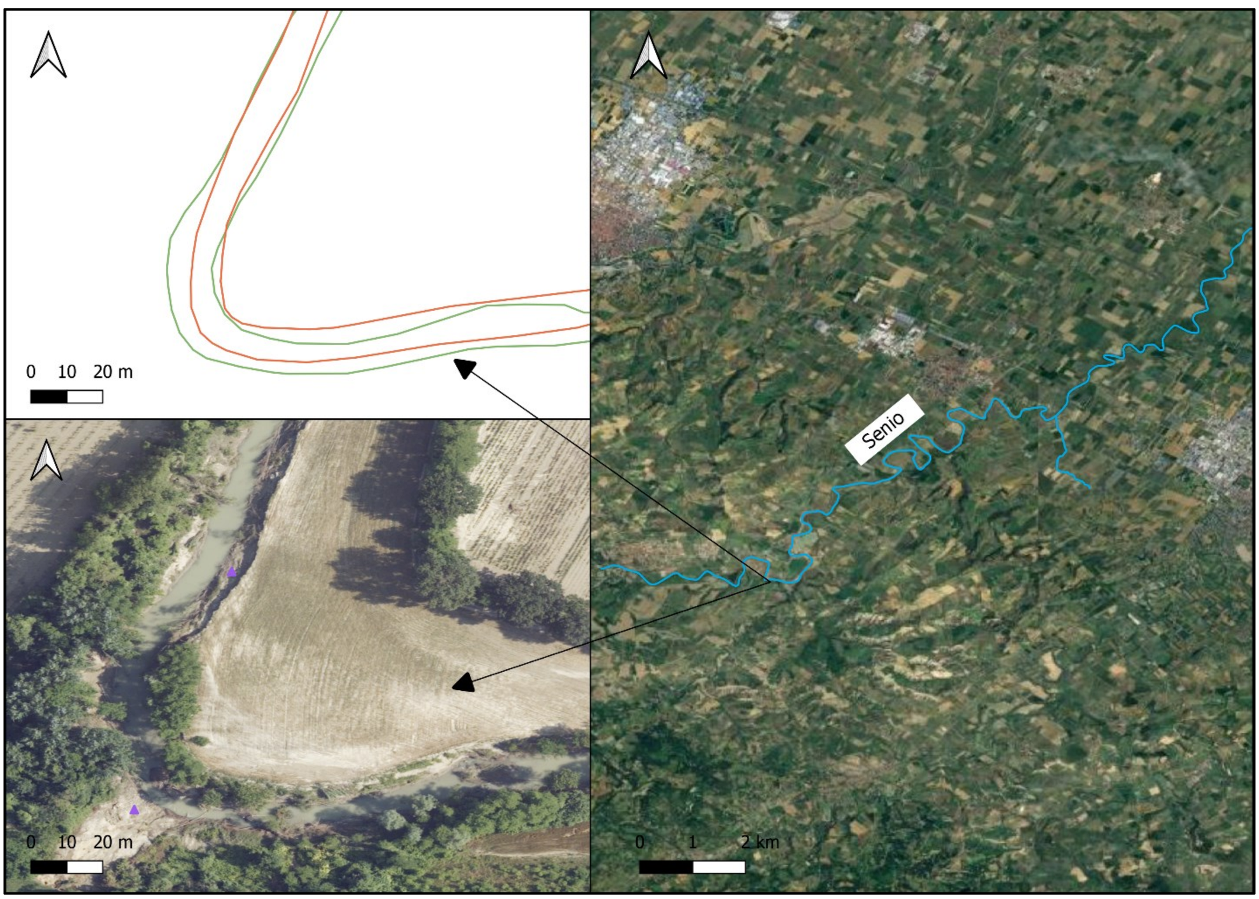

Figure 2.5: Example of meander migration in Senio River

3 GEOGRAPHICAL AND GEOMORPHOLOGICAL FRAMEWORK

3.1 GEOGRAPHICAL FRAMEWORK

3.1.1 Study Area

The Sillaro River and the Senio River are two prominent watercourses in the Emilia-Romagna region, running parallel from south to north, and bringing their courses closer together just west of Imola, at the latitude of Castel Guelfo and Castel Bolognese. The Sillaro River is a significant tributary of the Reno River. The Sillaro River basin mainly covers the Provinces of Bologna and Ravenna (about 70%), partly extending into the Province of Forlì-Cesena (20%), and includes limited areas in the Province of Florence. It is part of the Reno River basin, representing 3% of its area. It has a total surface area of approximately 400 km², with 30% of it in hilly regions. It is 66 km long and is bordered to the south by the Tuscan-Emilian Apennine ridge, extending from south to north. It has a average discharge at the mouth of 10 m³/s, making it a modest yet vital tributary of the Reno River.

The Sillaro River has been used historically for irrigation and local water supply. Castel San Pietro Terme, located along its course, has been a notable settlement due to its therapeutic thermal waters. Further, downstream, the river supports agriculture, providing essential irrigation in the fertile plains.

The Senio River, flowing near parallel to the Sillaro, also plays a significant role in the region's hydrology. The Senio River basin covers areas within the Provinces of Ravenna and Bologna, and like the Sillaro, it extends slightly into the Province of Florence. It is part of the Lamone River basin, contributing significantly to its flow. The Senio River basin has a total area of 358 km², with 35% of it in the Apennine foothills. It spans 92 km in length, flowing from the Tuscan-Emilian Apennines towards the north. The river has a flow rate at the mouth of approximately 12 m³/s.

The Senio River has been crucial historically, especially during World War II, where it marked significant battle lines and saw extensive fortifications. The town of Castel Bolognese, located along its course, has historically benefited from the river's resources for agriculture and local industries.

The sections of the Sillaro and Senio Rivers studied are the combination of the sinuous portions beginning from the Via Di Dozza and Via Bologna respectively and extending northwards passing through the relatively flat portions towards their respective confluences. In this stretch, both rivers pass through several important settlements. For the Sillaro River, these include Castel San Pietro Terme, Castel Guelfo (BO), and Mordano (BO). For the Senio River, key settlements include Riolo Terme (RA), Castel Bolognese (RA), and Lugo (RA) [9]. Both rivers exhibit a markedly torrential regime, with low summer flows (absolute minimums of just 0.5 m³/s for Sillaro and 1 m³/s for Senio) alternating with abundant spring flows and significant autumn floods (up to 300 m³/s for Sillaro and 500 m³/s for Senio), largely regulated by local retention basins [10].

In spring, the average flow at the plain outlet of the Sillaro River is usually around 15-20 m³/s due to the melting of snow in the Apennines, which continues until May. The Senio River shows similar patterns with spring flow averages of 20-30 m³/s, influenced by the same snowmelt dynamics. Both rivers' regimes are affected by these seasonal phenomena, as their basins are situated at relatively high altitudes and are frequently snow-covered in winter [11].

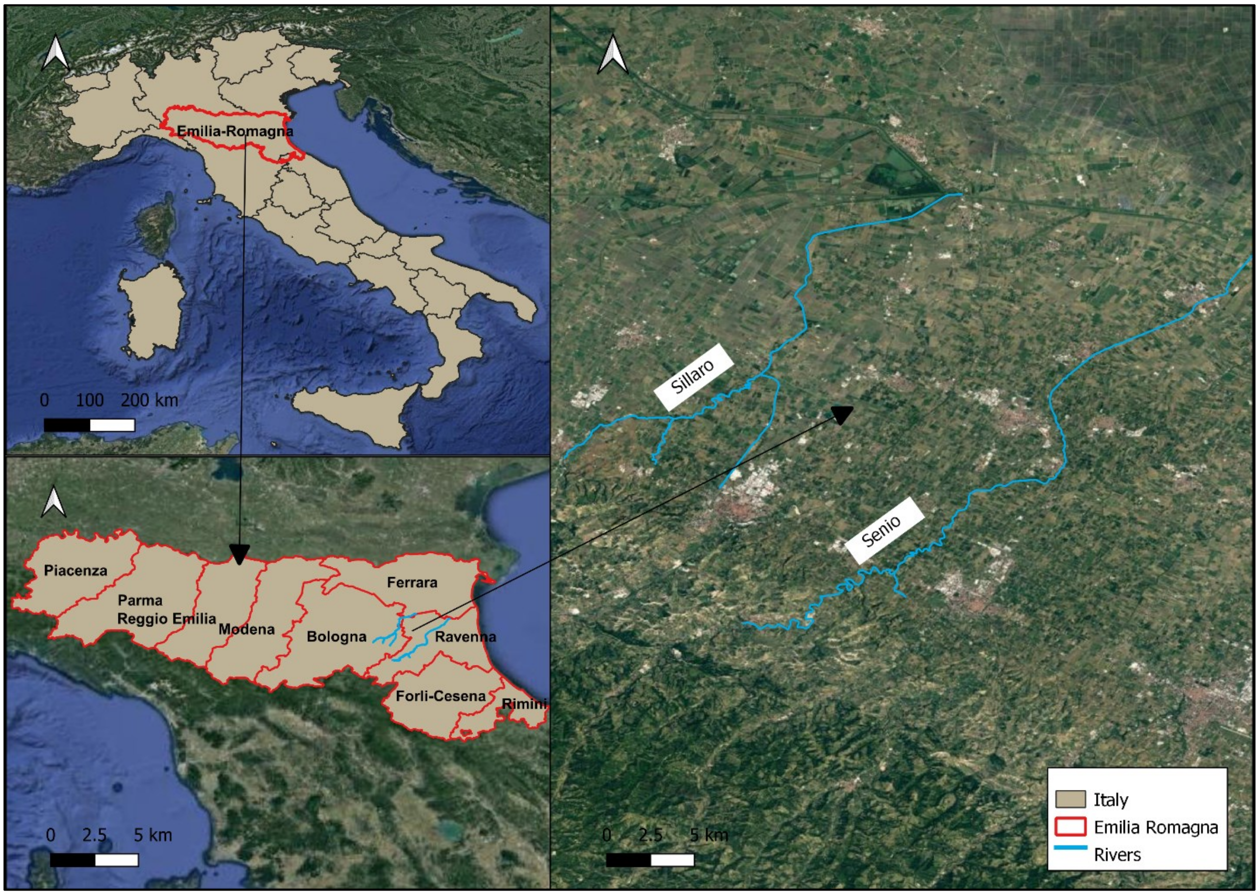

Figure 3.1: Location of the study area, depicting extent of rivers under consideration

3.1.2 Climatic Framework

The Emilia-Romagna region stretches from the Apennines in the south to the Po River in the north and the Adriatic Sea in the east. The region, including the basins of the Sillaro and Senio rivers, exhibits a temperate subcontinental climate typical of the Po Valley and mid-latitudes, as classified by (PINNA 1970) [12].

Winters in Emilia-Romagna are moderately harsh, characterized by limited rainfall and frequent foggy days. Summers, particularly in July and August, are hot and sultry, with temperatures often exceeding 35ºC and frequent thunderstorms. Springs and autumns are generally rainy, with milder and more humid conditions compared to the extremes of summer and winter.

Rainfall in this region is primarily concentrated during the autumn months, with secondary peaks in the spring. Annual precipitation varies significantly, ranging from approximately 550 mm/year in the plains to around 2100 mm/year in the Apennine ridge, where snow can persist for about three to four months each year. This pattern results in a pluviometric regime defined as sub-littoral Apennine, characterized by an autumnal peak in rainfall and a more pronounced summer minimum compared to winter [13].

The average annual temperature in Emilia-Romagna is 12.8°C, based on the observations (1961-1990) [41]. However, a recent study (ARPAE 2018) indicated an increase in the average temperature of approximately 1.5°C between 1991 and 2016. Additionally, cumulative precipitation has increased during autumn, while slightly decreasing in other seasons, especially summer, which has seen an increase in the number of consecutive days without rainfall [13].

The Hydrological, Meteorological and Climatological Service of ARPAE-SIMC have developed future climate projections for the Emilia-Romagna region. These projections, derived through statistical downscaling of various Global Climate Models and emission scenarios (RCP 4.5 and RCP 8.5), indicate significant changes in temperature and precipitation patterns.

By 2050, maximum temperatures are expected to increase by 1.5°C in winter and 2-2.5°C in other seasons under both RCP scenarios. By 2100, summer temperatures could rise by 4.5°C under RCP 4.5 and up to 8°C under RCP 8.5. This will likely increase the frequency and duration of heatwaves and tropical nights (nights with minimum temperatures not falling below 20°C). While by 2050, precipitation is projected to decrease by around 10% in spring and summer under RCP 4.5, while a positive trend is expected in autumn (20%). Under RCP 8.5, autumn precipitation may increase by 25-30%, with a 20% increase in extreme rainfall events. Conversely, summer is expected to see a 20% increase in the maximum number of consecutive dry days [13].

3.2 GEOMORPHOLOGICAL FRAMEWORK

Rivers in the Emilia Romagna region has a naturally changing character over time and space, leading to the evolution of the hydrographic network over centuries. This evolution is driven by natural causes, including changes in the courses of the river channel itself due to geological, geomorphological, sedimentary, and tectonic processes. In recent centuries, human activities have further altered their course and morphology. Despite structures such as dams, walls, and channel realignment, human interventions have not completely controlled the river's natural tendencies. Over the years, this has resulted in destructive phenomena affecting urban areas and agricultural lands.

3.2.1 Sillaro River

The Sillaro River originates in the northern Apennine Mountains at approximately 1,000 meters above mean sea level (MSL). From its source, the river flows initially in a northeastern direction, descending through steep, rugged terrain. In these upper reaches, the river exhibits high sinuosity, meandering through valleys and around natural obstacles such as boulders and outcrops. This sinuosity is characteristic of mountainous rivers shaped by dynamic erosional and depositional processes. As the river descends to around 300-500 meters above a.s.l, it enters the Middle Sillaro section, where the gradient begins to flatten. Here, the river flows northeast, gradually turning north-northwest through rolling hills and valleys. The sinuosity decreases somewhat, with broader and less pronounced meanders. Human interventions, including channelization and levee construction, become more evident in this section, aiming to control the river's flow and mitigate flood risks while altering its natural morphology. In the Lower Sillaro section, at elevations of approximately 50-200 meters above MSL, the river flows northwest through the flatter plains of Emilia Romagna. The gradient is very gentle, and the river channel becomes wider and less sinuous. This area is heavily influenced by agricultural development and urbanization, with modified riverbanks and various flood control measures.

Eventually, the Sillaro River flows northwest and converges with the Reno River near Castel San Pietro Terme. The Reno River, originating in the Tuscan-Emilian Apennines, flows northwest through the region, serving as a major drainage basin for several tributaries, including the Sillaro. Throughout its history, both natural geomorphological processes and human activities have shaped the Sillaro River. Natural erosion, sediment transport, and deposition have created a dynamic river system with evolving meanders and floodplains. In recent centuries, human activities have significantly influenced the river's evolution, with channelization projects, embankments, and land use changes altering its flow regime and hydrological connectivity.

3.2.2 Senio River

The Senio follows a distinct course influenced by the region's topography and historical changes. Originating in the northern Apennine Mountains at an elevation of about 800 meters above mean sea level (MSL), the river flows predominantly northeast before joining the Santerno River near Lugo. In its upper reaches, the Senio River begins its journey flowing northeast through the rugged terrain of the Apennines. The steep gradient in this section causes the river to carve a highly sinuous path through valleys and around natural obstacles. These tight meanders are formed as the river erodes the steep slopes and deposits sediment, characteristic of high-energy mountainous streams. As the river moves into the middle section, the elevation decreases to around 200-400 meters above MSL. The gradient flattens, and the river's flow becomes more subdued. In this section, the Senio continues to flow northeast through rolling hills and agricultural lands, with its meanders becoming broader and less pronounced compared to the upper section. Human interventions such as levees and channelization are evident here, altering the river's natural course to manage flood risks and facilitate land use. These modifications somewhat reduce the river's sinuosity and affect its natural flow dynamics. Further downstream, in the lower section, the Senio River flows north-northeast through the flat plains of Emilia Romagna, at elevations between 50-150 meters above MSL. The gradient here is very gentle, and the river widens, adopting a straight course compared to the upstream sections. This area is heavily influenced by human activity, including extensive agricultural development and urban infrastructure. Modifications such as embankments and drainage channels are common, aimed at controlling water flow and preventing floods. Despite these changes, natural processes like sediment deposition and occasional meander cutoffs still occur, influencing the river's morphology. Ultimately, it merges with the Santerno River near Lugo, contributing to the larger river system. Similarly, natural factors, including erosion, sediment transport, periodic flooding and human interventions have shaped its channel and floodplain over time.

3.2.3 Geomorphology

Figure 2 displays the geomorphological map of the Emilia-Romagna Plain, characterized by its broad, flat landscape, fertile soils, and extensive agricultural use. The plain is influenced by the Apennine Mountains to the south and the Po River to the north, with fluvial processes playing a significant role in shaping its features. Key elements include numerous rivers originating from the Apennines, such as the Sillaro and Senio, which have created extensive floodplains with meandering channels, oxbow lakes, and natural levees. The region's rich alluvial soils, composed of fine sediments like silt and clay have been deposited over millennia by these rivers, making it ideal for agriculture. However, human settlement and land use have significantly altered the natural geomorphology, with extensive drainage, irrigation systems, and agricultural practices modifying the landscape [7] [8] [40].

The geomorphological evolution of the Emilia-Romagna Plain has been influenced by tectonic activities, climatic changes, and sea-level fluctuations over geological time scales. The plain was formed through the subsidence of the Po Basin, shaped by the tectonic activity of the Apennine and Alpine mountain ranges, creating a depression gradually filled with sediments from the surrounding mountains. Climatic changes during the Pleistocene, including glacial and interglacial cycles, influenced sediment deposition patterns, with glacial periods increasing erosion and sediment transport, and interglacial periods leading to the formation of extensive floodplains and meanders. Sea-level changes during the Quaternary period also affected sedimentation patterns and river courses, with lower sea levels extending river courses further into the Adriatic Sea [7] [8] [40].

The Sillaro River currently exhibits a sinuous course with a series of bends mostly upstream forming a well-defined floodplain with natural levees and terraces. Historically, the Sillaro River has shifted its course multiple times due to natural fluvial processes, sediment load changes, water discharge variations, and human interventions, with its meanders and terraces reflecting periods of stability as seen in the geomorphological map. Similarly, the Senio River shows a meandering pattern with a wide floodplain and evidence of previous river courses, including paleo channels and oxbow lakes. The historical evolution of the Senio River has involved significant course shifts influenced by natural events and human activities, responding to climatic variations, tectonic activity, and changes in sediment supply [7] [8] [40].

The evolution of both rivers has been influenced by factors such as sediment supply from the Apennines, which has been deposited in the plain, variations in water discharge due to climatic fluctuations or land use changes, and human activities like agriculture, drainage projects, and flood control measures. These factors have collectively shaped the geomorphological landscape of the Emilia-Romagna Plain, with the current landscape reflecting a complex interplay of natural processes and human interventions over time. Understanding these factors provides valuable insights into the dynamic nature of river systems and their role in shaping the region's past and present landscape exhibited by the geomorphological map [7] [8] [39] [40].

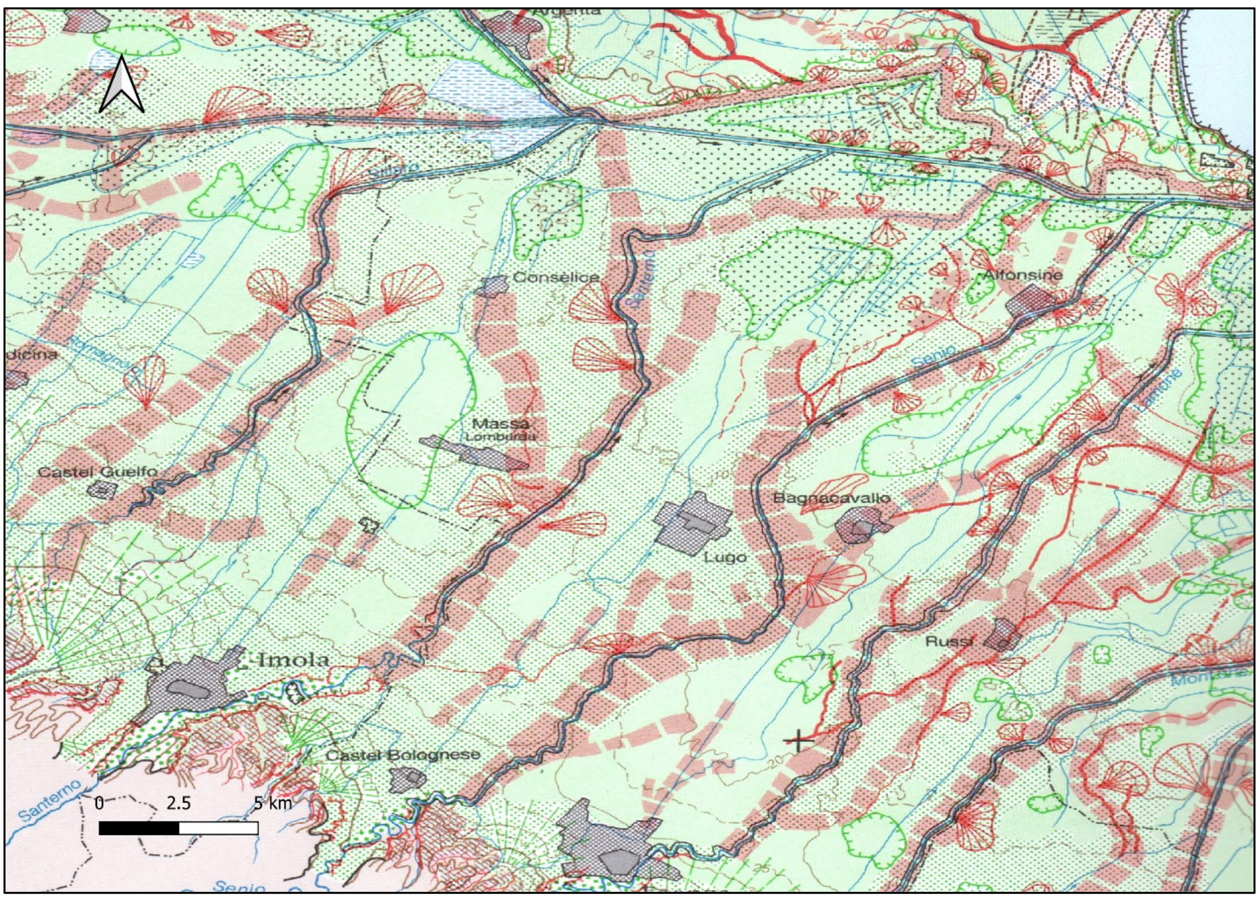

Figure 3.2: Geomorphological map of the Romagna plain [39]

3.2.4 Morphological Changes of the Rivers: The Palaeogeographical and Geomorphological Context

In order to understand how the landscape is shaped, reconstructing the channel diversions that happened in the last millennia is essential, especially for the Senio, a small river that represents the main watercourse in the area nowadays (Fig 3.3). However, its importance for the region dates back at least to the Middle Ages, when the same town of Cotignola was founded as Castrum on its left bank (see further). Thanks to the written sources and historical cartography, it is possible to reconstruct the recent history of the Senio with some precision. However, it is challenging to follow the possible diversions during the late Holocene and understand if other rivers were flowing in this area before the Modern period [14].

The oldest data that can be used to reconstruct the paleogeography of the study area comes from a recent archaeological rescue excavation carried out during the laying down of a gas pipeline. In 2011, remains of a possible large settlement were found in Via Agrippina (Faenza), just 600 meters from the border with Cotignola. The settlement was occupied from the Middle Bronze 2 (1550-1450 BCE) to the Recent Bronze Age (1340/1330-1170 BCE), based exclusively on a preliminary assessment of the finds collected during the two excavation campaigns (2011-2012). In addition, the existence of a river flowing thereabout was also suggested, to which the settlement was probably connected. This interpretation fits well with the previous hypothesis proposed by Stefano Marabini, who identified a mostly buried fluvial ridge, the so-called Paleodosso di Casanola - C. S. Eliseo, going from nearby Castel Bolognese to the south of Cotignola that he proposed as the course of the Senio during the Bronze Age [14].

Later on, the Senio probably started to flow within the present territory of Cotignola, with a course quite similar to the modern one up to Borgo Fabretti, where it probably joined the river Santerno, which used to flow in correspondence with the Paleodosso di via S. Bartolo. A confluence of these two watercourses is attested by some documents in the High Middle Ages, while for the Roman period, a petrographic study on sandy deposits recovered in a quarry in Cotignola has proved that a similar conformation was likely occurring already at the time. Indeed, sediments characterizing both Santerno and Senio rivers were deposited in the area already before and during the Roman period [14].

Further north, the Santerno-Senio River flowed towards Bagnacavallo, creating the Paleodosso di Bagnacavallo in post-Roman times. Finally, the last significant modifications experienced by the Senio, affecting the territory around Cotignola, were the separation from the river Santerno, which occurred for sure before 1259 and the avulsion from the course towards Bagnacavallo westwards of San Potito, dated in the literature around 1218 CE. After these two significant modifications, the course of the Senio has remained stable up to the north of Cotignola, also thanks to the construction of artificial embankments and the cutting out of many meanders naturally formed by its course [14].

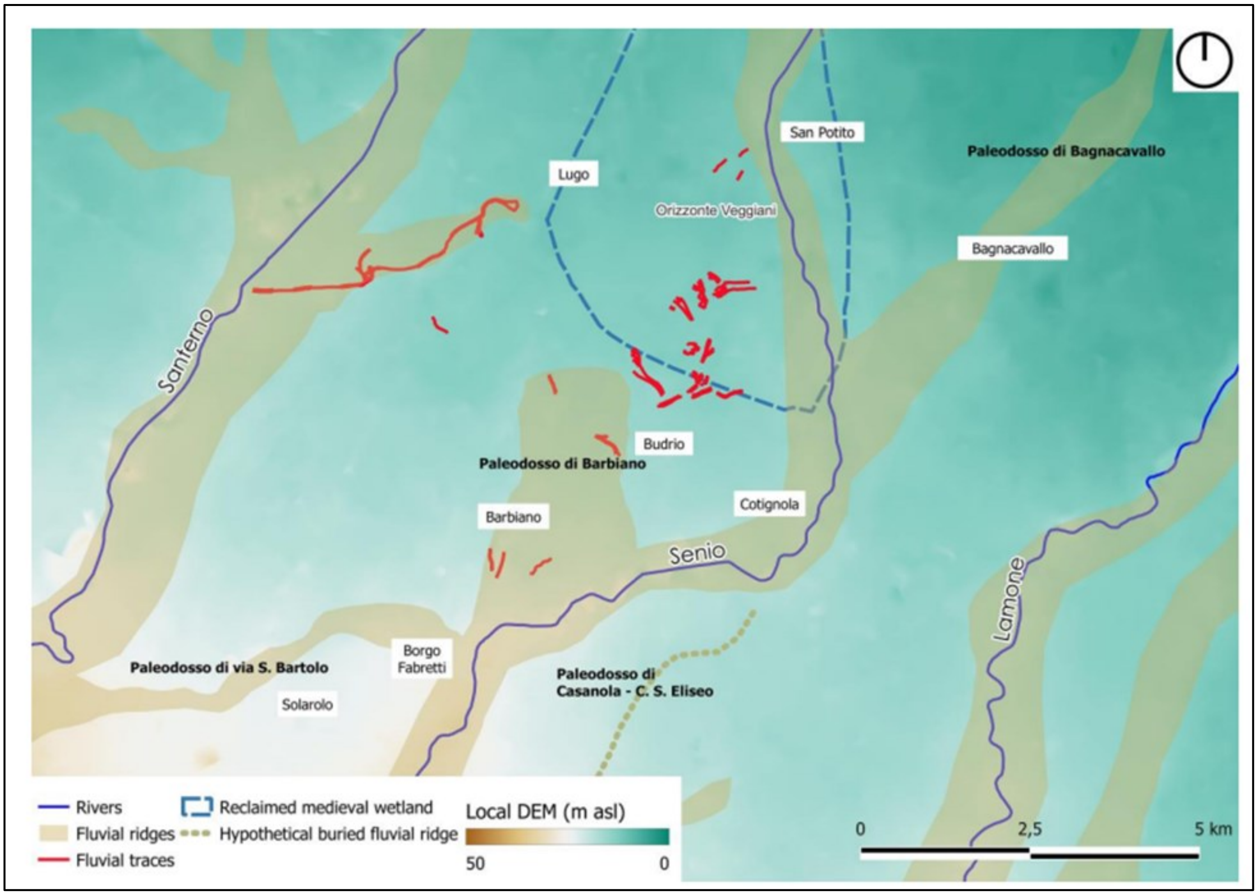

Figure 3.3: Geomorphological map of the territory of Cotignola with rivers, fluvial ridges (Italian names in bold), hamlets and towns mentioned, Visualization of a 10m resolution local DEM as basemap [14]

In a study, conducted by (Brardinoni et al., 2023) [15], the historical channel mapping of the Sillaro River, the portion of the valley comprised between Tomba (394 m a.s.l.) and Castel San Pietro Terme, for a total length of about 27 km is under consideration (Fig 4).

Reconstruction of historical channel changes has been conducted through multi-temporal mapping of the active channel. The Sillaro River has been subdivided into morphology-homogeneous channel reaches. Boundaries between reaches have been delineated based on critical geomorphic attributes and features to sediment supply and conveyance, including channel pattern, presence of confluences, and presence of anthropogenic hydraulic structures [15].

Figure 5 indicates that the river has experienced intense channel narrowing and an increase in sinuosity between 1954 and 1996. This pattern has progressively slowed down, even though narrowing continues until today. In 1954 and 1976, note the high degree of geomorphic activity in the southern tributaries, compared to 1996 and 2016.

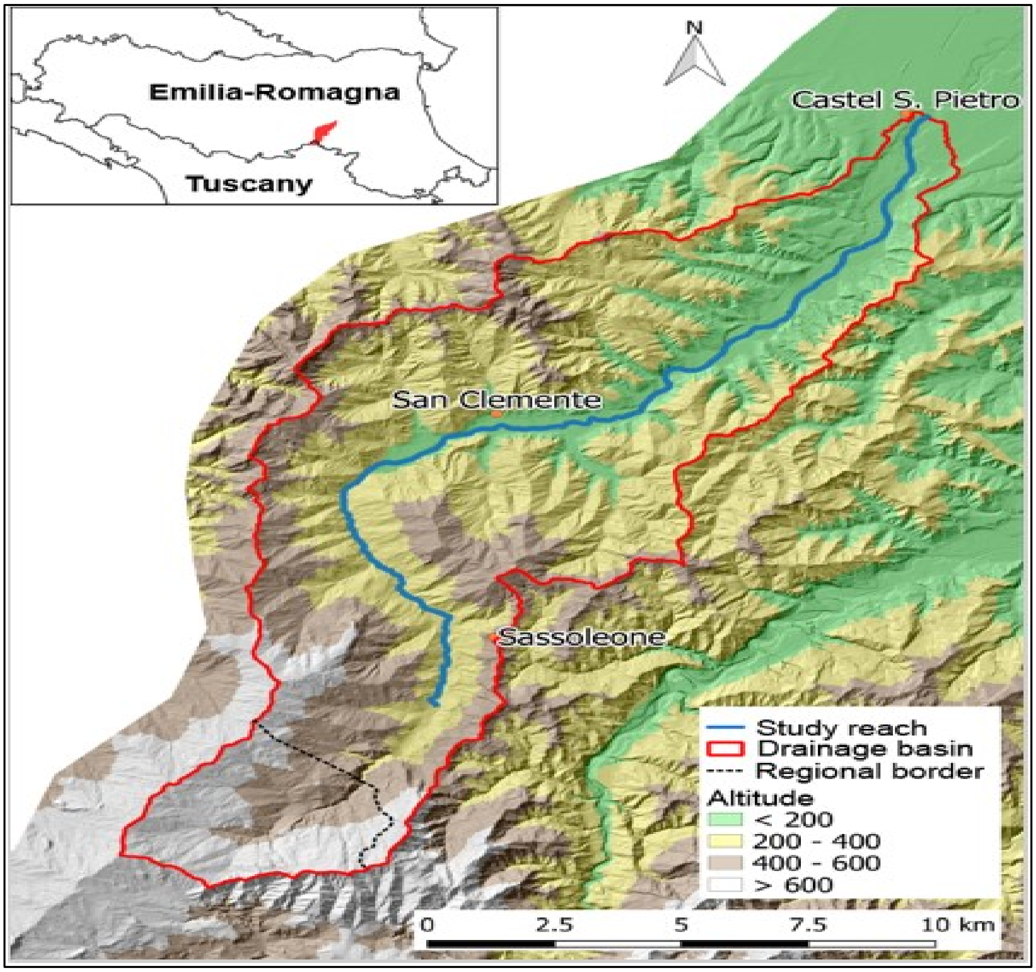

Figure 3.4: Area under consideration (Sillaro River) [15]

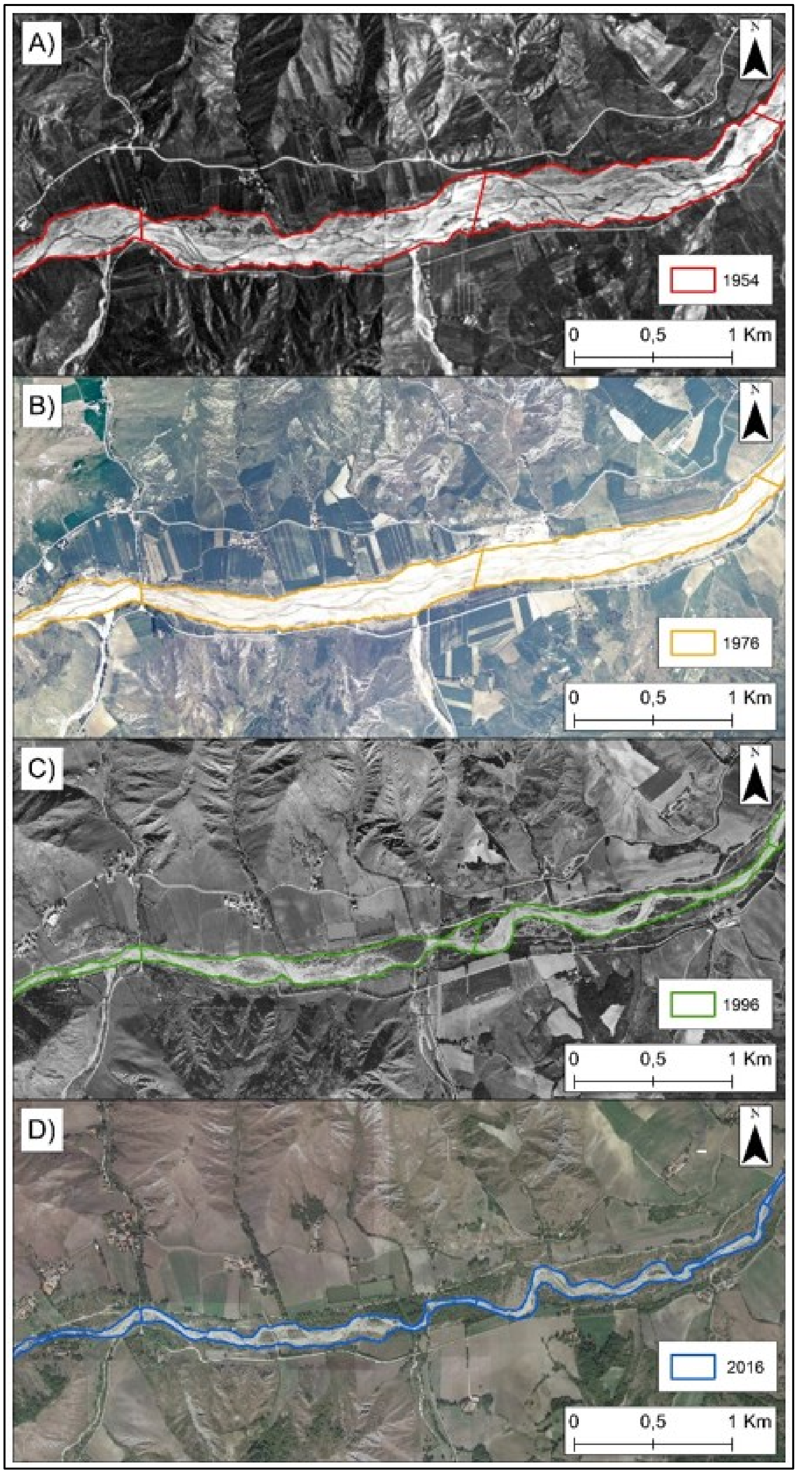

Figure 3.5: Examples of morphological change along the reaches of Sillaro river in the years A) 1954 B) 1976 C) 1996 D) 2016 [15]

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 downstream according to the system's dominant flow direction. The presence of embankments on the alluvial plain, confines the high water 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 [16].

One of the most important features in the Romagna plain is the morphological changes of the watercourses: south of Sillaro and Senio rivers, upper part of the plain, they run relatively deep in the alluvial plain. Whereas north of the rivers and on the confluence with Reno river (mid-lower part of the plain) they flow elevated or parallel with the surrounding areas within artificial or natural embankments (Fig 6). Therefore, because of these aspects, the flood hazard, related to morphological factors is much higher in the mid-lower part of the plain as in the upstream part of the rivers.

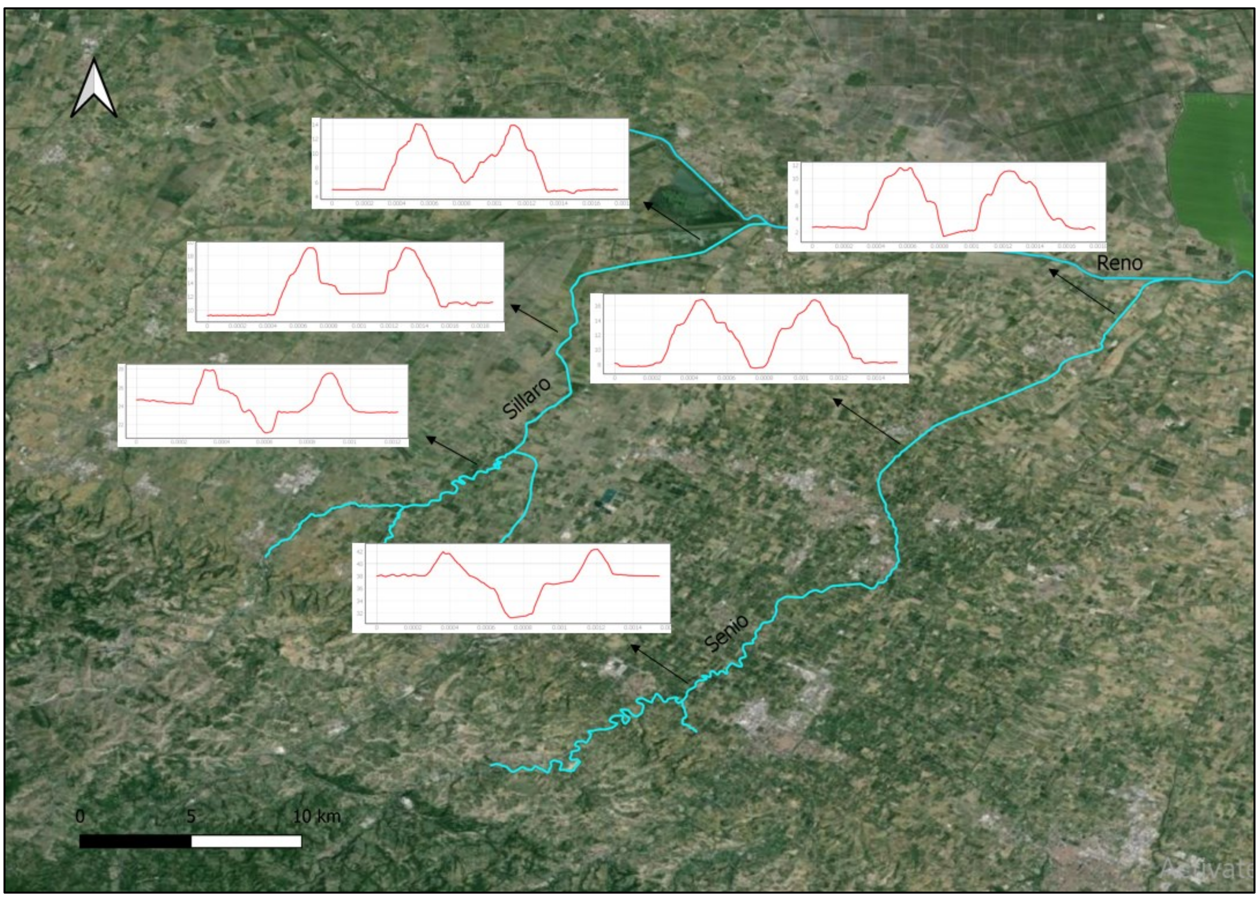

Figure 3.6: Examples of cross section of the Sillaro and Senio River showing elevation of channel bed and adjacent floodplain

4 MAY-2023 FLOODINGS

The Emilia-Romagna region experienced catastrophic flooding in May 2023, which highlighted the critical vulnerabilities in the area's flood risk management infrastructure. This chapter provides a comprehensive review of the May 2023 flooding, examining its causes, impact, and the role of existing geomorphological and hydraulic factors. The aim is to contextualize the event within the broader framework of flood susceptibility as discussed in previous chapters.

The flooding was primarily triggered by a combination of intense rainfall and the region's geomorphological predispositions. Following a prolonged period of drought, the region experienced torrential rains, first between May 2 and 3 with cumulative precipitation of 210 mm [2] and then between May 16 and 18 with cumulative precipitation reaching 240 mm [3]. This sudden influx of water overwhelmed the soil's absorption capacity, leading to rapid surface runoff and subsequent flooding. Key factors contributing to the flooding included a prolonged drought period that had desiccated the soil, reducing its permeability and increasing runoff during the heavy rains. This was compounded by an unprecedented amount of intense rainfall over a short period, far exceeding the typical meteorological patterns for this time of year. Consequently, the excessive rainfall caused rivers, particular focus on the Sillaro and Senio, to overflow their banks, exacerbating the flooding. Table 4.1 constitutes key particulars of the event. While figure 4.1 depicts the soil water index (SWI) of the Emilia Romagna region prior to the early and mid-May 2023 flooding [21].

The floods had widespread and severe repercussions, primarily affecting the eastern part of the region and its river basins, inflicting substantial damage to critical infrastructure such as roads, bridges, and levees. The integrity of several levees, vital for flood defense, was compromised, leading to breaches in multiple locations. The floods also resulted in significant economic disruptions, particularly in agriculture and industry, with extensive damage to crops, livestock, and industrial facilities. Thousands of residents were evacuated from their homes, and many areas remained inaccessible for days due to the floodwaters. The flood volume was estimated to reach 350 million cubic meters, inundating approximately 540 km^2 [2] [3]. Despite the damage, the levees played a crucial role in mitigating the extent of flooding by containing and directing the flow of water in several regions. With a particular emphasis on Sillaro and Senio rivers in the analysis, following sections will highlight and discuss the main criticalities that occurred during the event and its intervention measures.

Table 4.1: Key particulars of May 2023 flooding [2] [3]

ANTECEDENTS MAY 2023	MAY 2-3 2023	ANTECEDENTS MAY 16 2023	MAY 16-18 2023
Dry moisture condition	Heavy rainfall, cumulative up to 200 [mm]	Wet antecedent moisture condition	Intense rainfall, cumulative up to 240 [mm]
Prolonged drought period	Rainfall intensity 10 [mm/hr.].	Storage and natural mitigation capability of the region affected	Recorded cumulative precipitation levels of 200 [mm] within a 48-hour period
	Flooding in eastern part of Emilia-Romagna	Extension of a low atmospheric pressure trough over the region	Flooding of all major streams and tributaries of the region

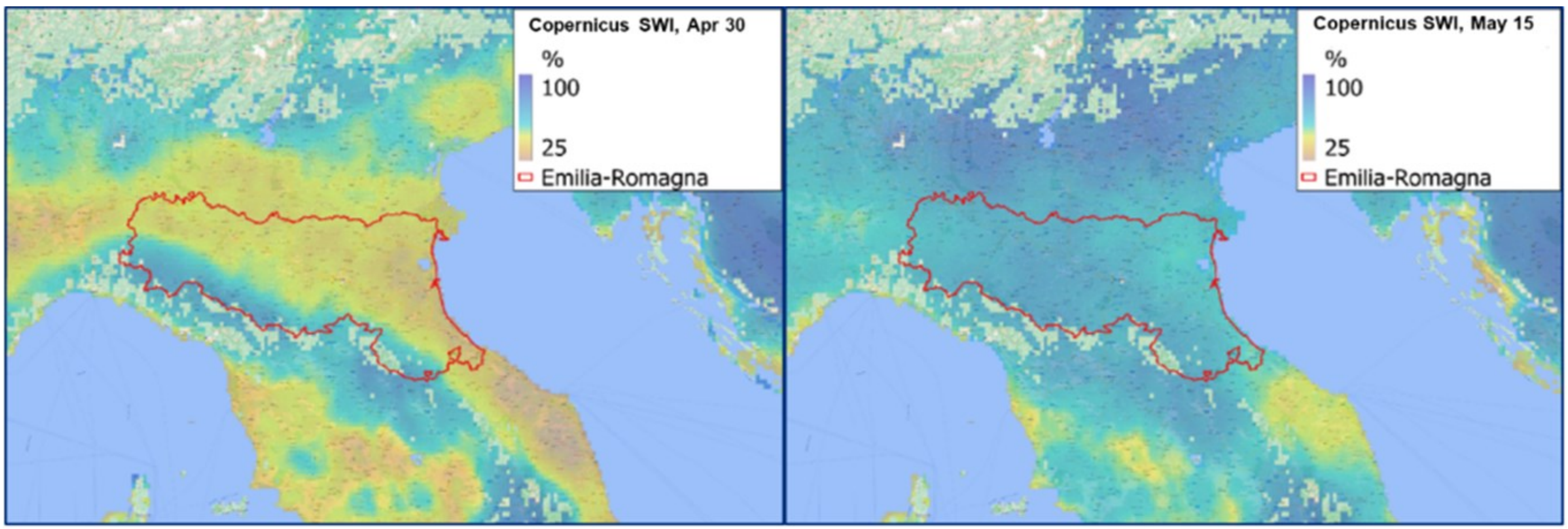

Figure 4.1: Soil water index (SWI) prior to the early and mid-May floods of 2023 [21]

4.1 MAIN CRITICALITIES

4.1.1 Sillaro River

During the first flood, a breach emerged in a privately owned embankment near Via Chiesa in Sesto Imolese. A site inspection on December 1, 2023 revealed a significant presence of burrowing animals along the banks in the vicinity of the breach (fig. 4.2). This suggests that animal burrows, and activity may have been a primary factor in the embankment's failure.

Figure 4.2: Animal burrows observed, Via Chiesa site investigation

Following the event, the earthen embankment was likely rebuilt to protect the area, with prioritization of rapid reconstruction using readily available materials from the surrounding area to limit further flooding. Materials might include soil (clay or sand) from nearby stockpiles or borrow pits, and possibly even recycled debris from the flood. The damaged embankment is rebuilt, and though these repairs are often temporary, they provide immediate protection. Solutions that are more permanent will likely require replacing the temporary materials with engineered and tested alternatives and may necessitate a geotechnical analysis for long-term levee stability.

Another breach occurred at Via del Tiglio. This point likely marks the location of an old breach, where the levee likely failed in the past (fig. 4.3). Observations through filed visit suggests that the breach was hastily repaired with a ring of boulders and then covered with soil – potentially without the crucial addition of a filter layer to prevent internal erosion. Despite the repair, the embankment remains significantly higher than the surrounding floodplain. Interestingly, it features distinct berms on the landward side, possibly indicating multiple attempts at reinforcement over time.

Figure 4.3: Post event orthophoto of Via del Tiglio breach

During the initial flood event, the breach occurred possibly at the junction where the previously repaired section met the original embankment. Field inspections revealed signs of water seepage through the embankment, gradually eroding the landward base (fig. 4.4) and exposing the boulders used in the prior repair. This exposure triggered minor collapse on the landward slope, indicating significant instability issues. The observations strongly suggest that the highly permeable materials used in the old repair's core allowed water to accumulate significant pressure within the embankment, thereby destabilizing the original levee structure. The junction where the boulder ring intersected the old embankment was particularly susceptible; the repair material's high permeability created substantial pressure, while the original embankment's resistance was likely compromised. Additionally, contact erosion might have contributed to the instability. This phenomenon occurs when two materials with vastly different grain sizes meet, causing water flow to transport small particles from the finer material into the coarser one, thereby increasing permeability, intensifying water flow, and further weakening the structure's integrity.

Figure 4.4 Erosion signs on levee body, Via del Tiglio site inspection

Amid the first event, a breach occurred in the levee at Via Merlo, Spazzate Sassatelli (fig. 4.5). Despite rapid repair efforts, the second event overwhelmed the reconstructed embankment, reopening the breach. Analysis of available videos does not suggest overtopping as the primary cause; rather, a localized defect within the embankment, such as an animal burrow, likely initiated concentrated erosion. The specific location of the embankment is notably high, which may have exacerbated the failure's severity. The breach extended approximately 50 meters, resulting in widespread flooding that affected the Spazzate Sassatelli district of Imola and Conselice (Ra).

In this particular reach, the watercourse runs elevated from the surrounding land. During the site visit, it is observed that the breach is hastily repaired using boulders, covered with soil likely sourced from nearby floodplains. Notably, the repair did not incorporate geosynthetics to separate these different materials. Reinforcement at the riverside base of the embankment includes 10-meter sheet piles, with boulders armoring the riverward slope to prevent erosion. To restore the embankments, 6,000 tons of rock were strategically positioned and an additional 23,500 cubic meters of earth were used to reinforce the structures. Current efforts focus on further strengthening the embankments, including the installation of sheet piling along a 100-meter stretch to increase impermeability and enhance overall stability, which is anticipated to significantly enhance the stability of this section.

Following the catastrophic breach at Via Merlo, a devastating chain reaction unfolded. Over a significant distance upstream, the overflowing water scoured away the floodplains. This erosion relentlessly progressed backwards, even compromising sections of the embankment itself at Via Dozza (fig. 4.5). The rapid flow and powerful erosive force were the primary drivers of this destructive process.

The floodplain has been altered, incorporating protective stonework to prevent further erosion. In regions where the embankment partially collapsed, large stones have been placed to reinforce its base, and the embankment has been meticulously rebuilt.

Figure 4.5: Post event orthophoto of Via Merlo and Via Dozza breach

At the PortoNovo Bridge, the second flooding event surpassed the structure's capacity, likely due to interference or blockage. This surge or overflow was forcefully redirected against the landward embankment, causing substantial erosion and potentially undermining the adjacent area. The scouring effect of the water may excavate a channel around the bridge's foundation, exposing it and heightening its susceptibility to future flood incidents. Should the erosion persist, it could precipitate the total failure of the levee segment, thereby compromising the structural integrity of the bridge.

Table 4.2 constitutes the summary and key attributes of the main criticalities formed in Sillaro River during the May 2023 event while figure 4.6 depicts the position of the criticalities along the watercourse.

Table 4.2: Summary and key attributes of the main criticalities (Sillaro River)

S.no	Location	Breach Details	Interventions
1	Via Chiesa	• Significant presence of burrowing animals. • Burrowing activity likely contributed to embankment failure.	• Prioritized rapid reconstruction using locally available materials. • Temporary repairs to provide immediate protection
2	Via del Tiglio	• Breach at a likely old failure point. • Field visit observed repair with boulders and soil. • Absence of filter layer may have led to internal erosion. • Minor landward slope collapse indicating instability.	• At first, the breach was closed with boulders, but later they were removed and the embankment was rebuilt. • Embankment higher than floodplain with distinct berms on landward side, indicating repeated reinforcement attempts.
3	Via Merlo	• Breach occurred during the first event, Rapid repair efforts initially made; second event overwhelmed the reconstructed embankment. • Videos suggest a localized defect, possibly an animal burrow, as the cause. • Elevated embankment may have exacerbated failure severity. • Breach extended approximately 50 meters, causing widespread flooding	• Repairs using boulders and nearby soil, without geosynthetics. • Riverside base reinforced with 10-meter sheet piles. • Riverward slope armored with boulders to prevent erosion. • Ongoing efforts focus on further strengthening with sheet piling along a 100-meter stretch

4	Via di Dozza	• Breach at Via Merlo triggered a chain reaction. • Erosion progressed backwards, compromising sections of the embankment at Via Dozza. • Rapid flow and powerful erosive force were primary drivers of destruction.	• Altered floodplain with protective stonework to prevent further erosion. • Large stones placed to reinforce the base in partially collapsed regions
5	PortoNovo	• Overflow during second event. • Surge redirected against landward embankment causing substantial erosion. • Persistent erosion risks total levee segment failure and structural compromise of the bridge	• Reprofiling scheme is proposed for the breached levee section.

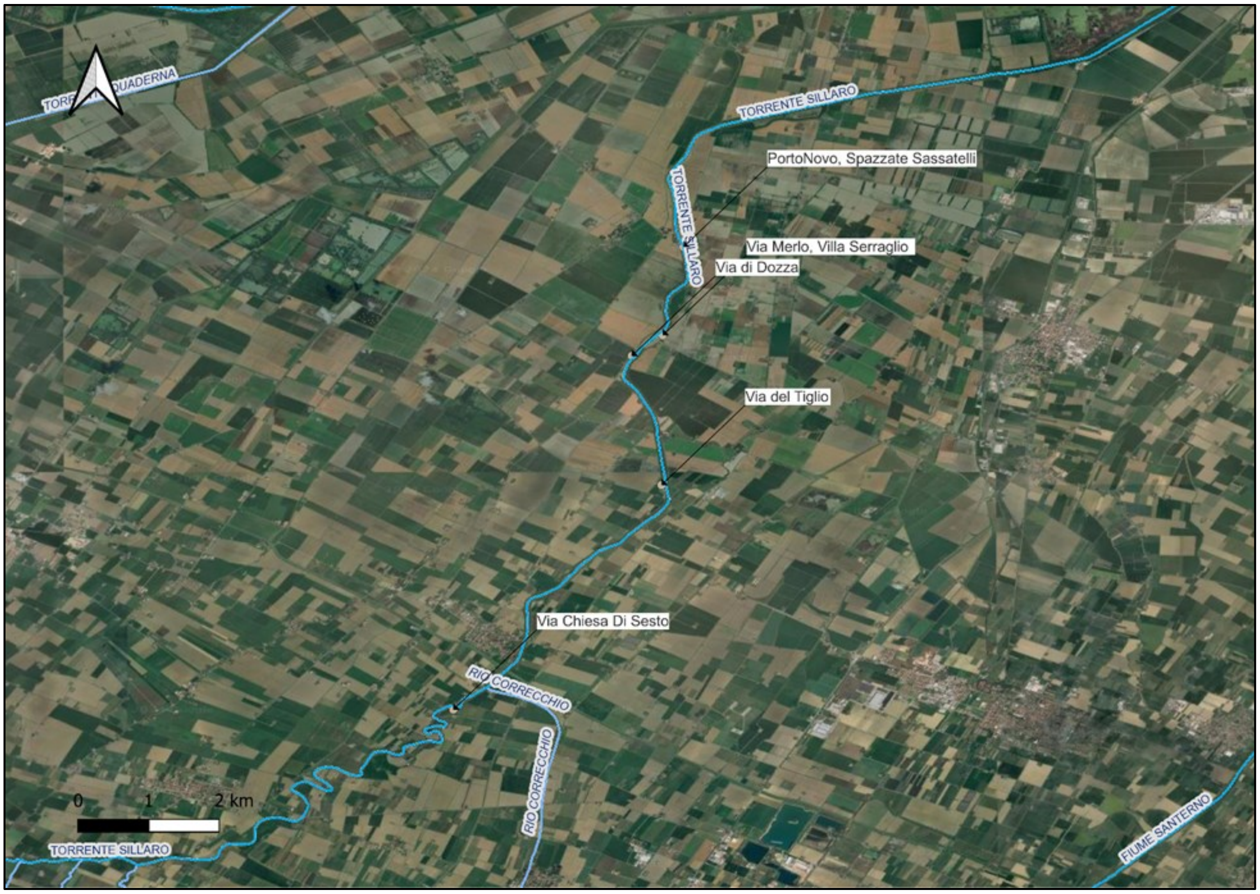

Figure 4.6: Breaches along the Sillaro watercourse

4.1.2 Senio River

During the May 2023 flood events, multiple breaches were reported along the meander part of the Senio River. Few major breaches occurred near the town of Castel Bolognese (fig 4.8), where the levee failed at multiple locations, causing extensive flooding of agricultural lands and residential areas. Breaches mainly occurred following the second event, probable causes can be attributed to hyrdraulic pressure and overtopping, intense rainfall caused high water level in the narrow section leading to overtopping (fig. 4.7). During the site investigation carried out on June 3, 2024, signs of erosion and scour at the base of the levee were also observed.

Following the event, the interventions proceeded in two directions: restoration of the hydraulic efficiency of the streambed and the restoration of the banks. Specifically, the structure of the watercourse between Riolo and Ponte del Castello is being strengthened and optimized to enhance lamination phenomena, while maintenance and arrangement of the full-bank section of the active riverbed aim to maximize flow capacity. Additionally, bank stabilization works are being implemented where lateral erosion threatens buildings and infrastructures, and a defensive system is being defined on the left bank to protect the town of Castel Bolognese.

Figure 4.7: Snap from a post event aerial survey near the reaches at Castel Bolognese [22]

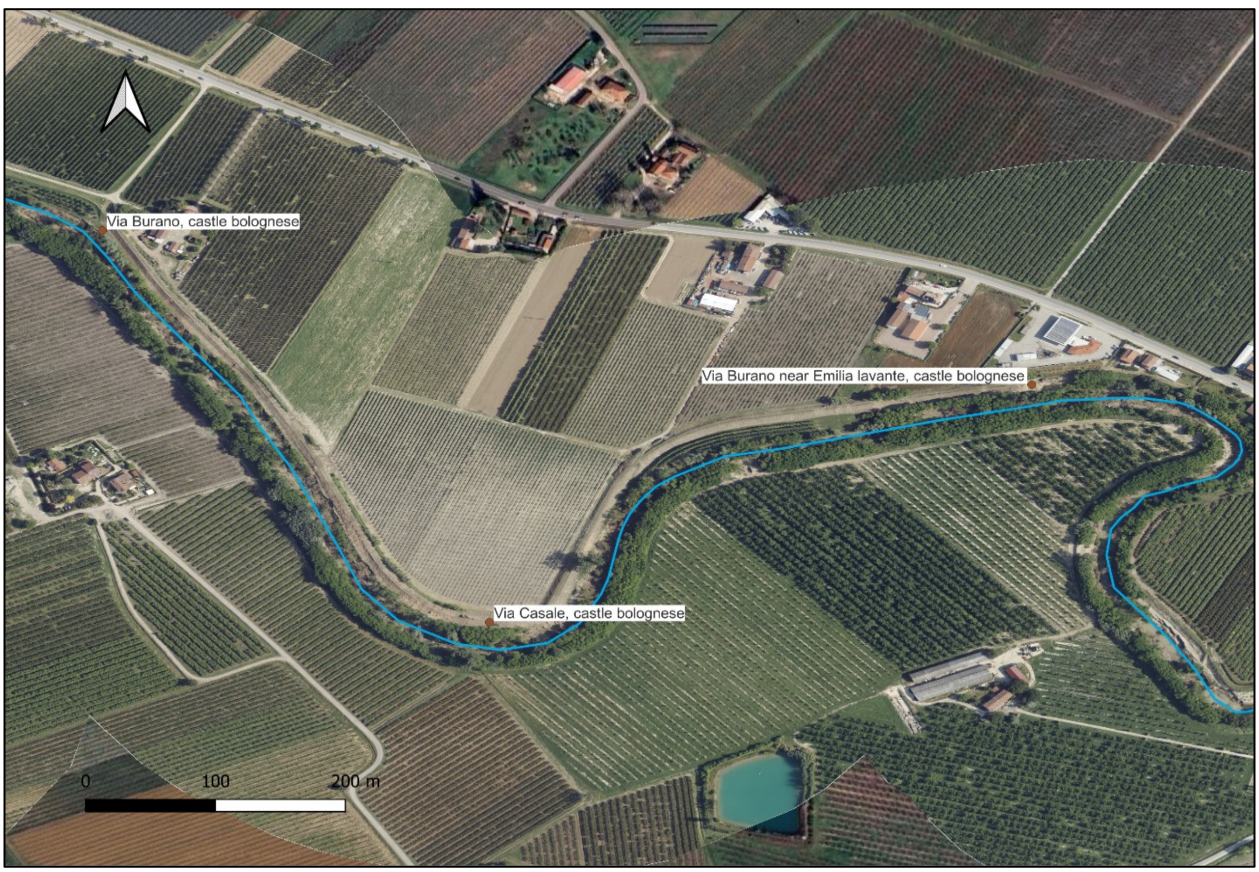

Figure 4.8: Post event orthophotos of main breaches near Castle Bolognese

Another significant breach was reported near Via Biancanigo, where the levee's structural integrity was compromised, possibly due to combination of the effect of occlusion of the riverbed and levels of water beyond design, leading to inundation of the surrounding countryside. Probably, continuous rainfall saturated the levee embankments, facilitating internal erosion or piping. Water seeped through the embankment body, creating underground channels that led to the collapse of the embankment. In addition, some sections of the levee were older and had not been maintained adequately, making them more susceptible to failure under extreme flood conditions. By using DTM with false color representation (Fig. 4.9), many significant breaches can be noticed in the said river reach.

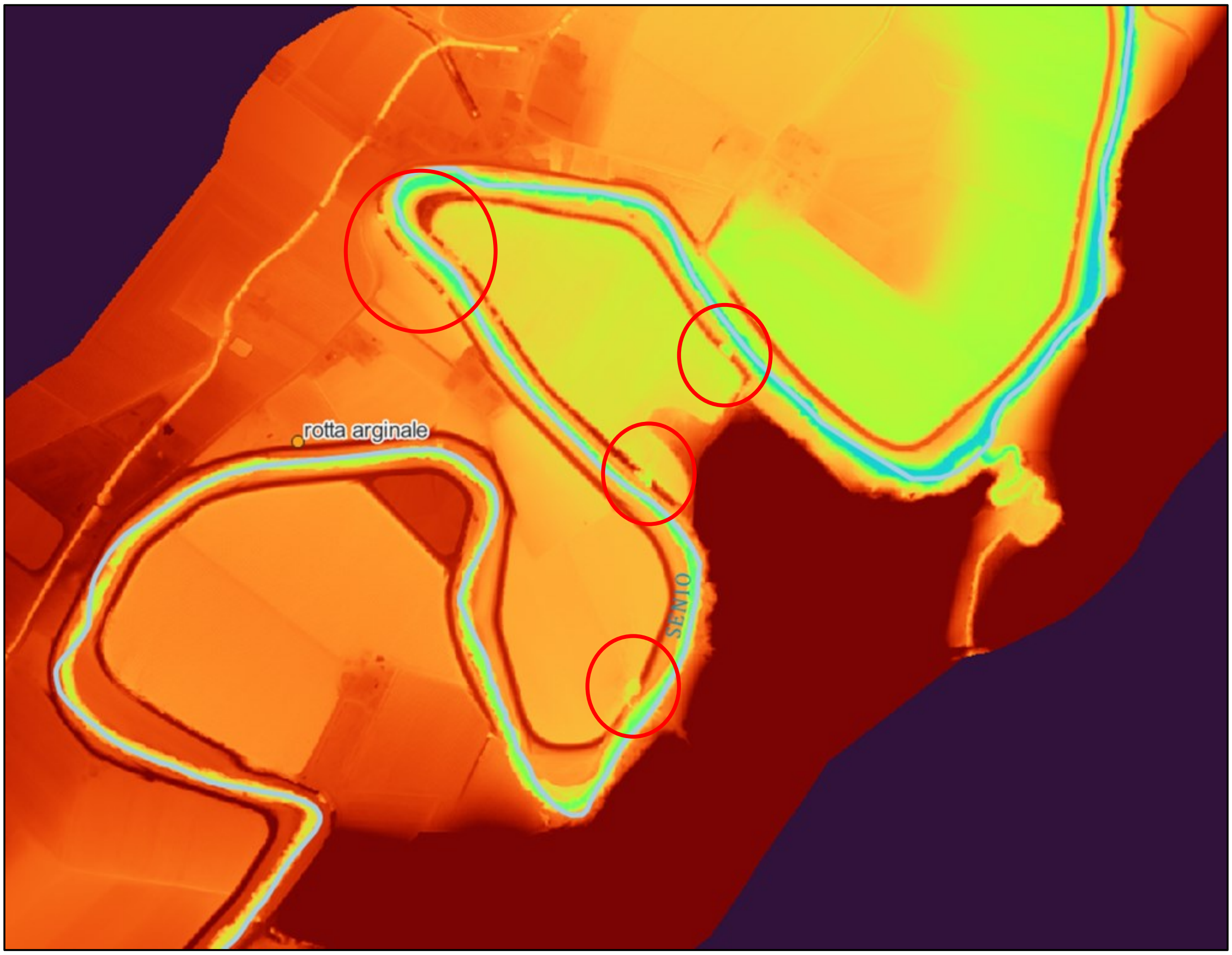

Figure 4.9: Observed breaches using post event DTM, false color representation at river section near Via Biancanigo

Following the second event, severe breach was reported near the bridge at Via Canale, Ruolo Terme. The failure was possibly due to the vulnerability to change of general parameters in the levee body. During the site investigation, it was reported that the riverbank level was high before the event, possibly due to occlusion of the riverbed near the bridge. Amateur video of the breach depicts the collapse of the embankment, which hints that water seeped through the levee, creating underground channels that led to the collapse of the embankment.

The intervention measures following the event includes the restoration of the riverbed's functionality and reconstruction of the hydraulic left embankment and removal of fallen vegetation (fig. 4.10). Table 4.3 constitutes the summary and key attributes of the main criticalities formed in Senio River during the May 2023 event while figure 4.11 depicts the location of the criticalities along the watercourse.

Figure 4.10: Intervention works at Via Canale breach, June 03, 2024 site inspection

Table 4.3: Summary and key attributes of the main criticalities (Senio River)

S.no	Location	Breach details	Interventions
1	Via Burano, Castle Bolognese	● Probable causes can be attributed to hyrdraulic pressure and overtopping. ● Intense rainfall caused high water level in the narrow section leading to overtopping	● Focus on the repair of the banks and clearing of riverbed of wood and sediments. ● No further report on the measures of repair of the levee segment.
2	Via Casale, Castle Bolognese and Via Burano near Via Emilia Lavante	● Failure probably induced by the erosion of the banks due to rapid drawdown, and high-water levels in this narrow reach, causing overflowing.	● The intervention includes: restoration of the hydraulic efficiency of the stream bed and the restoration of the banks
3	Via Biancanigo	● Combination of the effect of occlusion of the riverbed and levels of water beyond design ● Levee's structural integrity also compromised, potentially due to continuous rainfall saturating the embankments and facilitating internal erosion or piping. ● Older, inadequately maintained sections of the levee were particularly vulnerable to failure under extreme flood conditions.	● Post event orthophoto suggests interventions has been carried out to restore the embankment but details are not reported.

4	Via Canale, Ruolo Terme	● Breach reported near the bridge following the second flood event. ● Failure potentially attributed to vulnerabilities in the levee structure, exacerbated by changes in key parameters. ● Pre-event observations indicated elevated riverbank levels, likely due to occlusion of the riverbed near the bridge.	● Restoration of the riverbed's functionality. ● Reconstruction of the hydraulic left embankment. ● Removal of vegetation debris obstructing water flow.

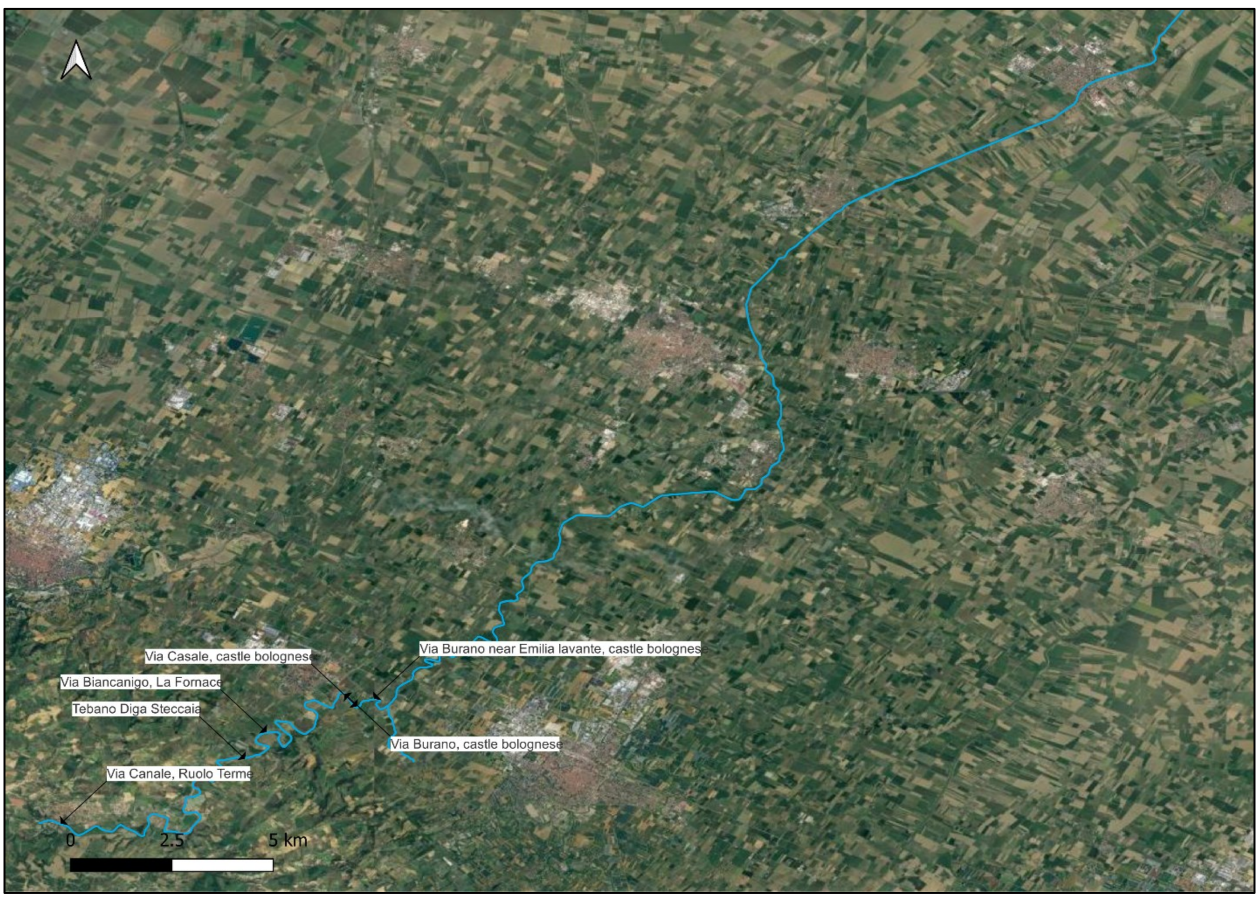

Figure 4.11: Breaches along the Senio watercourse

5 METHODOLOGY

The methodology involves a multi-step approach, integrating the synthesis of data analysis, GIS techniques, and the development of potential indicators for flood susceptibility. This comprehensive approach ensures a detailed and accurate assessment of flood risks in the Sillaro and Senio Rivers.

5.1 DATA ACQUISITION

The acquisition of data involved a rigorous and methodical process, ensuring the reliability and comprehensiveness necessary for this study. Initially, historical regional maps, geomorphological map, digital terrain models (DTMs), and various relevant files were sourced from online repositories and regional authorities within Emilia Romagna. These sources constituted the foundational datasets for the analysis. The data acquisition process was structured into several stages. Firstly, primary data sources were identified, including online repositories, regional authorities, and academic institutions. This phase entailed liaising with relevant organizations and accessing public databases to secure the requisite maps and models. Subsequently, historical maps spanning the years from 1800-2020 were collected, which were essential for delineating historical changes in river channels and geomorphology. Detailed geomorphological maps and DTMs were then acquired to furnish a thorough understanding of the region's topography and geological features. These resources, supplemented by relevant literature, elucidated landforms, geological structures, and elevation data, which are critical for flood susceptibility analysis. Lastly, an assessment of data quality and accuracy was conducted, involving the checks of distortions, identification of missing information, and ensuring the data were as stipulated and relevant to the study area. Table 5.1 constitutes key attributes of the obtained data and sources.

Table 5.1: Key attributes of data obtained

S.no	Data Type	Description	Temporal Coverage	CRS	Source
1	Raster	Historical Map	1808	EPSG:4326 - WGS 84	Geoportal – ER [33]
2	Raster	Orthophoto	1976	EPSG:4326 - WGS 84	Geoportal – ER [34]
3	Raster	Topographic Maps	1988-2021	EPSG:4326 - WGS 84	Geoportal – ER [38]
4	Raster	Geomorphological Map	1997	EPSG:4326 - WGS 84	Castiglioni et al., [39]
5	Raster	Orthophoto	2008	EPSG:4326 - WGS 84	Old maps online [31]
6	Raster	Orthophoto	2020	EPSG:4326 - WGS 84	Geoportal – ER [32]
7	Raster	Natural Watercourse in ER	2021	EPSG:4326 - WGS 84	Geoportal – ER [30]
8	Raster	Embankments	2021	EPSG:4326 - WGS 84	Geoportal – ER [37]

9	Raster	Post-Event Orthophoto	2023	EPSG:4326 - WGS 84	Geoportal – ER [35]
10	Raster	DTM	2023	EPSG:4326 - WGS 84	Geoportal – ER [36]

5.2 HISTORICAL ANALYSIS OF RIVER CHANNELS

Identification of geomorphological indicators for flood susceptibility necessitated a detailed historical analysis of the rivers. This analysis was conducted using remote sensing techniques within a Geographic Information System (GIS) environment. Historical maps were georeferenced, aligning the old maps with current geographic coordinates to ensure spatial accuracy. The steps involved in this process included.

5.2.1 Georeferencing Historical Maps

Georeferencing historical maps involves aligning these maps with current geographic coordinates to ensure spatial accuracy. Each historical map undergoes a digital transformation to match the modern coordinate system, facilitating accurate comparisons over time. Key landmarks that have remained unchanged, such as bridges, buildings, and road intersections, are selected as control points. Using these control points, the historical maps are warped and transformed to align with modern geographic coordinates through the use of the QGIS Georeferencer tool.

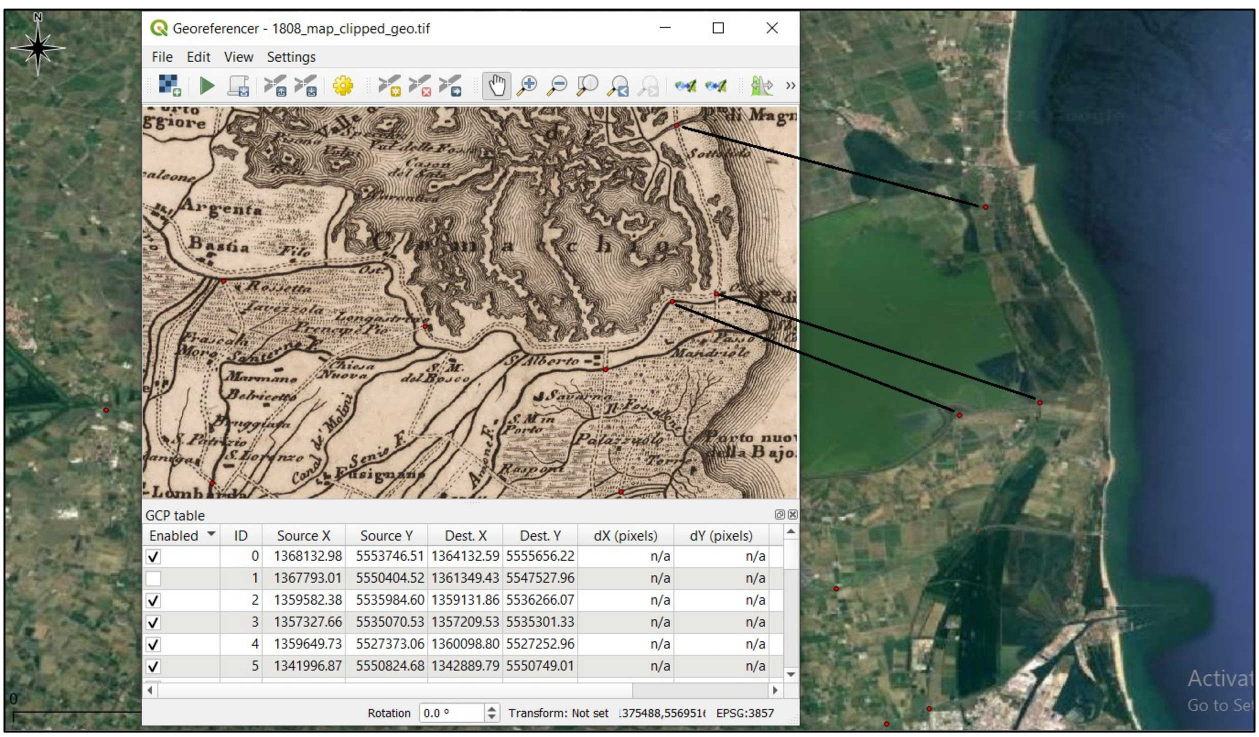

Figure 5.1: Georeferencing of a historical map using QGIS Georeferencer tool

5.2.2 Digitization of River Channels

Once the historical maps are georeferenced, the subsequent step involves the digitization of river channels, which entails tracing the historical river courses on the georeferenced maps to create digital representations of these channels. Each river channel is manually traced on the georeferenced map to ensure accuracy, and these traced river channels are then converted into digital layers within the QGIS software, facilitating easy manipulation and analysis.

The comparison with contemporary channels also involved digitizing the current river channels using contemporary maps and satellite imagery. This process includes utilizing modern data from contemporary maps and high-resolution satellite images to trace the current river channels accurately. These contemporary channels, like their historical counterparts, are then converted into digital layers, allowing for detailed comparison and analysis.

5.2.3 Analysis of Shifts and Paleo Channels

The analysis of shifts and paleo channels involves comparing the historical and current digital channels to identify significant shifts and paleo channels, thereby offering insights into how river patterns have changed over time. Through overlay analysis, historical and contemporary digital channels are superimposed to ascertain areas of significant change. Additionally, channels that no longer exist in their historical form are identified as paleo channels, thus providing a valuable record of past river dynamics.

5.3 GEOMORPHOLOGICAL MAP OVERLAY

To corroborate the findings derived from the historical analysis, a geomorphological map [39] of the region was georeferenced. This map delineated an array of landforms, geological structures, and crevasse splays, thereby providing a comprehensive context for the historical river channels. The digitized river channels were then superimposed onto the geomorphological map for:

5.3.1 Validation of Paleo Channels

To validate the paleo channels identified in the historical analysis, a geomorphological map overlay was employed, providing a robust confirmation of their presence. This process involved a detailed comparison of the paleo channels with various geomorphological features, such as fluvial ridges, altimetry reconnect, crevasse splays and other landforms that potentially influence river morphology. By juxtaposing the identified paleo channels with these geomorphological features, the map overlay facilitated a comprehensive assessment, thereby enhancing the accuracy and reliability of the historical findings.

5.4 SINUOSITY ANALYSIS

A comprehensive analysis of river dynamics was further advanced through the creation of a sinuosity map for the current river channels. Sinuosity, which is quantified as the ratio of the river's actual length to the straight-line distance between its termini, was meticulously computed for multiple 1,000-meter segments of the river. This process encompassed the following steps:

$$SI = \text{Actual Length} / \text{Straight Length}$$

5.4.1 Calculation of Sinuosity

The calculation of sinuosity was conducted by evaluating the ratio of the river's actual length to the straight-line distance between its endpoints for each 1,000-meter segment. This process involved a detailed measurement procedure using QGIS tools: the actual length of the river sections was precisely determined along their meandering courses, while the straight-line distance between the start and end points was directly measured. This methodological approach ensured accurate assessment of sinuosity, thereby facilitating a thorough analysis of river dynamics.

5.4.2 Categorization of Sinuosity Levels

The categorization of sinuosity levels involved organizing the calculated sinuosity values to effectively visualize classes with varying degrees of sinuosity. To facilitate this, a color-coding scheme was employed, with distinct colors representing different sinuosity levels, thereby simplifying the identification of regions with high and low sinuosity. Additionally, specific sinuosity thresholds were established to distinguish between straight, sinuous, and meandering sections, enhancing the clarity and interpretability of the sinuosity map. This systematic approach provided a comprehensive framework for analyzing and visualizing the river's dynamic characteristics.

Table 5.2: Sinuosity classes

S.no	Symbol	Values	Legend
1	(green line)	1.000 – 1.050	Straight
2	(yellow line)	1.050 – 1.500	Sinuous
3	(red line)	1.500 – 4.000	Meandering

5.4.3 High Sinuosity Areas: Potential Meander Cutoff Zones

The identification of areas with high sinuosity and potential of meander cutoffs is critical for understanding flood susceptibility and predicting future changes in river dynamics. High sinuosity regions were systematically analyzed to assess their propensity for meander cutoffs and shifts in river flow, both of which are central to evaluating flood risks. This analysis considered the implications of sinuosity on flood risk, including heightened erosion and the possibility of bank breaches, offering a nuanced understanding of flood vulnerability across various river segments.

Furthermore, the identification of potential meander cutoff locations integrated both sinuosity analysis and historical data on river shifts. By examining sections with elevated sinuosity and incorporating patterns of riverbank movement, the analysis facilitated precise predictions of future meander cutoff zones and significant alterations in river courses. This approach ensures a comprehensive assessment of regions prone to dramatic hydrological changes.

5.5 RIVER BANK DIGITIZATION

Alongside the analysis of river channels, orthophoto digitization of historical and contemporary riverbanks was employed to observe patterns of expansion or contraction. This entailed:

5.5.1 Tracing Riverbanks:

To accurately trace the riverbanks, orthophotos of year 2008 and 2020 were employed to offer a precise representation of the river's boundaries. The process involved manual tracing of the riverbanks on these images to ensure meticulous accuracy, paralleling the method used for delineating river channels. Subsequently, the manually traced riverbanks were converted into digital layers within QGIS software, facilitating their integration into a comprehensive spatial analysis. This approach ensured both precision and detail in the depiction of the river's boundaries.

5.5.2 Overlay Analysis:

The comparison of digitalized riverbanks necessitates a detailed analysis of the current riverbanks in relation to their historical (2008 orthophoto digitalized) counterparts to discern changes over time. This process includes overlay analysis, where historical (2008 orthophoto digitalized) and current riverbanks are superimposed to identify areas of expansion or contraction. The Digitization approach also assisted in a temporal analysis to examine changes in riverbanks across the period, thereby providing a comprehensive understanding of the dynamics of riverbank movement.

This pattern analysis of riverbank changes reveals critical insights into regions susceptible to potential breaches during future flood events. By examining observed patterns, areas exhibiting significant bank expansion or erosion are identified as particularly vulnerable to flooding. This identification process is followed by a thorough vulnerability assessment, where the likelihood of riverbank breaches based on their sinuosity index value is evaluated. This analytical approach provides a comprehensive understanding of areas at heightened vulnerability, informing susceptibility assessments.

5.6 ANALYSIS USING POST-EVENT ORTHOPHOTOS

The analysis using post-event orthophotos involves examining high-resolution aerial photographs captured after flood event to evaluate damage and pinpoint critical locations. These orthophotos facilitate a detailed post-flood assessment by revealing areas of substantial damage and changes in the river landscape. Through this analysis, key locations such as breached levees, possible piping signs, eroded banks, and overtopped areas are identified and mapped, providing essential insights for flood impact evaluation.

5.7 IDENTIFICATION OF POTENTIALLY CRITICAL LOCATIONS: DEVELOPMENT OF SUSCEPTIBILITY MAPS

For the implementation of a comprehensive GIS based framework, it was essential to conduct both historical and sinuosity analyses, in conjunction with the assessment of post-event orthophotos and digital terrain models, to effectively identify criticalities. Hence, the development of susceptibility maps harnessed the detailed perspective attained by synthesizing insights from historical analysis, interpretation of geomorphological maps, sinuosity analysis, and identification of critical areas from post-event orthophotos, thereby linking historical and geomorphological findings with actual flooding events. This integrative approach facilitated the creation of nuanced susceptibility maps that effectively depict the region's flood susceptibility. By employing this multi-faceted methodology, the analysis of flood susceptibility is robust and thorough, seamlessly incorporating both historical and contemporary data to identify areas potentially vulnerable to future flooding events.

6 RESULTS

The preceding chapters' analyses have established a comprehensive framework for elucidating geomorphological criticalities and their impact on flood susceptibility in the Sillaro and Senio Rivers. This chapter, includes the May 2023 flooding event criticalities, providing a brief analysis in relation to the identified historical and geomorphological factors and seeks to implement the methodology discussed and interpret the findings within the context of existing literature and theoretical paradigms, while also examining their implications for flood risk management and mitigation strategies.

6.1 ANALYSIS OF POST-MAY 2023 EVENT ORTHOPHOTOS

The analysis of post-flood event orthophotos is a crucial component in geomorphological assessments, particularly in identifying and quantifying flood-induced criticalities. The orthophoto utilized in this study serve as high-resolution visual documentation of the landscape post-flood, offering a comprehensive and detailed perspective on the extent of geomorphological disruptions caused by the event. This section delves into the systematic evaluation of the orthophoto, emphasizing the identification of key criticalities such as actual signs of bank erosion, possible piping signs, overtopping locations, current and not reported breaches. The recognition of these criticalities are crucial, as they may present vulnerabilities in future events.

6.1.1 Identification of Bank Erosion

Bank erosion, as captured in the post-event orthophotos, is a primary indicator of flood impact on the fluvial morphology. The orthophotos reveal several sections where the riverbanks exhibit significant erosion, characterized by the removal of vegetation and soil layers, leading to the destabilization of the riverbanks. These eroded sections, marked by irregular, scalloped edges along the river course, suggest high-energy water flow during the flood event. The extent of erosion, in conjunction with the geomorphological context of the surrounding area, provides insights into the intensity and direction of floodwaters, as well as the vulnerability of specific riverbank segments to future flood events. Figure 6.1 discerns extensive bank erosion observed at highly sinuous section of Senio River

Figure 6.1: Observed bank erosion at meander section of Senio River

6.1.2 Piping Signs and their Implications

Piping, or the subsurface erosion caused by water flow through permeable soil layers, is another criticality identified through orthophoto analysis. The presence of piping is inferred from the appearance of sinkholes, depressions, and irregular surface patterns on the orthophotos, particularly in areas adjacent to embankments. These features suggest the internal weakening of embankments or levees, which, if left unaddressed, could precipitate larger breaches in future flood events. The identification of these piping signs is essential for the formulation of targeted remediation strategies aimed at strengthening embankment integrity. Figure 6.2 displays piping signs near Via del Tiglio breach at Sillaro River.

Figure 6.2: Observed possible piping sign at Sillaro River

6.1.3 Overflowing Locations

The orthophoto analysis also highlights few overflowing locations, where floodwaters exceeded the height of natural or artificial embankments, leading to the inundation of adjacent low-lying areas. The deposition of sediments and the flattening of vegetation typically mark these overflowing events, which are clearly visible in the orthophotos. By mapping these overtopping locations, this study identifies the most vulnerable sections of the flood defense infrastructure, thereby informing the prioritization of structural reinforcements and flood management interventions. Figure 6.3 exhibits one of the overflowing location identified through post-event orthophoto in Senio River

Figure 6.3: Observed overflowing location at meander part of Senio River

Figure 6.4 constitutes all the criticalities observed utilizing the post event orthophoto and post event DTM including bank erosion, possible piping signs, overflowing, and May 2023 event breaches for Sillaro and Senio River. However, some criticalities remain uncertain and cannot be definitively linked to specific mechanisms.

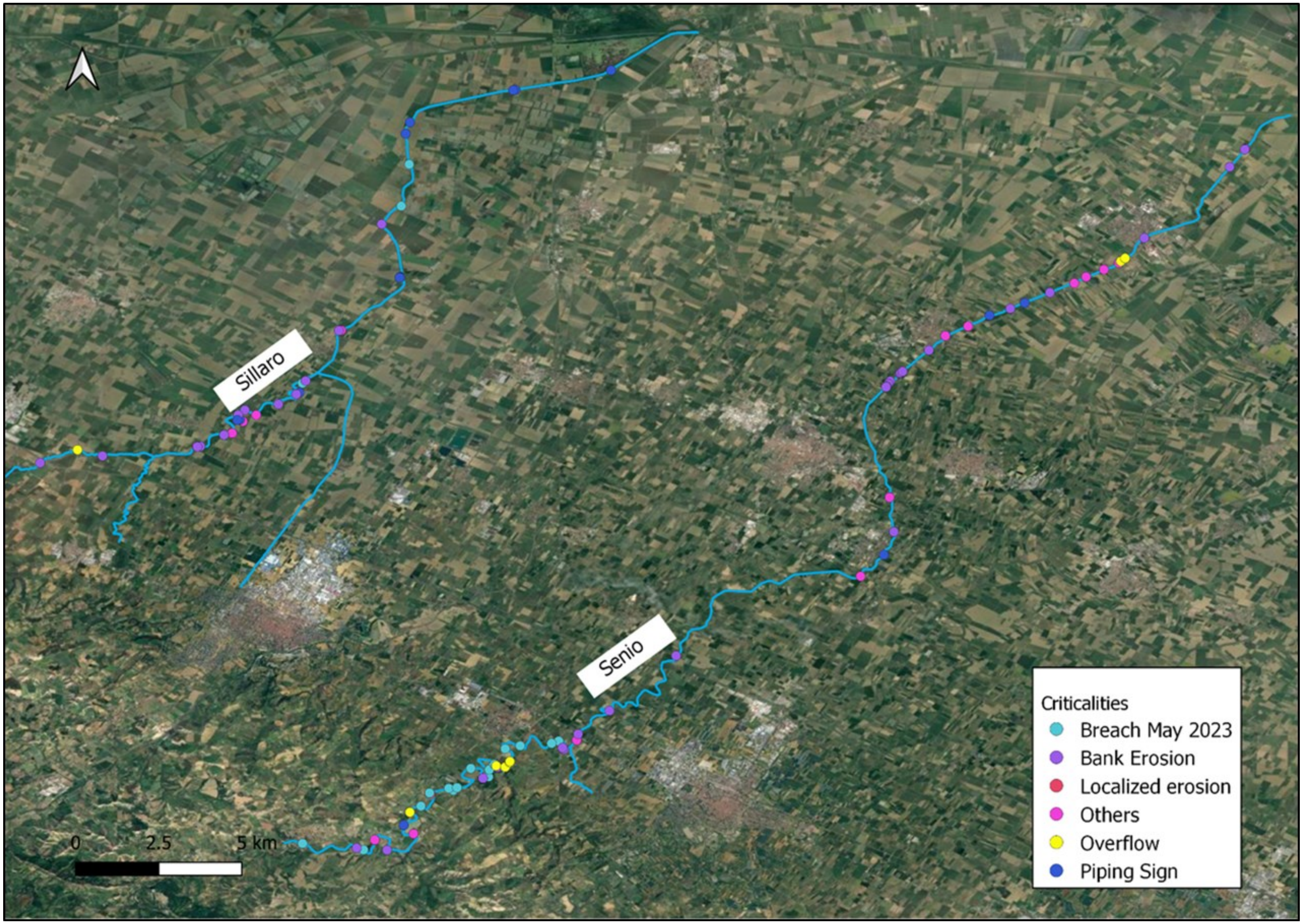

Figure 6.4: Observed criticalities utilizing Post-May 2023 event orthophoto for Sillaro and Senio rivers

6.2 HISTORICAL ANALYSIS

The historical analysis revealed significant shifts in the river channels over time. Paleo channels were identified, indicating previous river paths that have since changed. Figure 6.5 discerns the comparison of digitalized river channels obtained from georeferenced historical map of 1808 (yellow) with the current watercourse shape file (blue). On the west, Sillaro River exhibits significant shift of the channel course to the right side and indicates paleo channel upstream and on the confluence with Reno River downstream. While in the middle section of the river, more sharp meanders are observed as compared to the historical regime of the river, which indicates the dynamics changing nature of the river and possible critical location in terms of flood susceptibility. Eastwards, digitalized river channels for Senio river clearly illustrates that the river has evolved into significant dynamic change with sharp meanders to a long river reach upstream, which is prone to meander cutoff location during high flows causing damages to levees, ultimately breaches and inundation to the nearby land. A significant shift to the west as compared to the historical channel course can be observed as well with paleo channel to right on the upstream section while the downstream part of the channel seems to not have changed much, small shift may be due to georeferencing error.

These findings were corroborated by the geomorphological map overlay, which helped in identifying old breaches, creaverse splay along the evolution of the river course and affirms that the existence of the paleo channels aligns with the finding of historical maps. While also explaining that many of these paleo channels correspond with distinct geological features, suggesting a strong influence of the underlying geology on river dynamics. Relating historical evidences with current criticalities helped in identifying patterns and possible potential vulnerable location for future flood susceptibility and levee safety.

6.2.1 Coronella Identification: Indicators of Historical Breaches

The identification of coronellas, which indicate historical breach locations, plays a significant role in understanding flood susceptibility. These features, often appearing as linear depressions or subtle curvilinear patterns in the landscape, are not merely remnants of past embankment failures or intentional breaches. Their presence signifies areas with a persistent vulnerability to breach events, which is beneficial for contemporary flood susceptibility assessments. Coronellas are potentially critical because they reveal locations where the landscape has repeatedly failed to contain floodwaters, suggesting an inherent weakness or susceptibility in these areas. Mapping these historical breach sites is essential, as they can aid in assessment of potential future vulnerable locations. By mapping coronellas alongside other critical indicators, this analysis provides a more comprehensive understanding of flood dynamics and vulnerability in the region. Figure 6.6 exhibits the identification of a coronella along the Sillaro watercourse.

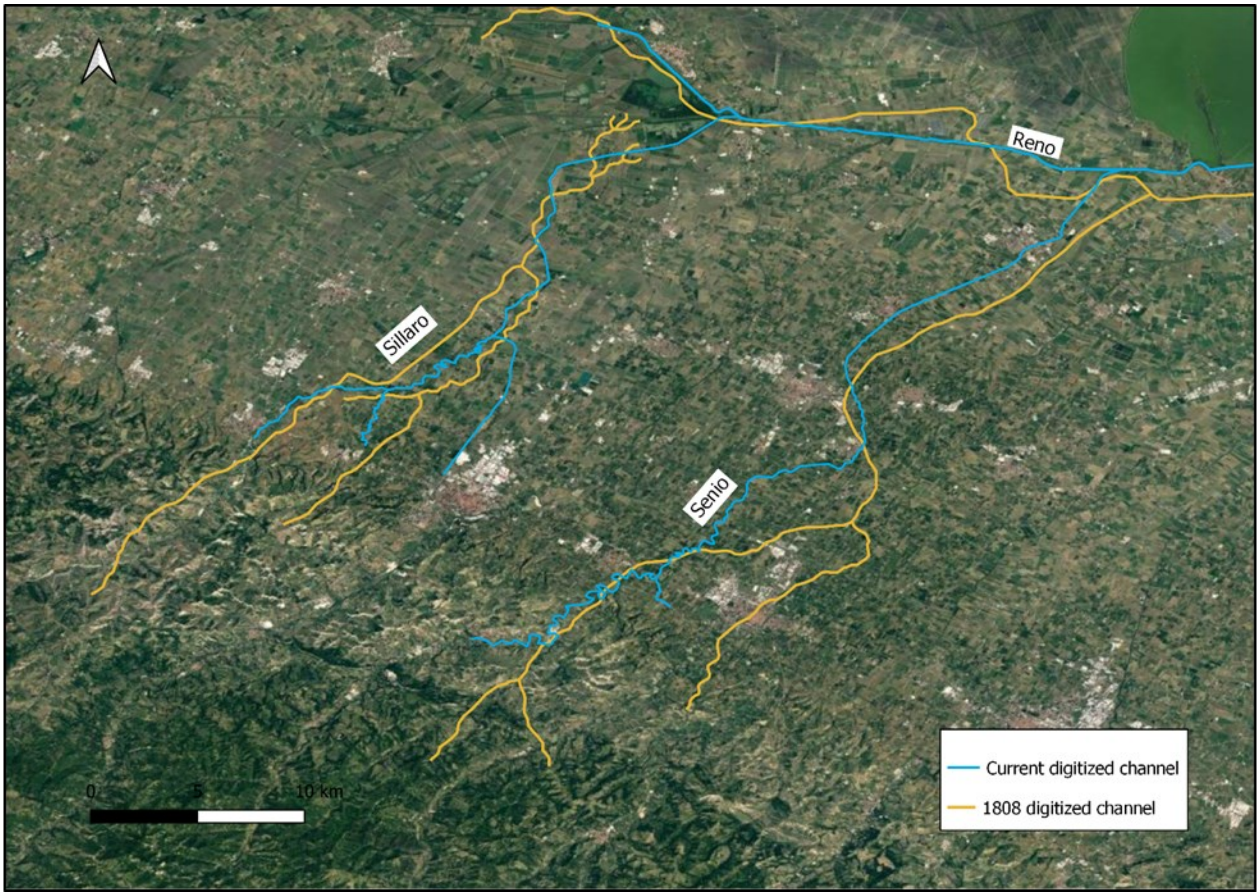

Figure 6.5: Comparison of digitalized river channels of Sillaro and Senio rivers from 1808 map (yellow) and current watercourse (blue)

Figure 6.6: Presence of Coronella along the Sillaro watercourse

6.3 SINUOSITY ANALYSIS

Sinuosity, a fundamental parameter in fluvial geomorphology, quantifies the degree of meandering exhibited by a river channel. It is an essential indicator of river dynamics, reflecting the intricate interplay between sediment transport, channel morphology, and hydraulic forces. The analysis of sinuosity provides invaluable insights into the geomorphological processes shaping the Romagna Plain's fluvial systems and offers critical information for assessing flood susceptibility in this region. The sinuosity analysis for the Sillaro and Senio Rivers involved the delineation of river channels and their respective valleys, followed by the calculation of sinuosity indices using Geographic Information System (GIS) tools. The derived sinuosity maps reveal spatial variations in the river courses, reflecting both natural processes and anthropogenic influences that have shaped the current riverine landscapes.

The sinuosity indices derived from the analysis of the extent of Sillaro and Senio Rivers under consideration highlight significant variations in channel meandering across different segments of the rivers. In particular, the relative upstream sections of both rivers extents under consideration characterized by milder gradients, exhibit higher sinuosity values, indicating pronounced meandering depicting lower river energy and sediment deposition. Conversely, as the rivers progress downstream near the confluence with Reno river, particularly in the plains where there is more anthropogenic interaction (i.e. channel strengthening, levee construction), the channels lose their sinuosity, indicative of relatively straighter channels with limited lateral migration.

The Senio River, traversing relatively narrow area in its comparative upstream reaches exhibits a high sinuosity index (close to 2.2-2.5), indicative of a markedly meandering course shaped by the dynamic interplay of geomorphic and bedrock influences. However, as the river propagates into the more downstream plains near confluence, its sinuosity decreases substantially (down to 1.02-1.05 in certain sections), reflecting a transition to a more subdued fluvial environment where lateral channel migration is minimized. The Sillaro River exhibits a comparable pattern, with corresponding high sinuosity in its considerable upstream reaches giving way to straighter channels as it nears its confluence with the Reno River, underscoring the influence of anthropogenic interactions on channel morphology.

The identified sinuosity patterns have direct implications for flood susceptibility in the Romagna Plain. High sinuosity areas, particularly in the upper reaches of both rivers extents under consideration, are often associated with increased flood risk due to the potential for channel avulsion and meander cutoff, which can lead to rapid changes in flow paths and localized flooding. The meander belts identified through the sinuosity analysis correspond closely with the areas historically affected by flooding particularly for Senio River (as apprised by the regional authorities during site investigation), underscoring the critical role of channel morphology in flood dynamics.

Moreover, the areas where sinuosity is rapidly increasing or where sharp bends are observed are particularly vulnerable to bank erosion and meander migration during high flow events. Such areas are likely to experience significant geomorphological changes during floods, contributing to the reactivation of old channels and the creation of new flow paths, thereby exacerbating flood risks. This understanding is pivotal for informing flood management strategies, as it highlights the need to monitor and possibly intervene in these high-susceptibility zones to mitigate flood impacts. Figure 6.7 and 6.8 discerns the sinuosity map of Sillaro and Senio rivers.

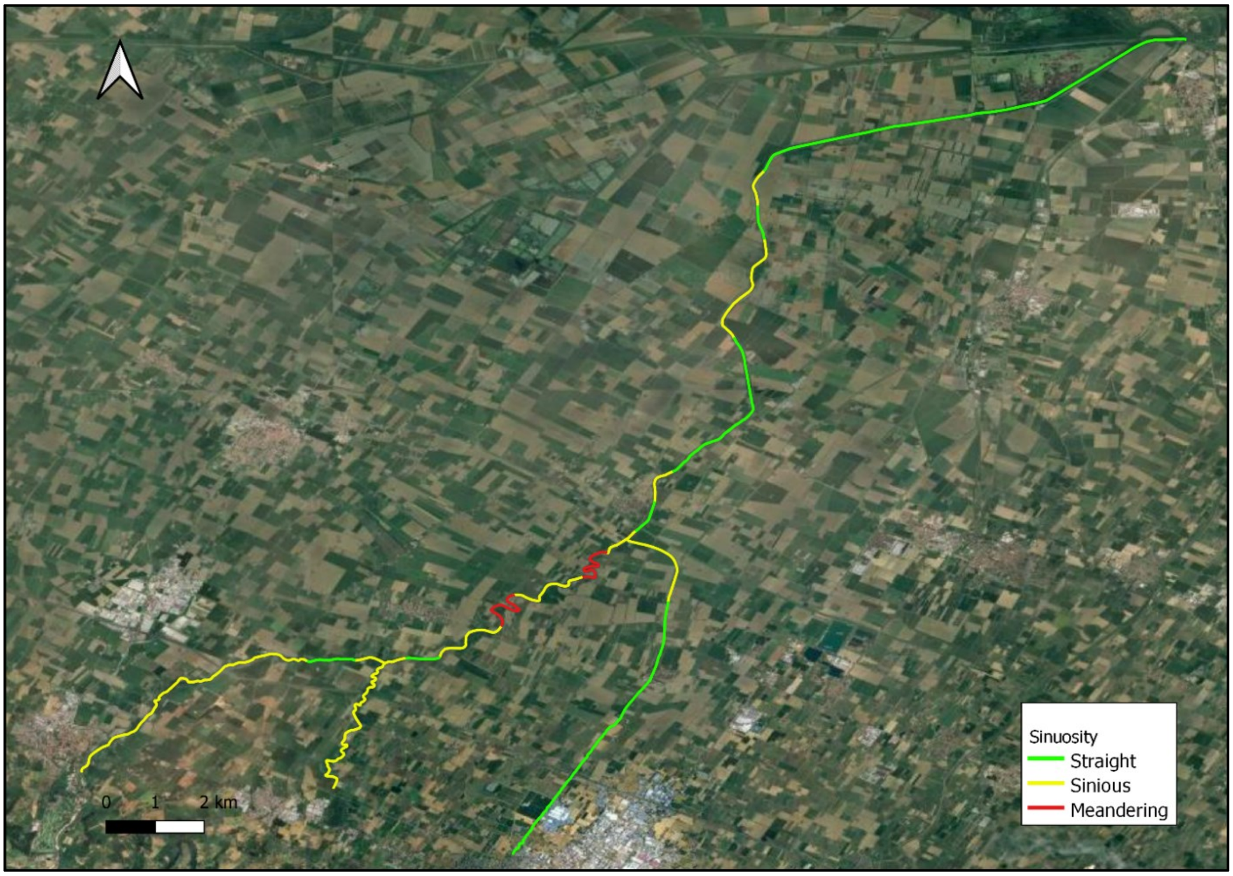

Figure 6.7: Sinuosity map of Sillaro River

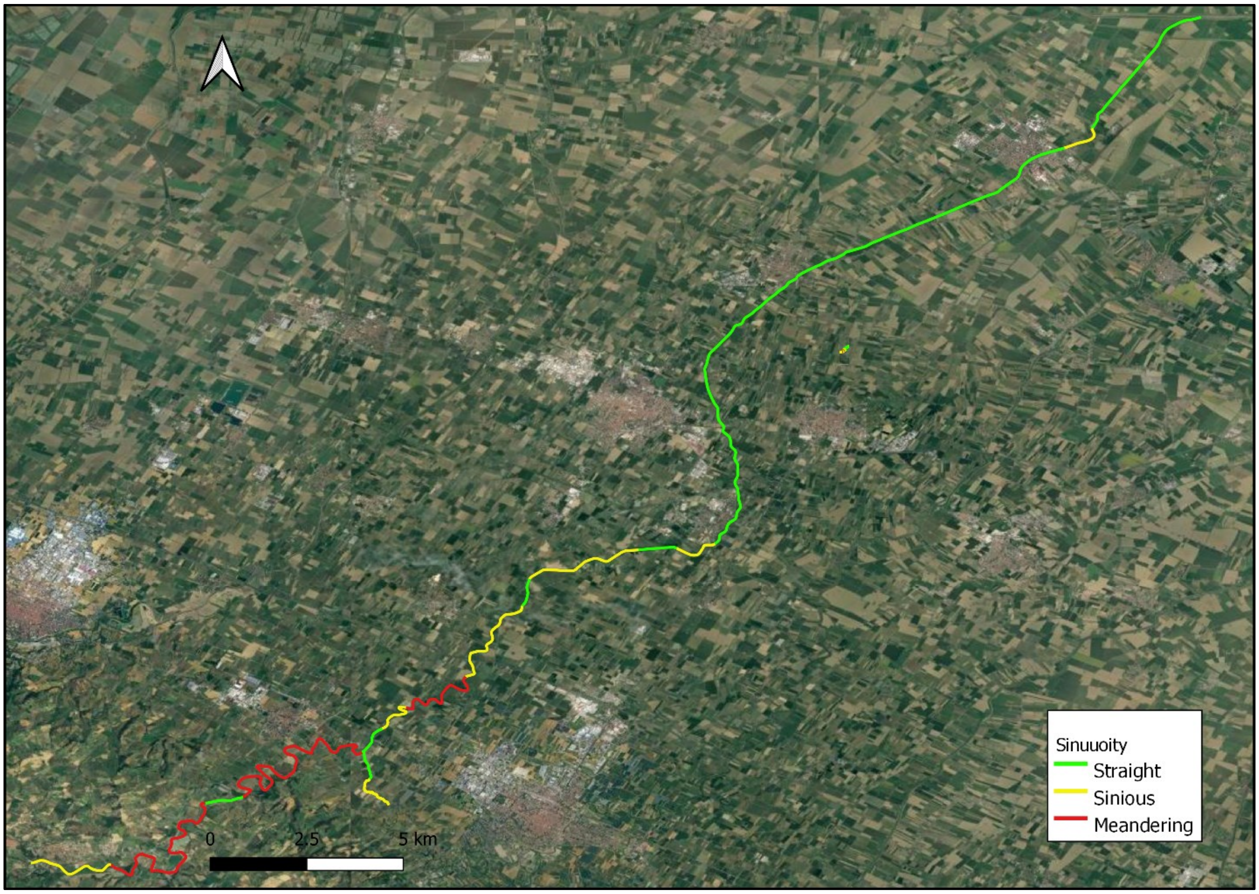

Figure 6.8: Sinuosity map of Senio River

6.3.1 High Sinuosity: Potential Meander Cutoff Regions

Drawing upon sinuosity analysis and the interpretation of riverbank characteristics, potential meander cutoff regions are deduced, where the natural course of the river may be altered in future flood events. These locations are identified based on the alignment and curvature of the river, with particular attention to areas where the river is actively eroding its outer banks while depositing sediments on the inner banks. The identification of these locations is critical for predicting future changes in river morphology and for implementing preemptive flood management measures.

Figures 6.9 and 6.10 illustrate the regions where potential meander cutoffs may occur in the Sillaro and Senio Rivers, respectively. The sinuosity analysis reveals a high sinuosity index, in these sections, predominantly > 2.5, while the riverbank digitization analysis shows that the banks within these meanders are progressively migrating toward the embankments. Furthermore, post-event orthophotos reveal evidence of erosion, piping and overflow in the highlighted river sections. Collectively, these indicators suggest areas of potential critical concern.

Figure 6.9: Regions vulnerable to cutoffs, Sillaro River

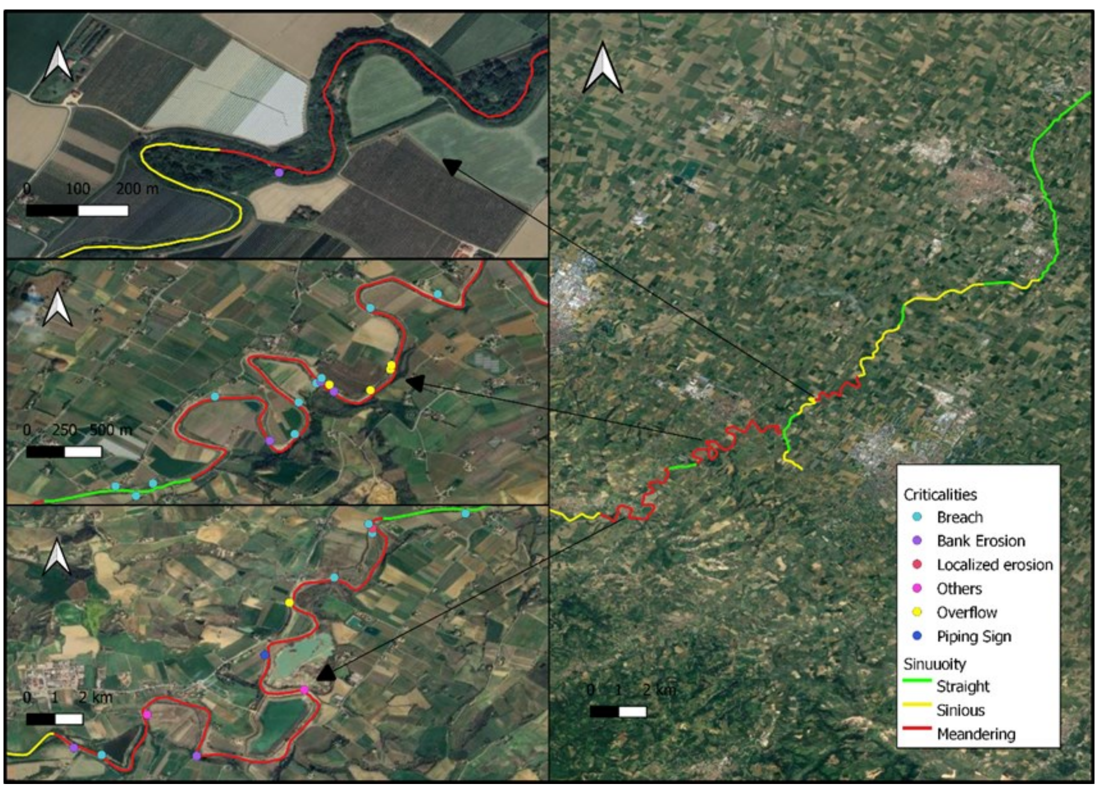

Figure 6.10: Regions vulnerable to cutoffs, Senio River

6.4 RIVER BANK EXPANSION AND CONTRACTION

The geomorphological processes of riverbank expansion and contraction play a pivotal role in shaping the floodplain dynamics and have significant implications for flood susceptibility, especially in regions like the Emilia Romagna. Understanding these processes is crucial for identifying potential criticalities in flood management and land use planning.

Riverbanks are dynamic features, constantly reshaped by the interplay between sediment transport, water flow, and the underlying geology. Over time, these banks may experience periods of expansion and contraction due to natural and anthropogenic influences. The meandering nature of rivers, especially in alluvial plains such as the Romagna Plain, exacerbates these changes, with the outer bends of meanders typically experiencing erosion (expansion), while the inner bends undergo deposition (contraction).

The analysis conducted as part of this thesis, utilizing orthophotos from 2008 and 2020, reveals significant insights into the spatial and temporal variations in riverbank positions. By comparing the historical and recent orthophoto, it is evident that the riverbanks in the study area have undergone noticeable shifts, with prominent patterns of expansion and locally contraction observed, particularly in the meander sections of the river.

The expansion of riverbanks is most pronounced in the outer bends of meanders, where the velocity of water flow increases, leading to higher rates of erosion. This process is driven by the centrifugal force that pushes water towards the outer bank, resulting in the scouring of bank materials and subsequent bank retreat. The orthophoto analysis between 2008 and 2020 demonstrates that certain meander bends have expanded significantly (up to 5m), with the erosion rates varying depending on the local geomorphological conditions and land use practices. The identification of these expansion zones is critical for flood management. Expanded banks often indicate areas of high energy where the river has the potential to breach during flood events, increasing the risk of flooding in adjacent areas. Moreover, the ongoing expansion could lead to the reactivation of old meanders, altering the hydrological network and potentially exacerbating flood hazards.

Contrastingly, the inner bends of meanders exhibit contraction locally, characterized by sediment deposition. As the water flow decelerates on the inner side of a bend, the reduced carrying capacity causes sediments to settle, gradually building up the riverbank. The orthophoto analysis reveals that at few places inner bends have experienced deposition, resulting in the somewhat tightening of the river channel in these areas. The contraction of riverbanks can have both positive and negative implications for flood susceptibility. On one hand, the buildup of sediments can raise the riverbed, reducing the channel's capacity to convey water and increasing the likelihood of overflow during high discharge events. On the other hand, the contraction process can lead to the stabilization of riverbanks, potentially reducing the lateral mobility of the river and limiting the extent of flood-prone areas.

The patterns of riverbank expansion and contraction observed in this study have direct implications for flood susceptibility. Areas experiencing bank expansion, particularly in the outer bends of meanders can pose a threat to levees as the river channel shifts towards the levee or embankments. Hence, should be prioritized for flood risk assessments and the implementation of erosion control measures. These areas are more susceptible to bank failure and river channel migration, both of which can significantly alter the flood dynamics of the region.

Figure 6.11 and 6.12 exhibits the digitalization of the riverbanks using the 2008 and 2020 orthophotos. Red color line represents the riverbanks digitalized from 2008 orthophoto while green color indicates the digitalized banks from 2020 orthophoto. The figures illustrate the area where meander migration towards the levees is observed and is particularly noticed in the meandering part of the river, which suggest that particularly Senio River have the tendency to move towards the meandering direction eroding the banks.

Between 2008 and 2020, the Sillaro River exhibited an average bank expansion of 2.5 meters, with the most significant increase of approximately 4.5 meters observed in the upstream section, identified as (b) in Figure 6.7. In comparison, the Senio River experienced more pronounced lateral migration; particularly around meander (a), the average expansion reached 5.5 meters. Significant lateral shift was recorded in section (b), with a maximum of 9 meters and an average expansion of 5 meters. Section (c) showed the most dynamic changes, with a maximum migration of 12 meters and localized shifts ranging from 6 to 8 meters, indicating a highly transitional area. Section (d) demonstrated a maximum lateral movement of 10 meters, with certain areas shifting by approximately 3.5 meters. However, these findings should be interpreted with caution, as digitizing riverbanks from orthophotos is inherently subject to errors, which may affect the precision of the measurements. Nevertheless, the analysis underscores considerable lateral migration and transformation of the Senio River's banks over the 12-year period.

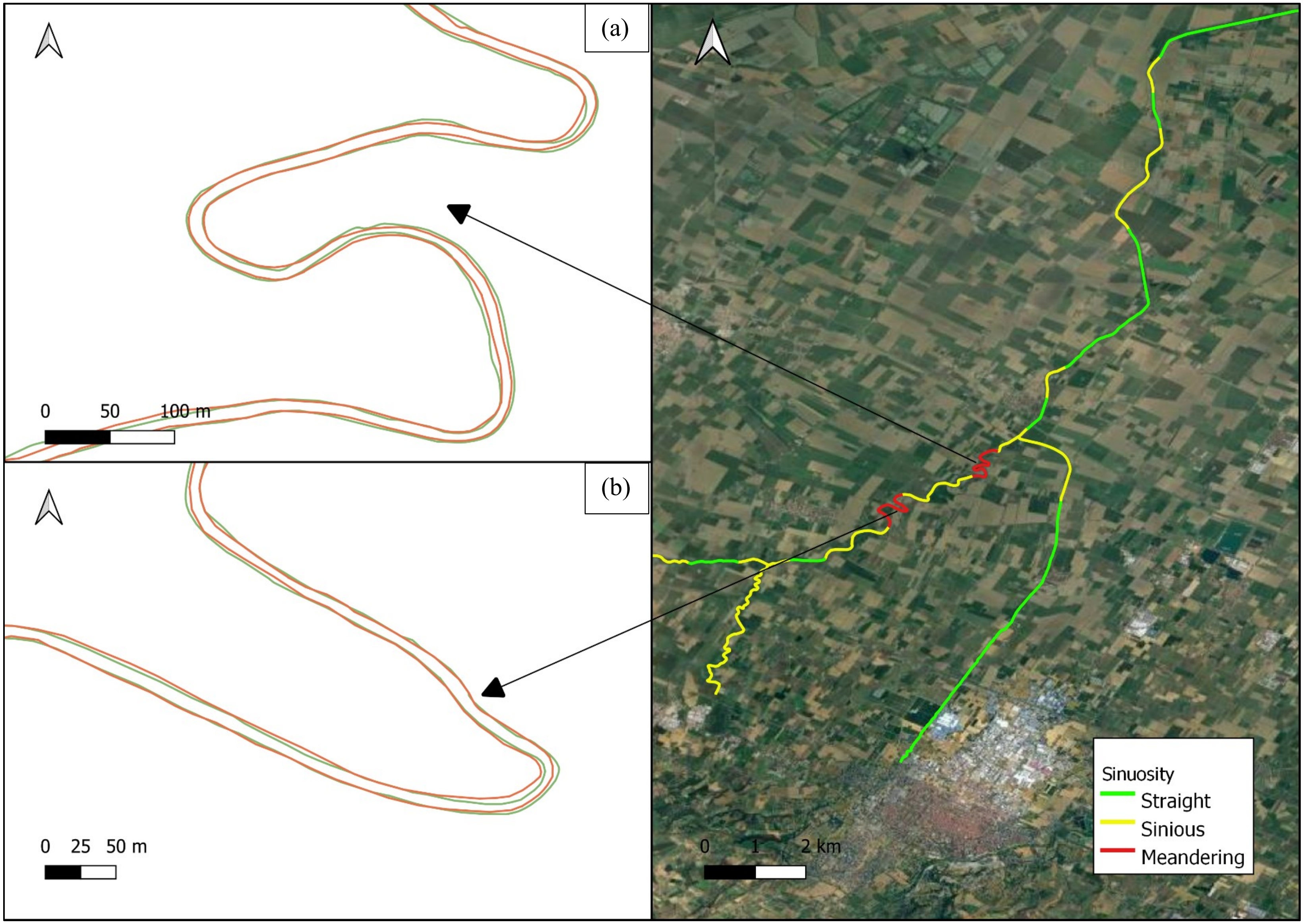

Figure 6.11: Comparison of digitalized riverbanks of Sillaro River from 2008 orthophoto (red) and 2020 orthophoto (green)

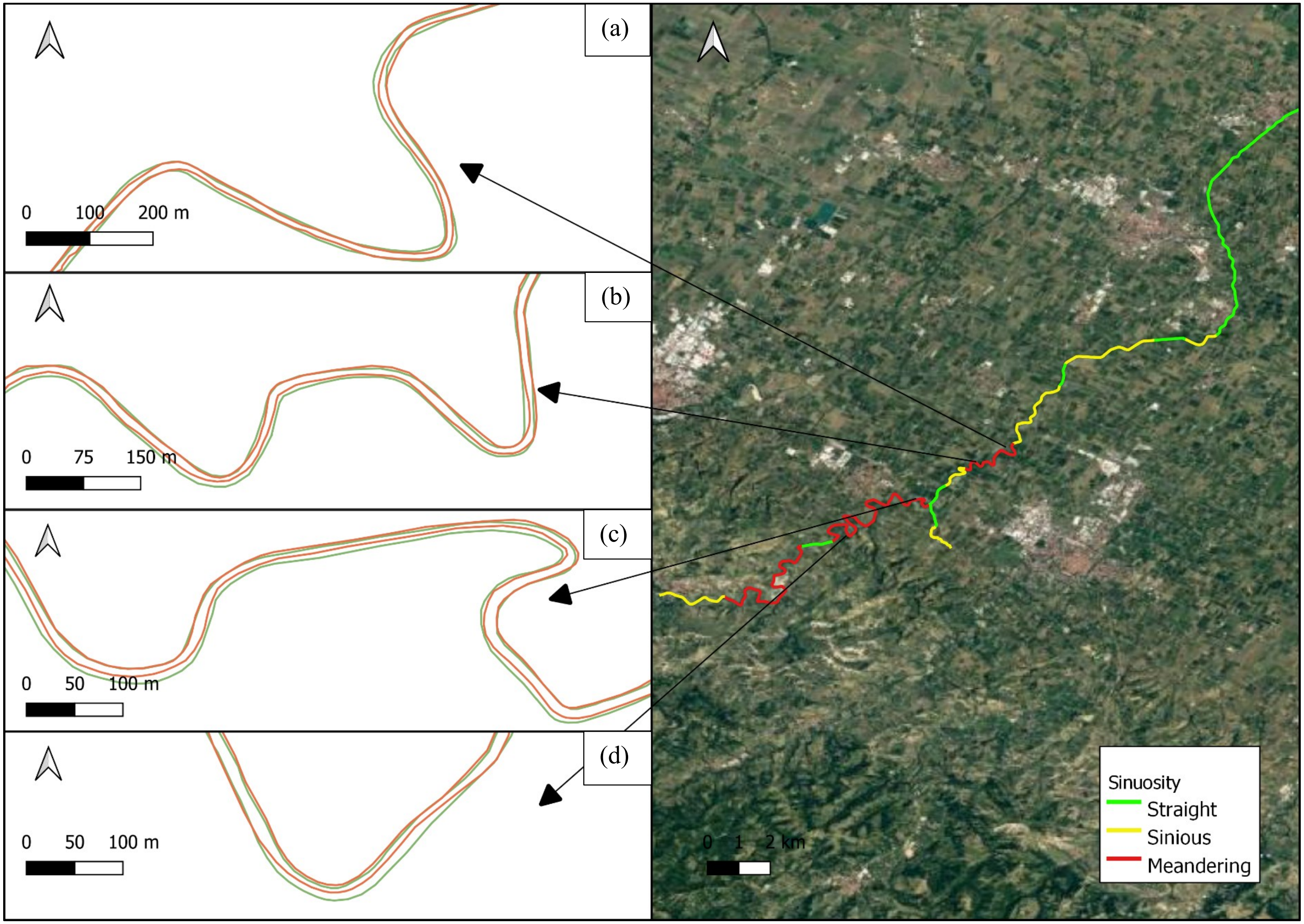

Figure 6.12: Comparison of digitalized riverbanks of Senio River from 2008 orthophoto (red) and 2020 orthophoto (green)

6.5 POTENTIAL FUTURE VULNERABLE LOCATIONS

The mapping of all identified criticalities onto a comprehensive map provides a holistic view of the flood susceptibility in the study area. This synthesis enables the identification of hotspots where multiple criticalities converge, thus highlighting areas of heightened flood susceptibility. The integration of historical and geomorphological insights with orthophoto analysis underscores the importance of a multidisciplinary approach in flood risk management, one that combines historical knowledge, landscape analysis, and modern imaging technologies. This section attempts to correlate identified criticalities with geomorphological findings and synthesizes the identified criticalities, groups them into key categories and discusses their implications for future flood events. By interpreting the spatial distribution of these criticalities, this study offers insights into potential future vulnerabilities and provides recommendations for targeted interventions.

Figure 6.13 discerns the geomorphological map overlaid with observed criticalities (bank erosion, piping sign etc) identified through post event orthophoto indicated by a point feature for Sillaro River. Area near point A indicates the presence of creaverse splay (location of an old breach or sign that at this location water flowed out of the channel). In addition, nearby signs of vegetation removal or a possible piping sign observed from post May 2023 event orthophoto indicating that this particular location may not been damaged or inundated in the recent event but is emphasized for consideration. Similarly, in the vicinity of point B and C, presence of creaverse splay can be observed and presence of Paleochannels are perceived as well. Moreover, in the region around point B, breach of Via di Dozza occurred during May 2023 event, which was mainly due to the rapid draw down in effect of the nearby breach at Via Merlo, there are indication of bank erosion perceived through post event orthophoto as well. Akin, in the area near point C, breach of Via del Tiglio occurred during the recent event and presence of coronella can be perceived with possible signs of irregularity or piping observed from post event orthophoto. These findings suggest the vulnerability of these locations for future flood susceptibility and levee safety.

As indicated in Figure 6.14, the analysis reveals a pronounced correlation between the geomorphological characteristics of the Senio River and the breaches observed during the May 2023 flood event. The majority of breaches were concentrated in the river's most sinuous sections, where the sinuosity analysis indicated heightened vulnerability (S.I > 2). Orthophoto assessments further substantiated these observations, identifying criticalities such as significant bank erosion and key overflow points, particularly in areas exhibiting pronounced lateral migration and bank expansion. The geomorphological complexities inherent in these meandering sections, including high curvature and bank instability, exacerbated the vulnerability, thereby undermining natural flood defenses and increasing the propensity for breaches. This intricate interplay between sinuosity, riverbank dynamics, and post-event criticalities underscores the necessity for more nuanced flood management strategies that specifically account for the geomorphological intricacies of the region.

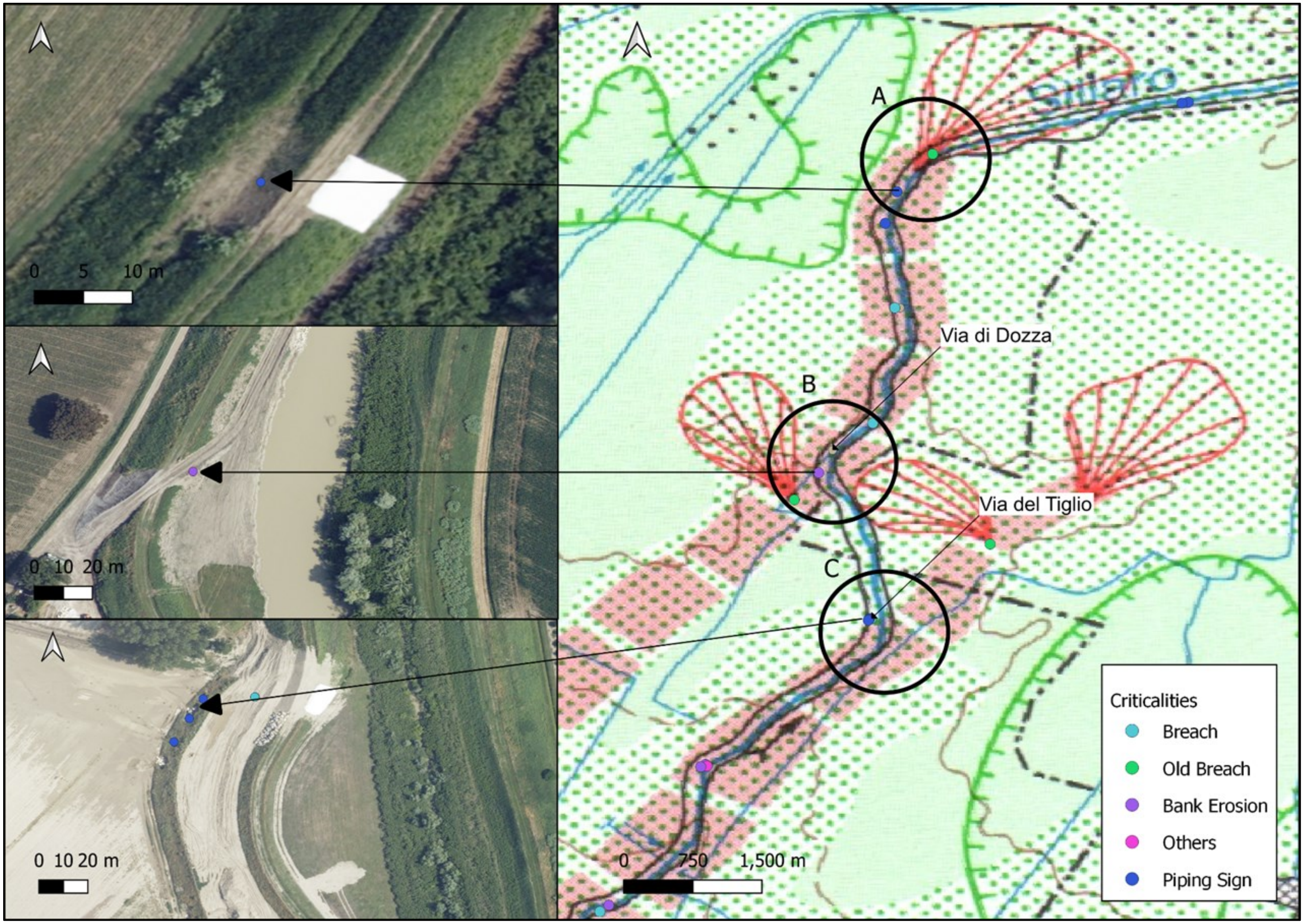

Figure 6.13: Geomorphological Map overlaid with criticalities observed from post May 2023 event orthophoto (Sillaro River)

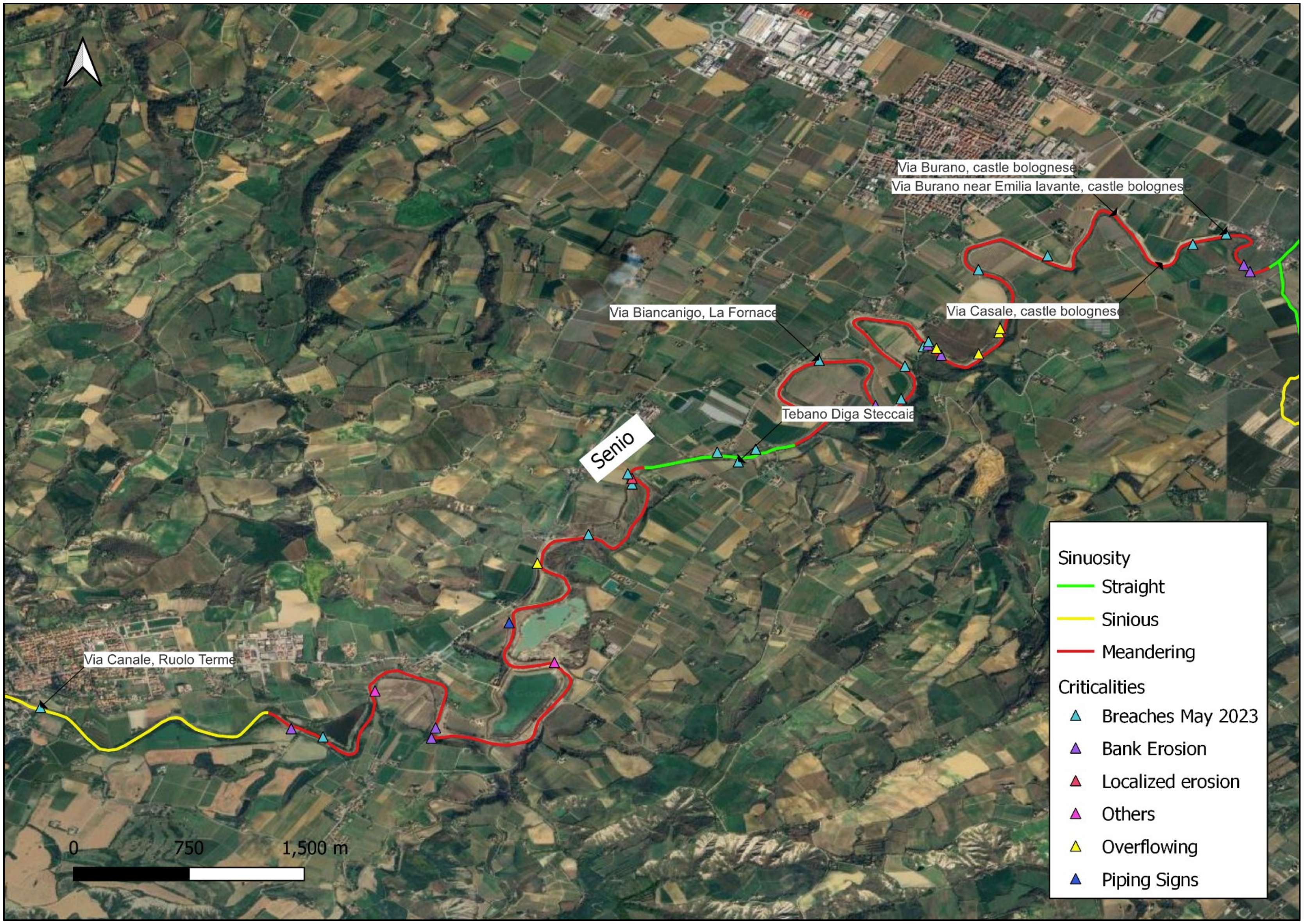

Figure 6.14: Observed criticalities in the meander part of Senio River

6.5.1 Geomorphological Evidences

The geomorphological analysis offers critical insights into the historical and ongoing processes that shape the floodplain and influence its vulnerability. The analysis revealed several indicators of potential future flood susceptibility. The identification of meander cutoff locations, for example, suggests areas where the natural river dynamics could lead to increased flood risk. The identification of paleo channels and the evidence of river channel shifts through historical analysis specify regions where the river has historically altered its course. These areas are inherently unstable, with a higher likelihood of channel migration during extreme events. Moreover, the presence of historical breach locations, identifiable through Coronella formations and crevasse splays evidenced through geomorphological map interpretation indicates zones with a predisposition to failure. These areas, having experienced breaches in the past, may have compromised levee integrity or other geomorphological weaknesses, making them susceptible to future failures. The mapping of such features, therefore, is essential in predicting where breaches are likely to occur again, especially under conditions of increased hydrological stress. Figure 6.15 discerns the mentioned criticalities group together as geomorphological evidences for Sillaro and Senio.

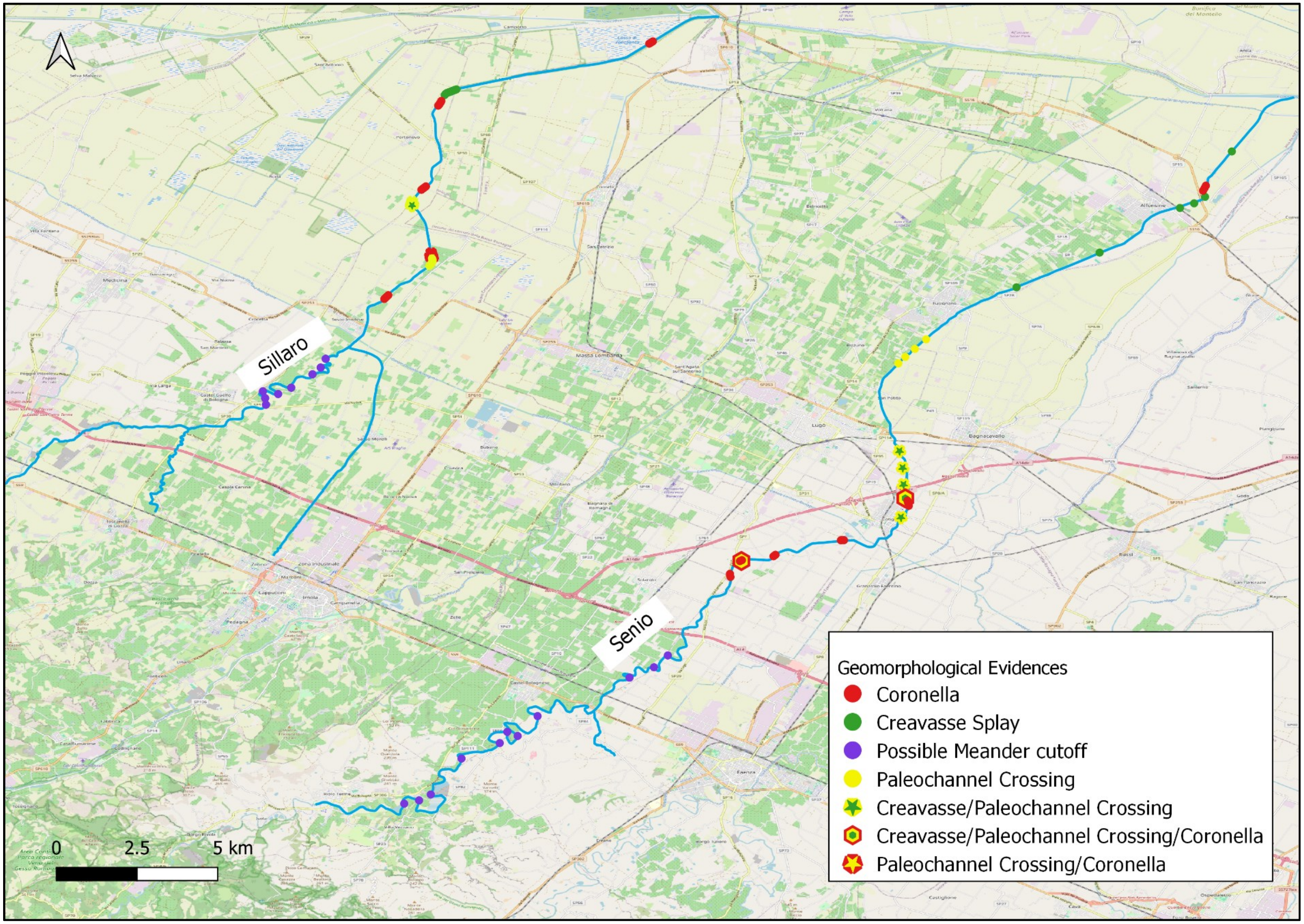

Figure 6.15: Geomorphological Evidences of criticalities for Sillaro and Senio Rivers

6.5.2 Criticalities Post-May 2023 Flooding

The criticalities observed during the May 2023 flood event provide empirical data on the areas that are currently vulnerable to flooding. These include instances of bank erosion, possible piping signs, overtopping events and May 2023 event breaches as grouped and presented in Figure 6.4. Bank erosion, in particular, is a significant indicator of potential future risk as it not only signifies areas where the riverbank is currently unstable but also highlights regions where further erosion could lead to catastrophic failures. Piping, another criticality identified, is a process where water seeps through levee embankments, leading to the formation of tunnels that can cause sudden and unexpected breaches. Moreover, Overtopping locations are also of critical concern. Areas where water levels exceeded the height of the levee during the 2023 flood suggest that the current levee heights may be insufficient to contain future flood events, particularly if climate change leads to more intense and frequent flooding. Mapping these features is thus crucial for anticipating potential breach locations, particularly in scenarios of heightened hydrological stress.

6.5.3 Interfering Structures

Infrastructural elements, particularly bridges and other man-made hydraulic interventions, play a critical role in influencing flood dynamics, often acting as both points of resistance and vulnerability. Orthophotos reveal instances, such as in Porto Novo, where bridges have either withstood or exacerbated flood impacts, highlighting their dual role. Structural damage to bridges, including scouring around abutments and partial collapse during past events, emphasizes the need for consideration. Additionally, these orthophotos document current breaches, visually capturing locations where flood defenses have failed, leading to the unchecked spread of floodwaters. The analysis further identifies several structures that interfere with the natural river flow and the integrity of levee systems, potentially weakening overall flood defenses. These intersections with levee bodies create points of vulnerability where water may breach during flood events, underscoring the importance of addressing these structures. Figure 6.16 pinpoints the locations of such interferences along the rivers under study, reinforcing the need for consideration on the subject.

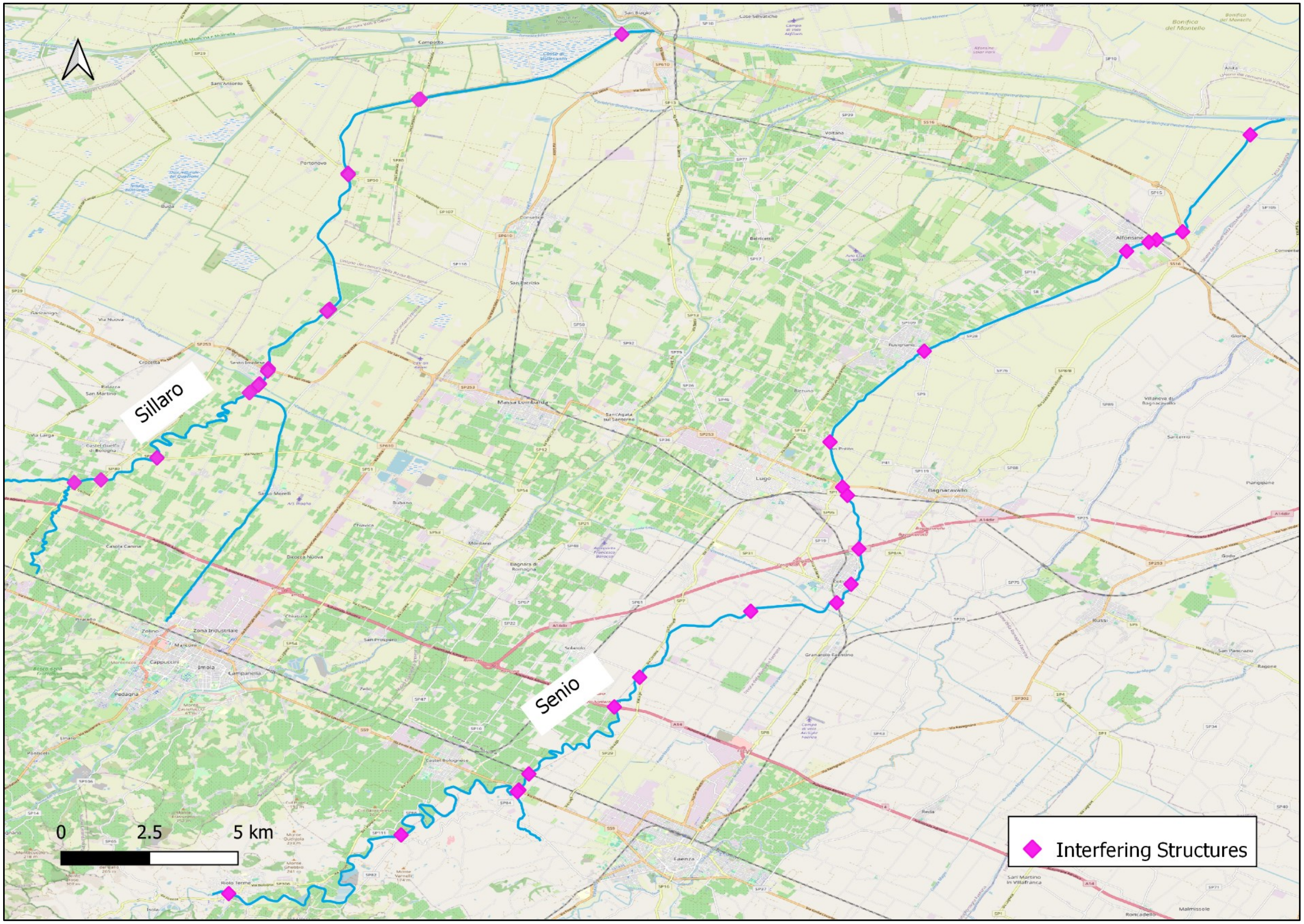

Figure 6.16: Interfering structures observed along the course of Sillaro and Senio Rivers

6.5.4 Synthesis and Future Implications

The integration of historical and geomorphological evidences, observed criticalities post the May 2023 floods, and the analysis of interfering structures provides a comprehensive understanding of the potential future vulnerable locations within the study area of Romagna Plain. The synthesis of these factors into a composite susceptibility map allows for the identification of high-risk areas where multiple criticalities converge, suggesting that these locations should be prioritized for intervention. For example, areas where historical breaches coincide with current piping signs and nearby interfering structures represent zones of heightened vulnerability. The mapping also reveals potential future meander cutoff locations that, if left unaddressed could lead to significant changes in flood dynamics. While it is crucial to recognize these areas for informed land use and management, interventions should not aim to restrict natural river dynamics. Instead, understanding these geomorphologically significant points can guide adaptive strategies that work with, rather than against, the natural processes of the river system.

The findings emphasize that effective land use and management, alongside the strategic strengthening of levees, the management of interfering structures, and careful monitoring of geomorphological changes, are essential for reducing the flood susceptibility of the Plain. By proactively addressing these vulnerabilities, the targeted interventions in the identified critical zones could significantly reduce the likelihood of future flood events, thereby protecting both the natural environment and the human settlements. The ongoing monitoring of these critical locations, combined with adaptive management strategies, will be crucial in ensuring the long-term resilience of the region. By consolidating all the potential criticalities, probable zones of elevated susceptibility where multiple critical factors converge and can pose threat to levee integrity based on the integrated analysis, which are synthesized and highlighted in figures 6.17 and 6.18 for Sillaro and Senio Rivers respectively.

Figure 6.17: Synthetic flood susceptibility map of Sillaro River

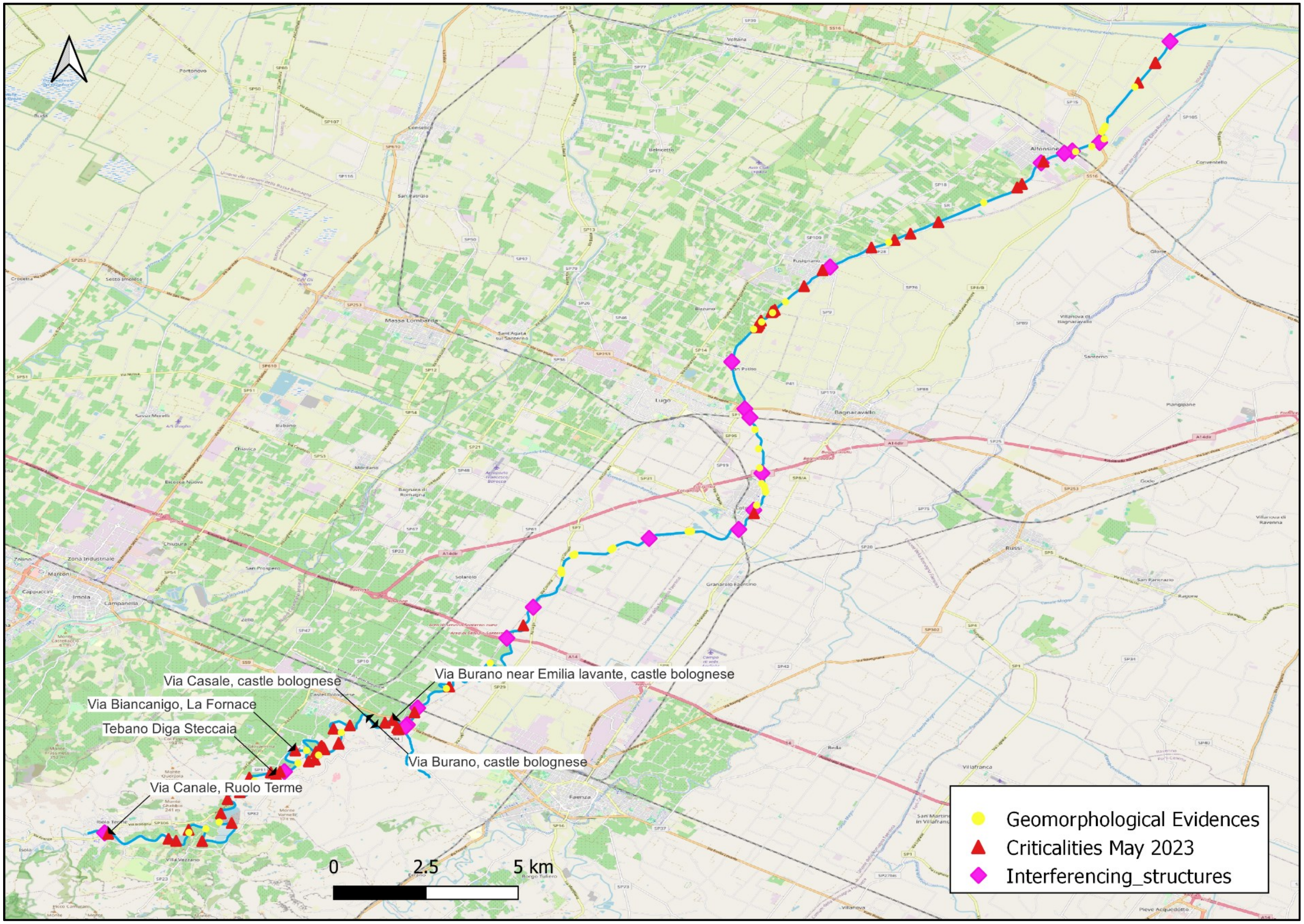

Figure 6.18: Synthetic flood susceptibility map of Senio River

6.6 LAND SUBSIDENCE IN EMILIA ROMAGNA

Emilia-Romagna, located in northern Italy is characterized by diverse landscapes, including the Apennine Mountains and the fertile Po Valley. The region is prone to both land subsidence and flooding, which have historically caused significant damage. The land subsidence in the region is due to a combination of natural factors (sediment consolidation and tectonic activity) and anthropogenic factors (groundwater pumping and gas production) [23]. Over the last century the Emilia-Romagna coastland, south of the Po River delta has been affected by a widespread land subsidence of both natural and anthropogenic origin. Anthropogenic land settlement dramatically increased after World War II primarily because of groundwater pumping and subordinately gas production from a number of deep onshore and offshore gas reservoirs [23]. The groundwater pumping has led to a significant decline in the water table and the resulting compaction of the aquifers, leading to land subsidence. The analysis and monitoring of the subsidence is critical to evaluate its causes and effects on the region's vulnerability.

6.6.1 Land Subsidence and Flood Susceptibility

Land Subsidence rates in the Po plain ranges from 0 to 70 mm/year, the maximum occurring in synclinal areas at the Po Delta and near Bologna, the minimum located at the top of buried, probable tectonically active anticlines (Mirandola – Ferrara). Modern subsidence is at least an order of magnitude higher than due solely to long-term natural processes. This implies that most subsidence in the Po Plain has been induced by human activities. The main factor controlling modern subsidence is water withdrawal, which was particularly intense during the second half of the 20th century, coinciding with accelerating economic growth. On evaluating the impact of rapid subsidence on floods in low areas by comparing subsidence velocity maps with flood maps, it showed that there is a clear-cut correlation between flood frequency and rapid subsidence. In contrast, few floods occurred in low subsidence areas, which generally correspond with the top of buried anticlines [24].

A Research conducted by (Carminati and Martinelli, 2002) [24] stated modern vertical velocities (in mm/year) for the Po Plain and are shown in Fig 6.19 based on regional data sources. Negative and positive velocities indicate subsidence and uplift rates, respectively. Subsidence rates range from about 0 to 70 mm/year. The maximum subsidence rates (up to 60 –70mm/year) occur in two general areas: the Po Delta, east of Rovigo, and the zone north of Bologna (Fig.6.19). These areas are separated by low subsidence (10mm/year) in the form of a ''saddle'' centered around the town of Ferrara.

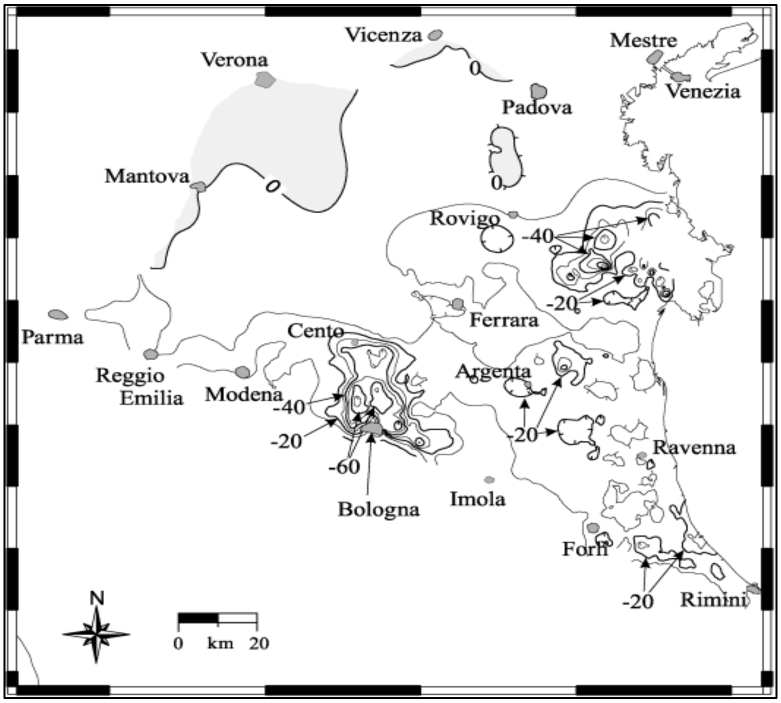

Figure 6.19: 2002 Vertical velocities in (mm/year), Negative and positive velocities indicate land subsidence and uplift, respectively [24]

Carminati and Di Donato (1999) have determined the natural subsidence rates in the Po Plain by stratigraphic analysis of commercial well data and by geodynamic modelling. The main components of natural subsidence in the Po Plain are tectonic loading, sediment loading, sediment compaction (Sclater and Christie, 1980) and post-glacial rebound (Mitrovica and Peltier, 1991). Carminati and Di Donato (1999) estimated the subsidence rate is up to- 2.5 mm/year, with the largest rates (greater than -1mm/year) occurring in the southern part of the Po Plain and in the Po Delta as shown in Fig 6.20.

(Carminati and Martinelli, 2002) [24] Also stated the difference (Fig. 6.21) between present-day subsidence (Fig. 6.19) and the long-term geological subsidence (Fig. 6.20) which provides a measure of the anthropogenic influence in regional and local subsidence rates. A comparison between Figs. 6.21 and 6.19 shows that they are almost identical, mainly because contemporary and natural subsidence rates differ by more than one order of magnitude. Accordingly, most subsidence in the Po Plain is of anthropic origin.

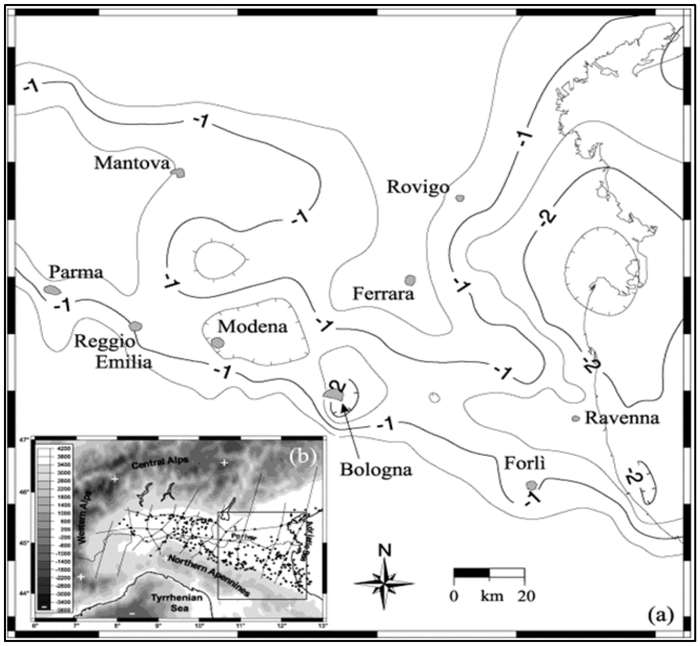

Figure 6.20: (a) Long-term geological subsidence rates (in mm/year) redrawn by Carminati and Di Donato (1999). (b) Filled circles identify wells used to calculate regional subsidence averaged over the last 1.43 Ma. Well data were integrated with sediment thicknesses measured on published seismic lines (thin lines). The grey scale indicates the elevation (in m) [24]

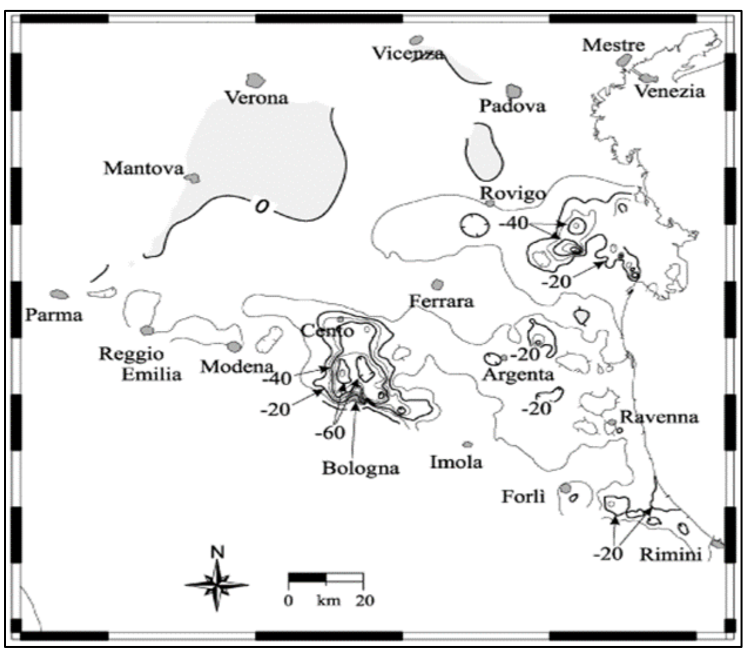

Figure 6.21: Difference (in mm/year) between modern (Fig. 6.19) and long-term geological subsidence (Fig. 6.20). The resulting subsidence rate is the anthropogenic component of vertical motion [24].

(Carminati and Martinelli, 2002) [24] Also noted two particular societal impacts of subsidence in the Po Plain: the need for recognition and planning especially in the coastal areas in the Po Delta area, and the increase of regional flooding. The coastal area is particularly impacted by accelerated subsidence; roads and canals are destroyed, infrastructure is inherently affected and even large and historical cities are subject to increased frequency and magnitude of tidal and storm surges (Carbognin et al., 1990). The societal impact of floods in the Po Plain is documented by Fig. 6.22, which shows a column on which the levels reached by floods in Ferrara during the past three centuries have been recorded. The increase with time of flood levels shows a sharp acceleration during the 20th century. It was noted that the accelerated subsidence often gives rise to more frequent flooding in low-lying areas. For example, total subsidence (Fig. 6.23) is calculated that occurred in the Po Plain since 1897 until 2002. Fig. 6.23 shows that up to 3 m of subsidence occurred near Bologna and in the Po Delta area. Intuitively, these rapidly subsiding areas now have a higher flood risk. This is borne out by the increased floods that occurred during the 20th century shown in Fig. 6.24 based on data collected by ‘‘CNR Gruppo Nazionale per la Difesa dalle Catastrofi Idrogeologiche,’’ from local administration archives and from press archives (CNR-GNDCI, 2000). The apparent correlation between accelerated subsidence and historical floods is striking. The only non-flooded areas (identified by A and B in Fig. 6.24) overlie buried active anticlines. Area ‘‘C’’ was probably not flooded owing to the presence of local drainage channels. Floods during the first half of the 20th century were relatively limited in area (Fig. 6.25). However, with accelerated groundwater pumping and subsidence in the second half of the century, flooding increased in both magnitude and frequency. Hence, underscoring the essentials of incorporating land subsidence analysis in flood susceptibility mapping in the Emilia Romagna region. This suggested holistic approach ensures that flood susceptibility maps reflect both static topography and dynamic ground-level changes, leading to more effective and resilient flood management plans.

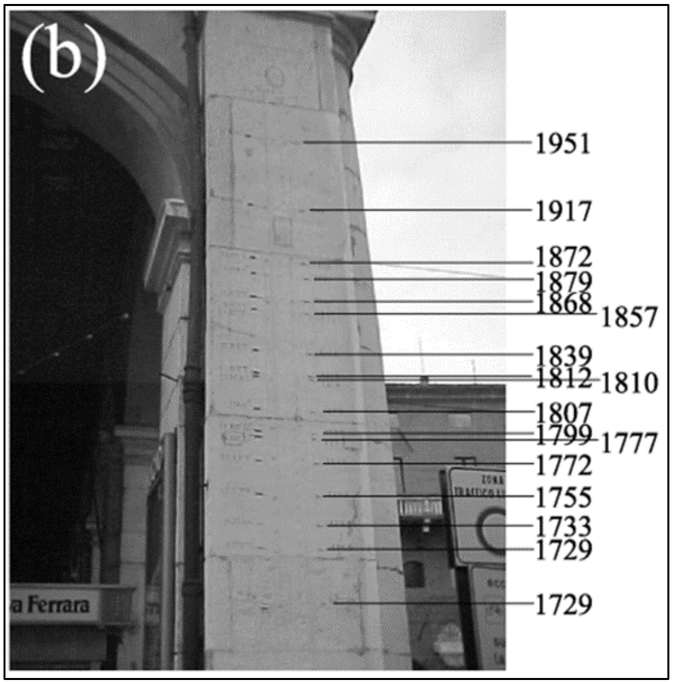

Figure 6.22: The column located in the center of Ferrara shows the levels (increasingly higher with time) reached by floods in Ferrara during the past three centuries [24].

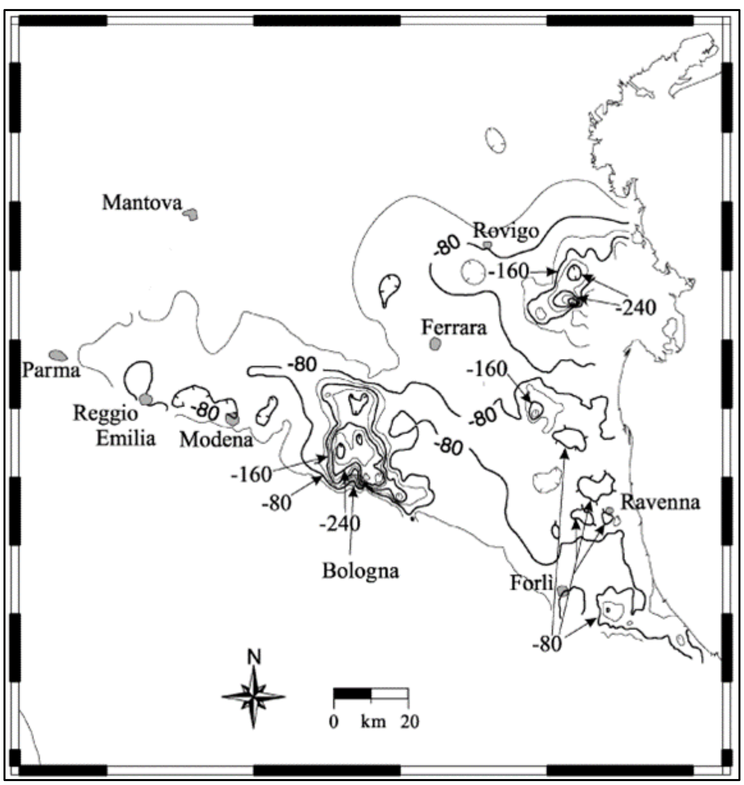

Figure 6.23: Absolute subsidence (in cm) in the Po Plain area since 1897 until 2002 [24].

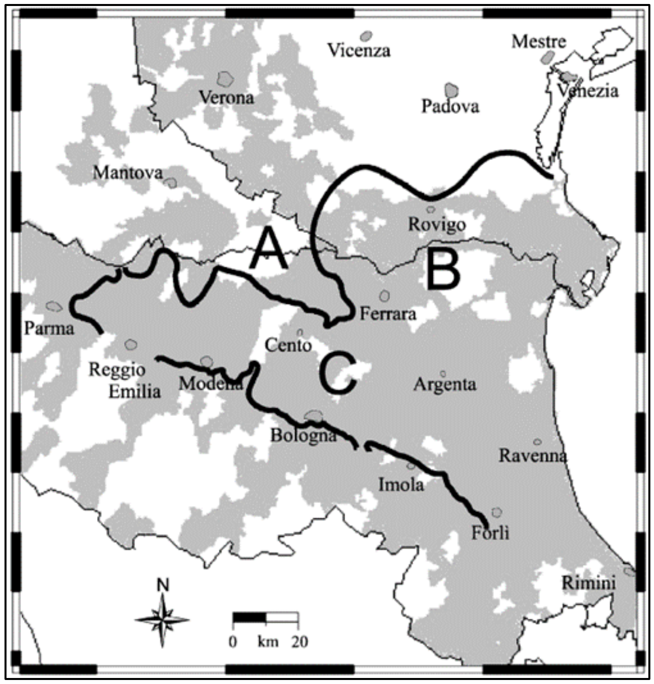

Figure 6.24: Distribution of towns and villages affected by at least one main flood in the 20th century. The thick lines define areas affected by at least 80 cm of subsidence (fig. 6.23) [24].

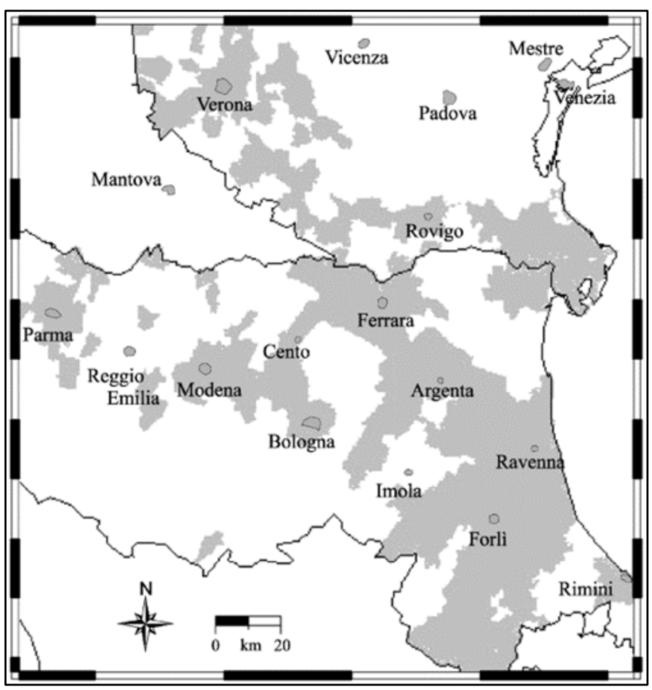

Figure 6.25: Distribution of towns and villages affected by at least one main flood between 1900 and 1950 [24].

7 CONCLUSIONS

The May 2023 flooding in the Emilia-Romagna region serves as a stark reminder of the increasing vulnerability of both natural and human-engineered systems to high magnitude events. It emphasized the need for an integrated approach that combines infrastructural resilience with advanced geomorphological and remote sensing analyses. This thesis explored the multifaceted nature and complex dynamics of flood susceptibility in the region, addressing the vulnerabilities of critical infrastructure, the importance of geomorphological and sinuosity analyses, the role of post-event orthophoto assessments and the value of historical analysis in identifying critical zones for intervention.

A key finding of this research is the integration of geomorphological analysis including river sinuosity into flood susceptibility assessment, which emerged as a critical aspect of this venture. The sinuosity analysis revealed how variations in river meandering patterns can influence flood susceptibility, with highly sinuous sections (S.I > 2) being particularly prone to cutoffs, overflow and ultimately breaches during high flow events. Understanding these dynamics is crucial for predicting areas of heightened vulnerability. In this research, an attempt was made to correlate the areas most affected by the 2023 floods with historical and geomorphological features attained by interpretation of historical and geomorphological data, such as Paleochannels crossing and presence of crevasse splays and coronellas. The historical analyses further demonstrated that the Sillaro and Senio rivers have developed more pronounced meandering courses, particularly in their upstream sections, where they have also undergone significant contraction. These findings suggest that a deeper understanding of the geomorphological history of a region can provide valuable insights into current and future vulnerable zones. Thus, offering a powerful tool for enhancing susceptibility assessments.

Moreover, the historical analysis of river geomorphic dynamics utilizing GIS tools presented in this thesis, offers a comprehensive long-term perspective on flood susceptibility in the region. By digitalizing and tracing changes in river courses and examining patterns of riverbank migration (expansion > 8 meters in some section of Senio River), this assessment highlights the zones where bordering levees or embankment should be strengthened. These insights were further validated through post-event orthophoto assessments, which illuminated signs of erosion in the identified zones and sinuosity maps highlighted high SI, emphasizing the essentials of adopted multi-faceted approach. This evaluation has contributed to a more nuanced understanding of how historical factors continue to influence present-day flood vulnerabilities. This historical context is essential for developing informed risk management strategies that are not only reactive but also proactive in anticipating potential future changes in flood susceptibility.

The synthetic flood susceptibility map produced through the integration of historical data, geomorphological analysis, and post-event orthophoto assessments pinpoints susceptible zones and represents a significant advancement in flood management for the region. This map can be a crucial resource for policymakers and planners, offering a comprehensive overview of the flood vulnerability of the region. The use of such detailed and evidence-based mapping can guide the implementation of targeted interventions, ultimately reducing the overall flood hazard.

A significant limitation encountered during these analyses was the availability and resolution of data, particularly records on flood defense system (i.e. Levees) and high-resolution topographical information. The accuracy of flood susceptibility mapping is heavily dependent on the availability and quality of the input data, and any gaps or inconsistencies can lead to limited assessments or inaccuracies in the analysis. This limitation highlights the need for improved data collection and integration methods to enhance the reliability of flood susceptibility assessments.

Building upon the insights gained from this research, future flood susceptibility assessments should place greater emphasis on detailed geomorphological analyses, particularly river sinuosity, channel processes and historical geomorphological evolution. Understanding how river meandering influences flood susceptibility and evolution of the landscape can aid in more geomorphological and geological informed mitigation measure and in the identification of areas that require special attention.

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