Received: 3 September 2025 | Revised: 24 February 2026 | Accepted: 6 March 2026

DOI: 10.1002/esp.70280

RESEARCH ARTICLE

ESPL WILEY

Reconstructing human-induced geomorphic changes through historical maps and multitemporal remote sensing data in the Cancano–San Giacomo di Fraele reservoirs (Central Alps, Italy)

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Funding information
Ministero dell'Istruzione, dell'Università e della Ricerca, Grant/Award Number: PRIN202223RAZZO; Università degli Studi di Milano, Grant/Award Numbers: WP2, WP3

Abstract

This paper investigates human-induced geomorphological transformation along the Fraele Valley (Central Alps, Northern Italy) following the construction and operation of the Cancano I, San Giacomo di Fraele and Cancano II hydroelectric dams. By integrating historical maps (1866–1931), aerial imagery (1945–1954), declassified satellite data, recent remote sensing products and field geomorphological mapping, we reconstruct the evolution of the Adda River corridor from a natural braided river system to a regulated and largely submerged hydrographic network. The results show that the original fluvial landforms, characterized by debris-flow fans, gravel bars and dynamic channels, were progressively submerged and reworked by reservoir development and seasonal water-level fluctuations, promoting the formation of fan deltas, shoreline gullies and subaqueous landforms and redirecting sediment fluxes into the artificial basins. Field surveys during an exceptional low-lake level in 2023 improved remote-sensing interpretations, revealing submerged landforms, reactivated drainage pathways and localized shoreline erosion. These multiscale observations highlight how repeated water-level oscillations act as a key morphodynamic driver, enhancing sediment reworking and slope–reservoir nexus. This work contributes to the understanding of anthropogenic geomorphology in high-mountain regions, underscoring the value of combining remote sensing data, historical cartography and field evidence to assess large-scale and subtle diachronic transformations of the Alpine catchment. The study highlights the need for integrated approaches to evaluate long-term landscape change and geomorphic feedbacks in regulated mountain catchments.

1 | INTRODUCTION

Human geomorphology provides a basis for understanding how human activities affect natural landscapes (Goudie, 2016). Today, mountain regions are among the most disturbed environments, as they are intrinsically fragile and highly sensitive to external pressures such as human agency (Brown et al., 2017; Forti et al., 2025; Mathieu, 2019; Tarolli & Sofia, 2016; Tarolli et al., 2019). In these contexts, different morphogenetic processes, especially glacial, fluvial and gravity-driven, interact in dynamic ways (Brandt, 2000). Even small changes in the intensity or duration of each process can lead to significant alterations in landforms. Streams and their associated geomorphological processes play a fundamental role as dynamic systems shaped by both climatic conditions and human interventions (Fryirs & Brierley, 2013; Goudie, 2016; Kondolf et al., 2016). The construction of dams, such as those built in the Alpine environment like at Cancano and San Giacomo di Fraele in the Valtellina region, represents a major anthropogenic modification of high-altitude fluvial systems (Petts & Gurnell, 2005; Brandt, 2000; Ligon, Dietrich, & Trush, 1995; Maavara et al., 2020; Graf, 2006; Lane, Gaillet, & Goldenschue, 2022).

In fact, dam construction can profoundly alter river channels, modify flow regimes and disrupt sediment dynamics, with consequences for slope stability, channel bed composition, channel geometry and floodplain processes (Forti et al., 2022). These modifications are also evident upstream of artificial reservoirs, where backwater effects modify the hydrological dynamics of tributaries, causing seasonal fluctuations in the extent and intensity of valley inundation (Liro et al., 2020 and references therein). All these effects are amplified in steep mountain valleys, where sediment disconnection downstream of dams limits the natural reworking of the streambed. Nonetheless, unregulated tributaries can partially restore coarse sediment inputs, mitigating some anthropogenic impacts (Lane, Gaillet, & Goldenschue, 2022). These transformations also have important consequences for aquatic habitats, riparian ecosystems, surrounding tree vegetation and can influence local climatic conditions (Carolli et al., 2023; Cavalli et al., 2013; East et al., 2018; Fryirs & Brierley, 2013; Larsen, Larsen, & Lane, 2021; O'Connor, Duda, & Grant, 2015; Pelfini et al., 2004; Pizzuto, 2002; Tonolla, Geilhausen, & Doering, 2021). Over the past century, the landscape of the Valtellina valley has undergone deep transformations due to the development of hydroelectric infrastructure (AEM, 1997; Polatti, 2003; Toso, 2014). In particular, the upper sector of the Adda River has been profoundly reshaped, with evident changes in geomorphological processes and related landforms. To visualize and quantify, over time, the changes induced by both natural processes and human activities in Alpine hydroelectric landscapes, the integration of historical satellite imagery, aerial photographs and historical and thematic maps is required. These sources allow the reconstruction of morphologic evolution and the original landforms prior to major anthropogenic modifications (Schiefer & Gilbert, 2007; Trimble, 2008; James et al., 2012; Grabowski & Gurnell, 2016; Sevara et al., 2018; Azzoni et al., 2019; Williams et al., 2022; Forti et al., 2022; Forti et al., 2024). In dam-regulated landscapes, however, such methods are typically applied to reconstruct past flood events and to assess hydrological risk, rather than to analyse the gradual transformation of landforms (Elleder et al., 2020; Hajdukiewicz & Wyżga, 2019; Raška & Emmer, 2014; Sardou et al., 2018; Schmitz et al., 2009; Tropeano & Turconi, 2004) and the consequence for the evolution of local geodiversity (Pelfini & Bollati, 2014; Vidal-Garduño et al., 2025). Despite the widespread use of historical imagery and remote sensing in dam-regulated catchments, geomorphological reconstructions explicitly integrating submerged landforms, field validation and multi-decadal landscape trajectories in high-mountain environments remain rare. However, the complex interplay between geomorphic processes and hydraulic infrastructure is not only a matter of gradual landscape transformation, but also of catastrophic risk. In fact, geological investigations on historical dam failure (Barla & Paronuzzi, 2013; Bonomelli et al., 2023; Nemnem et al., 2025; Pilotti et al., 2020; Si, 2016; Valiani, Caleffi, & Zanni, 2002) demonstrate the need to integrate geomorphological analysis, hydraulic modelling, structural monitoring and climate forecasting into the management of dammed mountain catchments.

This study aims to reconstruct the geomorphological evolution of the catchment of one of the most important hydropower plants in the Italian Alps through a detailed analysis of historical maps and imagery, with a focus on major geomorphological transformations induced by the construction of dams along the upper reaches of the Adda River and other human interventions. By analysing these changes, we can better understand the complex interactions between human activities and natural processes, ultimately contributing to the development of more sustainable management strategies for Alpine environments. This study represents the first integrated geomorphological reconstruction of a high-mountain hydroelectric system, providing a novel methodological framework for assessing landscape transformation in regulated Alpine catchments, representing one of the geomorphic expressions of the Anthropocene.

2 | STUDY AREA

The Fraele Valley, located in the upper Valtellina (Alta Valtellina) in the Lombardy region of northern Italy near the Swiss border, lies within the Stelvio National Park. It hosts two major artificial lakes, San Giacomo di Fraele reservoir (hereafter San Giacomo) (46.5435° N, 10.2676° E; 1,949 m a.s.l.) and Cancano reservoir (46.5224° N, 10.3065° E; 1,884 m a.s.l.), constructed within a steep, glacially carved valley close to the Braulio valley. These reservoirs are part of a complex system of water intakes and diversion channels that extend across multiple alpine valleys, collecting water from catchments such as Viola, Braulio, Forni and Gavia valleys (Morosini, 2024). The surrounding landscape is characterized by rugged relief, with prominent peaks and by a geomorphological setting shaped by Quaternary glaciation and subsequent paraglacial adjustment processes (Figure 1). The area experiences a continental alpine climate, with temperature and precipitation maxima in July and August. The mean annual temperature for the period 1978–2003 is 2.7°C, with a seasonal range of 16.8°C from January to July (Pelfini, Leonelli, & Santilli, 2006). Frost events typically occur between November and April, while they are infrequent during the vegetative season (May–October). Precipitation is concentrated in summer months, with over one-third falling between June and August. The mean annual precipitation recorded at the Milan Municipal Electric Company (Azienda Elettrica Municipale, AEM) Cancano meteorological station for the period 1936–2003 is 828 mm. This climatic setting produces a highly dynamic and heterogeneous alpine environment, where cryogenic, gravitational and fluvial processes continue to actively influence landscape evolution.

From a geological point of view, the study area lies within the Austroalpine Domain of the Western Alps and includes exposures of the Ortles and Pejo units. These are tectonically juxtaposed along the east–west trending Zebrù Fault, which places Permo-Mesozoic cover sequences above a Palaeozoic metamorphic basement (Figure 1). Similar east–west deformation zones within the Ortles Unit locally culminate in basement slivers overlying the carbonate succession. This tectonic configuration is Alpine in age and predates the emplacement of Oligocene dykes (Zucali, Chateigner, & Ouladdiaf, 2020). The Mesozoic bedrock is subdivided into three informal lithostratigraphic units. The Stratified Dolomite Unit (Norian) is widely exposed north of the Zebrù Fault and exceeds 1,000 m in thickness. It consists of decimetric-bedded dolostones alternating with darker limestones, displaying microbialitic textures, parallel lamination and normal grading. Fine-grained dolomicrites dominate, with doloarenitic beds locally containing bivalves, gastropods and dasycladacean algae. This unit corresponds to the Dolomia Principale Formation (Montrasio et al., 2012), also known as Dolomia del Cristallo or Plator–Cristallo Formation, equivalent to the "Strata of Monte delle Scale" (Pozzi &

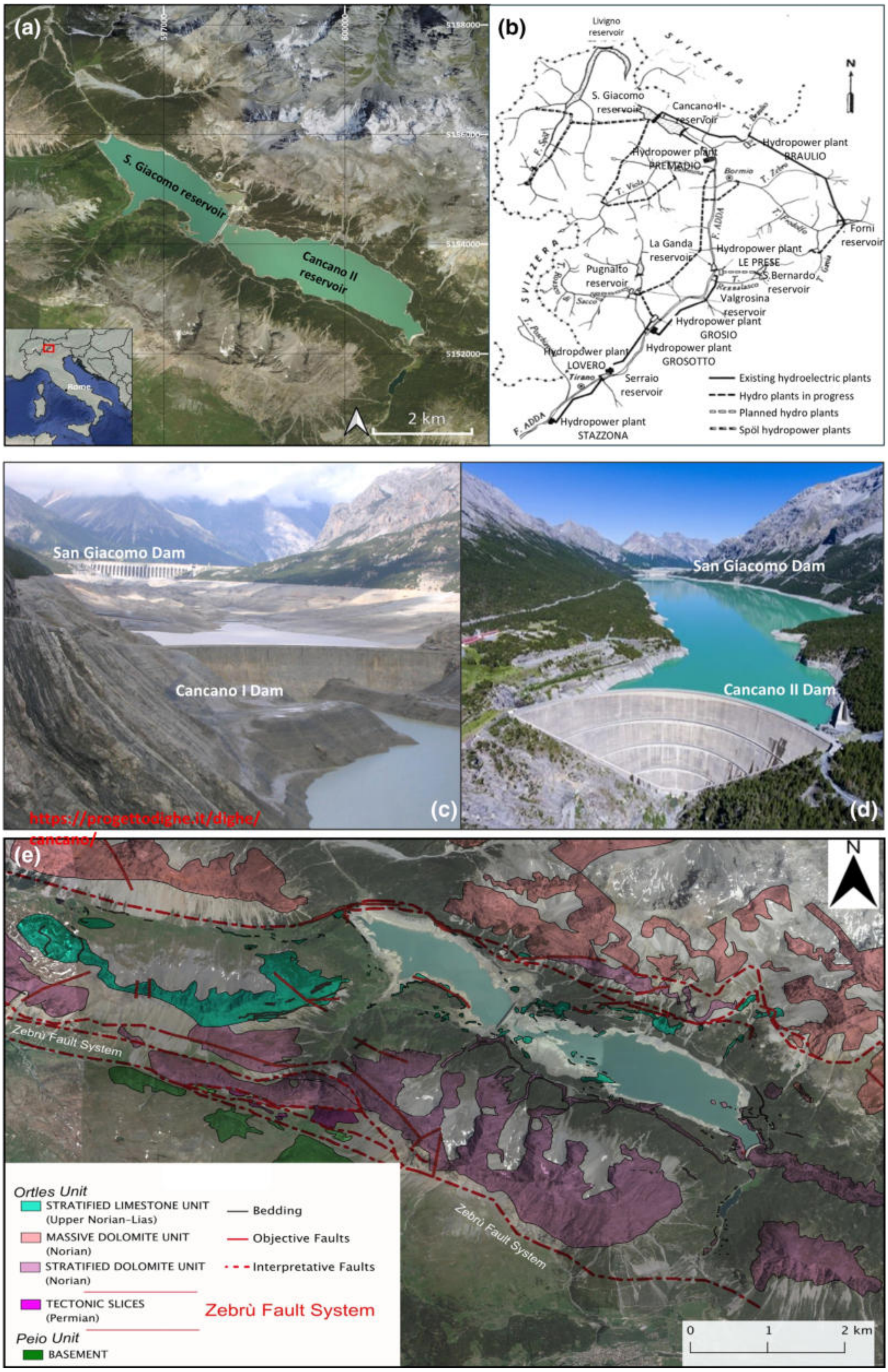

FIGURE 1 (A) Satellite view of the Fraele Valley (Lombardy, northern Italy) from Google earth™, showing the artificial lakes of Cancano and San Giacomo within the Stelvio National Park. (B) Overview of the Cancano–San Giacomo hydroelectric system, showing the reservoirs and the network of water intakes and diversion channels extending across multiple alpine valleys in Alta Valtellina. (C–D) photographs of the San Giacomo and Cancano dams, showing structural characteristics and reservoir extent. (E) Geological sketch of the study area.

Giorcelli, 1960). The Massive Dolomite Unit (Norian) crops out along an east–west belt north of the Cancano and San Giacomo Lakes (Figure 1). It consists of thick to massive dolostones, often repeated by tectonic slicing. Dolomicrites are predominant, with subordinate bioclastic doloarenites. This unit corresponds to the Dolomia di Pra Grata or Cassa del Ferro Formation, equivalent to the 'Strati di

Quattervals' (Montrasio et al., 2012; Pozzi & Giorcelli, 1960). The Stratified Limestone Unit (Upper Norian–Lias), also shown in Figure 1, is exposed north of Cancano and San Giacomo Lakes. It comprises alternating dark limestones and shales with abundant macrofossils (corals, brachiopods, bivalves, crinoids) and local chert nodules. It reflects subtidal basin conditions, with a shallowing upward trend (Berra, 1995; Berra & Cirilli, 1997) and includes the Fraele Formation and Monte Motto Limestone Formation (Pozzi & Giorcelli, 1960). All units are intensely deformed, as evident in Figure 1, with brittle-ductile shear zones, polyphase folding and faults. East–west trending folds traceable across the area indicate a dominant north–south tectonic transport direction. Deformation temperatures reached 250–300°C (Zucali, Chateigner, & Ouladdiaf, 2020).

The geomorphology of the area is characterized by widespread slope processes, closely controlled by bedrock structure and by several debris-flow channels flowing into the lake. In the northwestern sector, where the lake is absent, debris-flow fans reach remarkable dimensions (Pelfini & Santilli, 2008). The impact of past glaciation is also clearly recognizable across the area. On north-facing slopes above 2,200 m, well-preserved moraines and recent glacial deposits are evident and can be attributed to the Little Ice Age. Although no active glaciers are currently present, several active rock glaciers are found in the area. In the valley floor, particularly at the confluence with Pettini Valley, moraines ridge are evident that likely date back to the Last Glacial Maximum.

3 | HISTORICAL CONTEXT OF SAN GIACOMO AND CANCANO DAMS

The development of hydroelectric power in Valtellina, promoted in Italy since the last quarter of the 19th century (Morosini et al., 2010; Parrinello, 2018), played a fundamental role in the region's industrialization and in the construction of its energy infrastructure. This process began in 1883 with the installation of the first electric generator in the Province of Sondrio, in Chiavenna. The push toward hydroelectric development intensified after the foundation of the Milan Municipal Electric Company (Azienda Elettrica Municipale, AEM) in 1903, established to meet the rising energy demand of the city of Milan, driven particularly by industrial growth, public lighting and the tram network (AEM, 1997). The company was granted water concessions on the Adda River and the Roasco stream in 1908 and 1909, respectively, enabling a broad expansion of the hydroelectric sector in the area (AEM, 1997).

Following the construction of the plants at Grosotto and Fusine, the San Giacomo and Cancano II dams were built during the late 1930s and 1950s. Despite delays due to harsh climate conditions and the war context, these dams became a central component of the hydroelectric system in Valtellina (AEM, 1997). During World War II, regional development was hindered by shortages of materials and political instability, which slowed down the implementation of new projects (AEM, 1997). After the war, Valtellina entered a phase of expansion and growth, exemplified by the construction of the Premadio hydroelectric plant in 1956, which further contributed to the development of the valley's energy network.

Preliminary planning for the exploitation of the area's watercourses for hydroelectric purposes dates to the early 1920s. Construction of the Cancano I dam, originally designed to retain 10 million cubic meters of water from the Adda River, began in 1922. The structure reached a height of 43 m. Although the project was relatively modest in scale, its construction, completed in 1928, involved numerous challenges, including transporting materials through difficult alpine terrain and managing the worksite during severe winters (AEM, 1997). In 1940, construction began on another large reservoir in the Fraele valley, upstream of the Cancano basin. With the San Giacomo Dam, 83 m high and an impressive 960 m long, a reservoir with a capacity of 64 million cubic meters was created. Due to the Second World War, construction work suffered continuous delays and was completed only after the war. The San Giacomo Dam was officially tested and commissioned in 1953. This is an earthfill gravity dam with a central clay core, designed to suit the geological conditions of the valley (Figure 2D,E,F). Those years, the economic expansion led to a sharp increase in electricity demand, and for that reason, it was therefore necessary to build a new reservoir with greater capacity: the Cancano II dam (1953–1956) (AEM, 1997). This new structure, a buttress dam made of reinforced concrete, represented a significant technological advancement. Standing 136 m high, the dam increased reservoir capacity to 123 million cubic meters (AEM, 1997) (Figure 2G,H,I).

This large-scale hydroelectric system is fed not only by local streams but also by a wide network of water intakes and diversion channels, such as the Viola canal, Braulio canal and later the Forni-Braulio channel, which intercept tributaries from distant catchments, including the Gavia and Livigno areas. These gravity-fed channels significantly extended the basin's hydrological reach, modifying multiple alpine valleys and highlighting the extensive environmental and territorial impact of the Cancano–San Giacomo system across Alta Valtellina (AEM, 1997).

4 | MATERIALS AND METHODS

The geomorphological mapping of the Fraele Valley and the areas of the San Giacomo and Cancano reservoirs was carried out following the protocol proposed by Forti et al. (2022, 2024) and was based on the comparative analysis of multitemporal satellite imagery and declassified remote-sensing photographs. All sources were integrated to produce a detailed geomorphological map aimed at documenting landform distribution and landscape evolution. This approach enabled a detailed analysis of landscape evolution and allowed for the assessment of anthropogenic impacts on natural geomorphic processes and pristine ecosystems (Forti et al., 2022, 2024; Gurnell, Peiry, & Petts, 2003). The study specifically focused on the transformations induced by the construction of the Cancano I, San Giacomo and Cancano II dams and subsequent hydraulic works, canalization and slope stabilization interventions (Figure 3). The analysis relied on multiple sources (Table 1): (i) historical maps dated 1866, 1885 and 1931; (ii) historical aerial imagery from 1945 to 1954; (iii) recent high-resolution satellite imagery; (iv) archival photographs of the valley taken between the 1920s and 1980s.

Historical maps and the 1945 aerial imagery were obtained from the Swiss Geoportal (https://www.swisstopo.admin.ch/en/historical-maps) and the Italian Military Geographic Institute (IGM) (https://www.igmi.org) and served as fundamental references for reconstructing the conditions prior to reservoir construction. Specifically, the 1866 Dufour map (Swiss Geoportal, scale 1:100,000) and the 1885 San Giacomo di

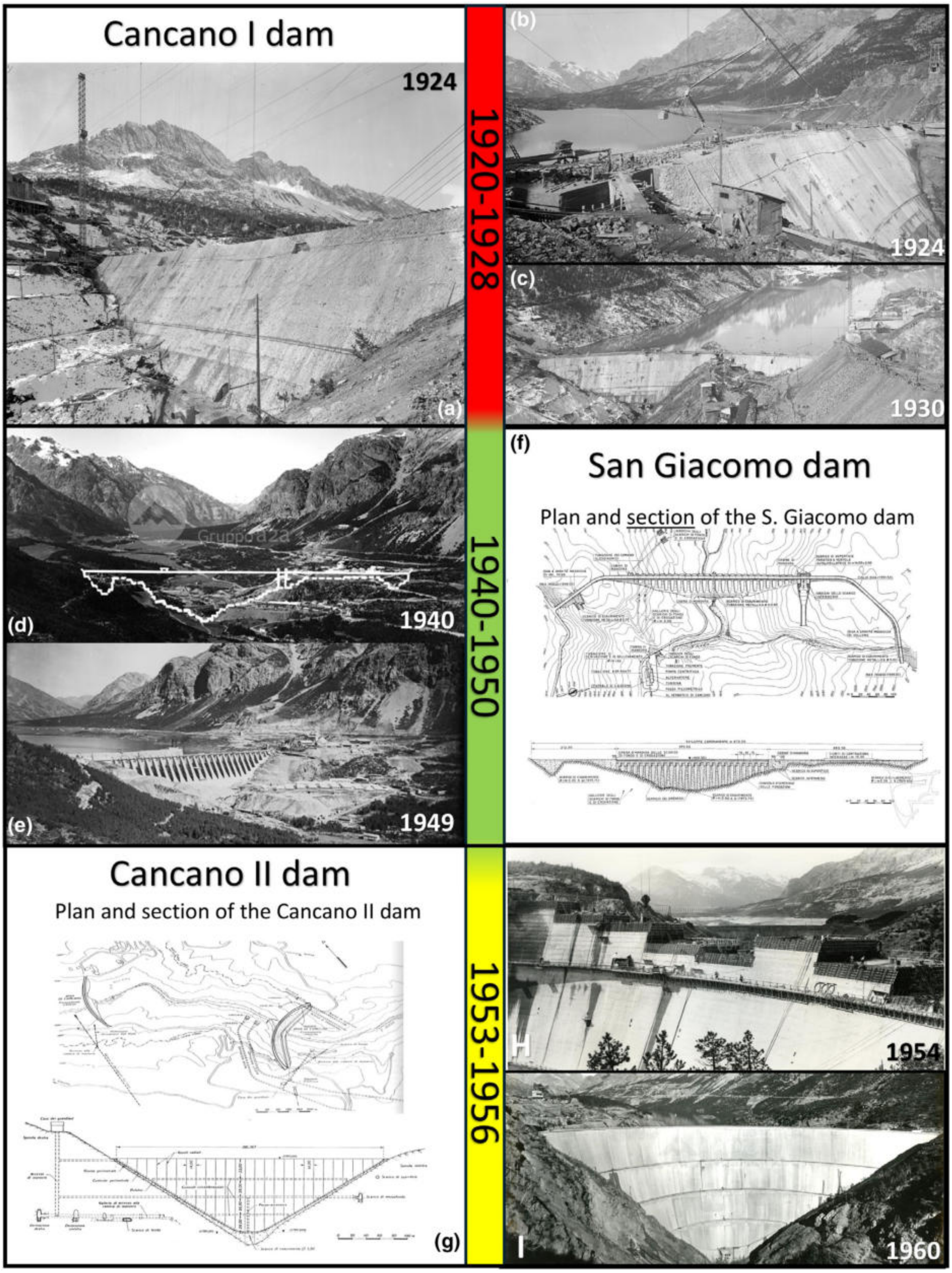

FIGURE 2 Chronological evolution of dam construction in the Fraele Valley, illustrating key geomorphological and engineering transformations: (A–C) 1920–1928 – construction of Cancano I dam: initial excavation and structural development of the first gravity dam. (A) Early construction phase with extensive slope modification. (B) Advanced construction stage showing infrastructure development. (C) the completed Cancano I dam with the formation of the first artificial reservoir. (D–E) 1940–1950 – planning and construction of San Giacomo dam: (D) engineering cross-section of the valley, outlining the projected dam. (E) The completed San Giacomo dam, a multiple-arch structure, (F–I) 1953–1956 – development of Cancano II dam: (F) technical schematics illustrating dam design and hydrological adjustments. (G) and (H) construction phases showing structural reinforcement and reservoir expansion. (I) The completed Cancano II dam, a double-curvature arch structure (image source: © AEM historical photographic archive, Fondazione AEM – Gruppo A2A, Milan).

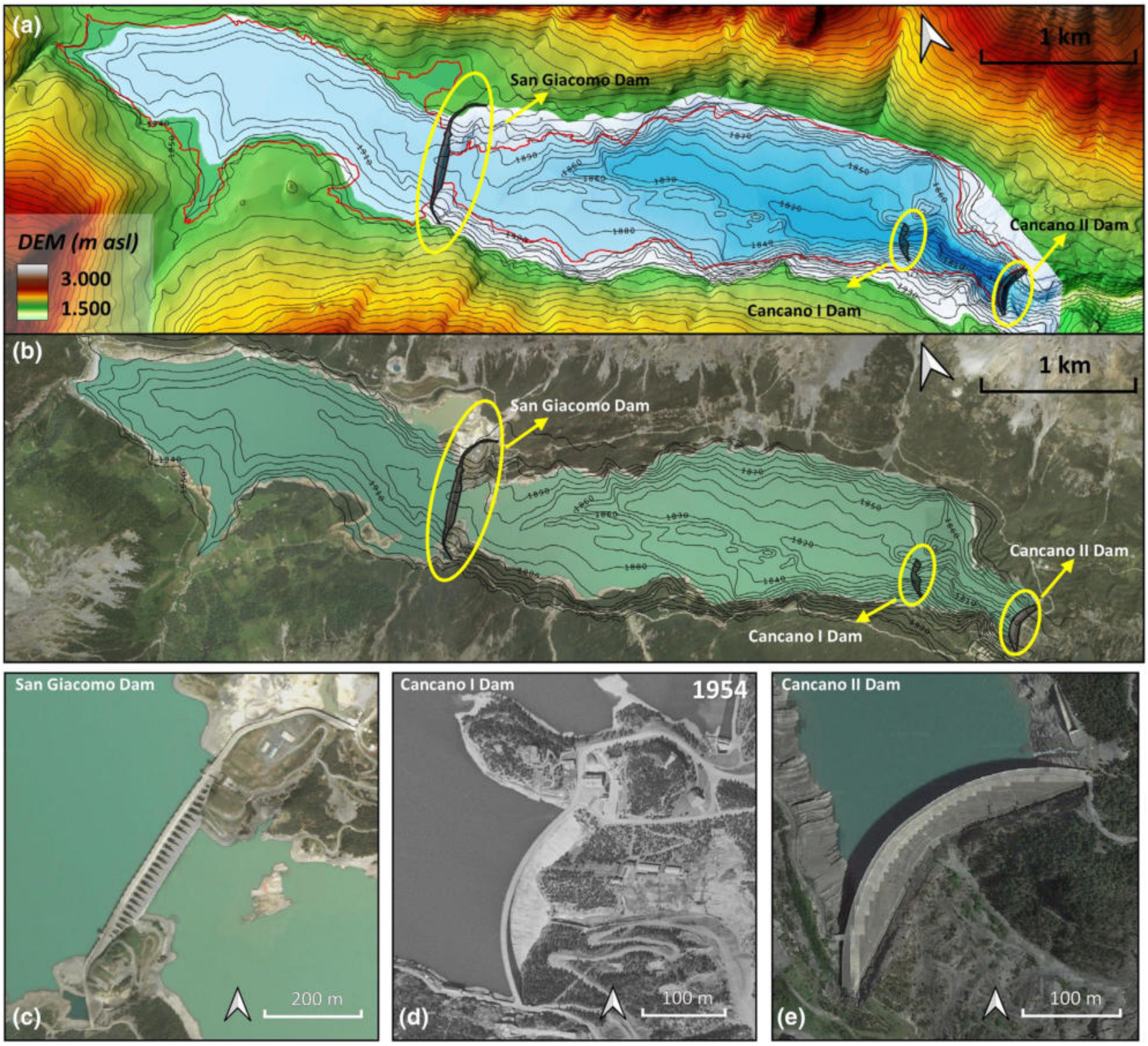

FIGURE 3 (A, B) digital elevation model (DEM) and satellite imagery highlighting the geomorphological context of the San Giacomo and Cancano dams, with contour lines indicating variations in elevation and submerged valley morphology. Yellow ellipses mark the dams. (C–E) aerial and satellite images detailing the layout of the dams.

Fraele map (IGM, scale 1:25,000) provided key insights into the landscape before major anthropogenic modifications, especially dam construction. The 1931 IGM map documented the valley's condition after the completion of Cancano I, capturing a transitional phase preceding further transformation. In addition to historical maps, historical aerial photographs from 1945 and 1954, retrieved from the IGM, the Lombardy Regional Geoportal (https://www.geoportale.regione.lombardia.it) and the Swiss Geoportal, were analysed to detect landscape changes linked to dam construction. These images provided direct or indirect evidence of valley morphology modification during the initial phases of reservoir construction, including modifications around the San Giacomo Dam and early construction work for Cancano II. Recent high-resolution satellite imagery from 2016, 2020 and 2021 allowed for comparisons between present-day and historical landscapes, enabling an assessment of long-term geomorphological trends and their relationship with past human interventions. Additionally, archival field photographs from the 1920s to 1980s, sourced from the Fondazione AEM (© AEM Historical Photographic Archive, Fondazione AEM – Gruppo A2A, Milan) (https://fondazioneaem.it/), offered valuable visual documentation of landscape transformations over time. Remote-sensing imagery was projected using the UTM Zone 32 reference system and served as the basis for remote observations conducted using QGIS 3.34 software (NextGis, 2024). A 5 × 5 Digital Terrain Model (DTM), with a horizontal resolution of 1 arcsecond (approximately 5 m at the equator), was obtained from the Lombardy Geoportal and used to highlight the regional distribution of landforms. Reservoir bathymetry was derived through the manual digitization of contour lines from the 1885 IGM map, which documented topographic conditions prior to the filling of the artificial reservoirs (Figure 3A and B).

To reconstruct the submerged former landforms, several geomorphological maps were produced through a multitemporal approach. The course of the Adda River and its associated fluvial features were reconstructed using historical cartography and IGM aerial photographs (1885 and 1931 maps; 1945 imagery), which documented the valley

TABLE 1 Database of historical charts, and aerial imagery, satellite imagery and the repository of the photographic archive used in this work.

Dataset	Institution	Name	Scale/resolution	Acquisition	Type of data
Historical maps	Swiss Geoportal	Topographic map of Switzerland Svizzera 1:100.000 (Dufour map) Sheet n° 20 Name: Bormio	1:100.000	1866	Historical chart
Topographic map of Italy. Scale 1:25.000 SERIE 25/V	Italian Military Geographical Institute (IGM)	San Giacomo di Fraele Sheet: n° 008 I-SO	1:25.000	1885	Historical chart
Topographic map of Italy. Scale 1:25.000 SERIE 25/V	Italian Military Geographical Institute (IGM)	San Giacomo di Fraele Sheet: n° 008 I-SO	1:25.000	1931	Historical chart
	Italian Military Geographical Institute (IGM)	San Giacomo di Fraele (1945–8,600-8-8-106) F.106; Sheet 8	1:33.000/1.21 m/px	27/08/1945	Aerial imagery
	Swiss Geoportal	lubis-luftbilder_schwarzweiss_000–176-977	1:26.410/ 0.80 m/px	17/06/1947	Aerial imagery
Gruppo Aereo Italiano (GAI) Italian Military Geographical Institute (IGM)	Lombardy regional geoportal	NO NAME Several tiles available in WMS service	1:45.000/1,26 m/px	16/09/1954	Aerial imagery
		Google Satellite imagery	≈ 0.50 m/px	12/2016	Satellite Imagery
		Bing Virtual Earth	≈ 0.50 m/px	06/2019	Satellite Imagery
		Google Satellite imagery	≈ 0.50 m/px	06/2022	Satellite Imagery
Historical photographic archive	AEM Historical Photographic Archive, Fondazione AEM – Gruppo A2A, Milan	Several field pictures		1920 to 1984	Historical Photographs

morphology prior to reservoir construction and proved particularly useful for identifying different geomorphic units (Gilvear & Bryant, 2016; Gurnell, Peiry, & Petts, 2003). The mapping integrated fluvial, slope and anthropogenic features to illustrate their combined effects on landscape evolution. Historical field-based photographs (1937–1941) further refined the reconstruction of fluvial forms and dynamics, providing direct evidence of channel morphology change, bar arrangement and sediment transport before dam construction. Fluvial geomorphic units were classified following the framework proposed by Brierley and Fryirs & Brierley (2013), enabling the description of variations in channel morphology along the Adda River and its tributaries.

The present-day geomorphological map was performed in a GIS environment using data from the Lombardy Regional Geoportal (Applied Geomorphology Map, available at https://www.geoportale.regione.lombardia.it/carta-geomorfologica-applicata). This dataset was further refined through the integration of detailed field-based geomorphological surveys, which improved the accuracy of landform representation. Additional information from the geomorphological map by Pozzi, Bollettinari, & Clerici (1991) was also incorporated, enabling a more comprehensive understanding of the geomorphological characteristics of the area and the broader landscape evolution. The graphic representation of the main landforms is developed according to the methodological framework, classification system and symbology adopted by the Geomorphological Map of Italy (Campobasso et al., 2018), as outlined in the national geomorphological mapping guidelines.

The mapping of active and relict landforms considered both the geomorphic influence of reservoir fluctuations and the independent evolution of slope processes. Debris-flow fans were classified as reservoir-controlled active features, whereas talus and debris cones upslope, with preserved morphology and continuous sediment supply, were interpreted as active forms unrelated to lake dynamics.

Field activities were carried out during two main periods (2023–2025) to validate geomorphic features interpreted from historical and remote-sensing imagery. The exceptionally low-water stage in summer 2023 allowed the direct observation and detailed mapping of submerged landforms previously identified through remote analyses, while subsequent surveys documented further modifications, confirming the reliability of the multitemporal geomorphological reconstruction. Field observations and several landforms were recognized and georeferenced in situ using QField for QGIS on a handheld device, enabling real-time validation and digitization of geomorphic features at multiple locations within the reservoir area (OPENGIS.ch, 2025). Where submerged features could not be directly accessed, validation relied on the concordance of multiple independent evidence sources, including archival field photographs (1920s–1980s), historical maps and multitemporal satellite imagery. This multi-source cross-validation approach substantially increased the reliability of geomorphic interpretation and ensured methodological robustness in distinguishing natural and man-made submerged features.

5 | RESULTS

The geomorphological analysis carried out in the Fraele Valley area allowed the identification of three main phases of landscape change associated with the construction and evolution of the Cancano and San Giacomo dams: (i) the pre-dam fluvial landscape of the Adda River (1866–1885); (ii) major landscape modifications during the construction of Cancano I and the early development of the San Giacomo reservoir (1931–1954); and (iii) the long-term geomorphological evolution and partial stabilization of the valley after the dams' completion (post-1954).

5.1 | The Fraele Valley before the dams (1850–1928)

The earliest cartographic representations of the Fraele Valley, along with the course of the Adda River, appear in both Italian and Swiss maps produced between 1866 and 1885. In particular, the Swiss Dufour map, at a scale of 1:100,000, highlights the course of the Adda River and the main geomorphological and topographic features, including the presence of scattered dwellings, the secondary drainage network and the general slope direction and inclinations of the valley sides (Figure 4A). The 1885 Italian map, produced by the Italian Military Geographic Institute (IGM), offers a significantly higher level of detail and allows for the identification of numerous geomorphological and topographic elements (Figure 4B). From this map, contour lines at 10-m intervals were extracted for the area currently occupied by the artificial reservoirs, enabling the reconstruction of the modern reservoir bathymetry (Figures 4C and 3A–B). The geomorphological map reveals that the

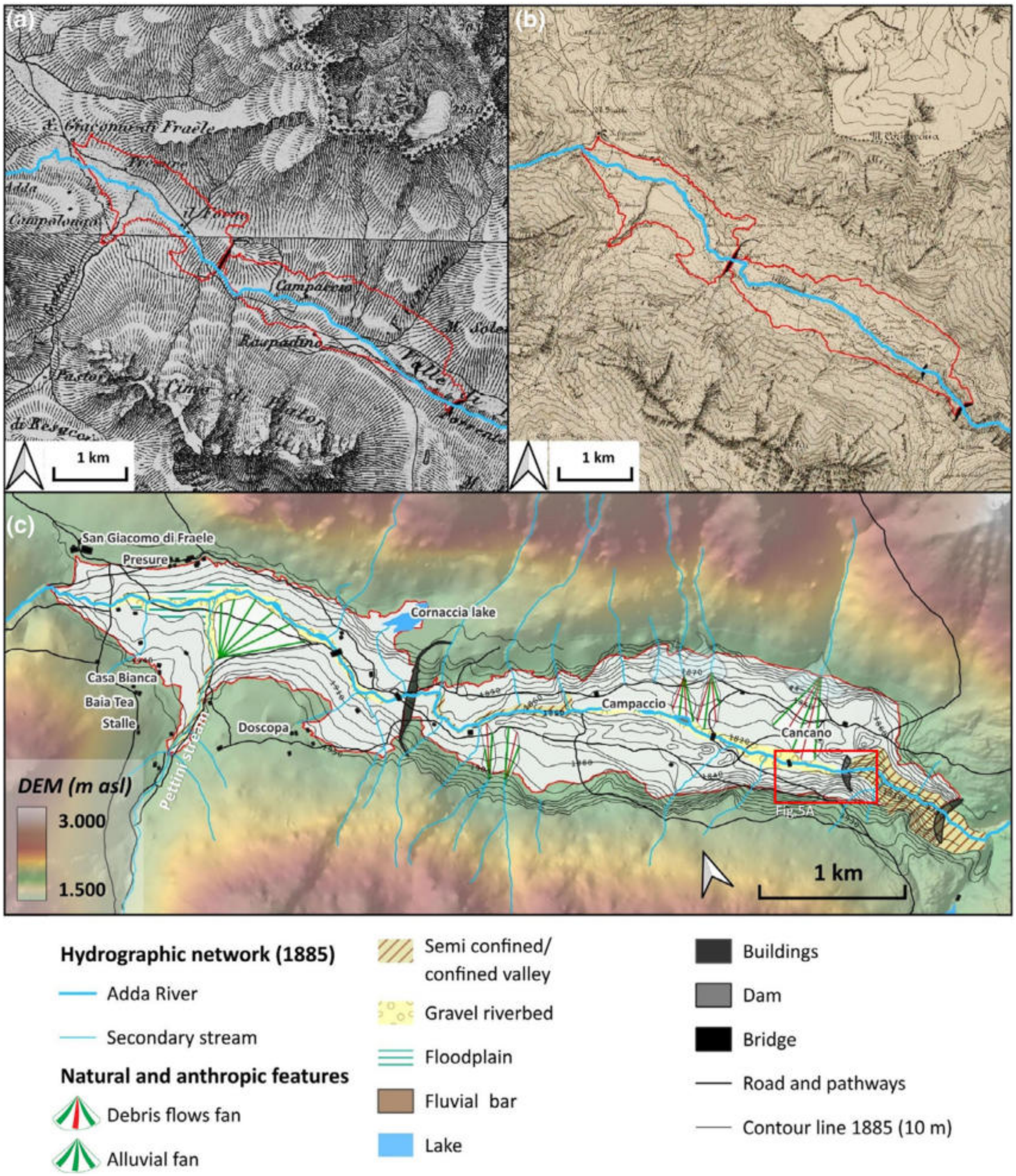

FIGURE 4 (A) 1885 Dufour map (Switzerland) illustrating the topographic configuration of the Fraele Valley and the Adda River course at a 1:100,000 scale (the red line represents the current configuration of the lakes). (B) 1885 IGM map (Italy) providing a more detailed representation of the valley's geomorphology at a 1:25,000 scale (the red line represents the current configuration of the lakes). (C) Geomorphological map of the present-day lake area, highlighting key landforms. The hydrographic network, alluvial fans, fluvial bars and anthropogenic features, such as roads, bridges and buildings, are represented to infer historical and contemporary landscape evolution (the red box marks the approximate area corresponding to the viewpoint of the historical photographs shown in Figure 5A).

main landforms were associated with the dynamics of the Adda River and hillslope processes. The map shows that the Adda River, from its source to the entrance of the valley below the village of San Giacomo di Fraele, flowed from east to west. Upon entering the valley, the river changed direction from NNW to SSE, aligning with the general orientation of the valley. In this section, the Adda exhibited a fluvial morphology ranging from low sinuosity to wandering, with a gravel bed and diagonal or longitudinal bars. Further downstream, at the confluence with the Pettini Stream, a flat area developed where the Adda's flow direction was slightly diverted and an alluvial fan formed. This fan developed because of material accumulation from slope processes and the deposition of coarse sediments transported by both the Pettini Stream and the Adda River. Further downstream, near the present-day location of the San Giacomo Dam, the valley narrows and the Adda becomes increasingly incised, transitioning from an unconfined to a semi-confined or confined setting. In this segment, immediately downstream of the dam, the river exhibited a higher degree of sinuosity, forming at least two well-developed meanders. Further downstream, within the area now occupied by the Cancano reservoir, the Adda flowed through a valley that ranged from unconfined to semi-confined, characterized by a predominantly straight course with some meanders and gravel-bed fluvial bars. The valley slopes were affected by mass-wasting processes, including debris flows transporting coarse material and colluvial processes that led to the accumulation of loose debris at the foot of the slopes. Numerous debris-flow fans were identified in this section on both the right and left sides of the Adda River. Near the site of the former village of Cancano, one of these fans exerted a slight influence on the direction of the Adda's flow. Beyond this point, the Adda flowed through a deeply incised gorge, where the Cancano I and Cancano II dams were later constructed. During this period, anthropogenic features in the Fraele Valley were minimal, limited to small settlements and rudimentary road infrastructures. Villages such as San Giacomo di Fraele and nearby structures represented the only buildings or farms in the valley, connected by dirt roads and trails that crossed the river at various locations via small bridges. In contrast to the current landscape, the historical maps depict the valley in a largely natural and unaltered state, with human activity confined to small, isolated areas. The construction of the Cancano I Dam (1920–1928) marked the first major human intervention in the valley. The site was strategically chosen at a point where the Adda River flowed through a confined section of the valley, at the beginning of the gorge segment (Figure 5A). The resulting reservoir completely submerged the debris-flow fans from the valley slopes, thereby altering the potential for lateral channel migration of the Adda River (Figure 5B). Conversely, in the central sector of the valley, where the San Giacomo Dam is currently located, the Adda River progressively merged into the Cancano reservoir, with a reduction in flow velocity and an increase in clastic sediment input, resulting in a backwater inundation configuration. A more detailed analysis of the upstream sectors of the river will be discussed in the following subsection.

5.2 | The landscape after the realization of the Cancano I reservoir (1930–1940)

The geomorphological map drawn on the historical chart highlights that the valley was modelled by a combination of natural and anthropogenic features, including well-developed alluvial and debris-flow

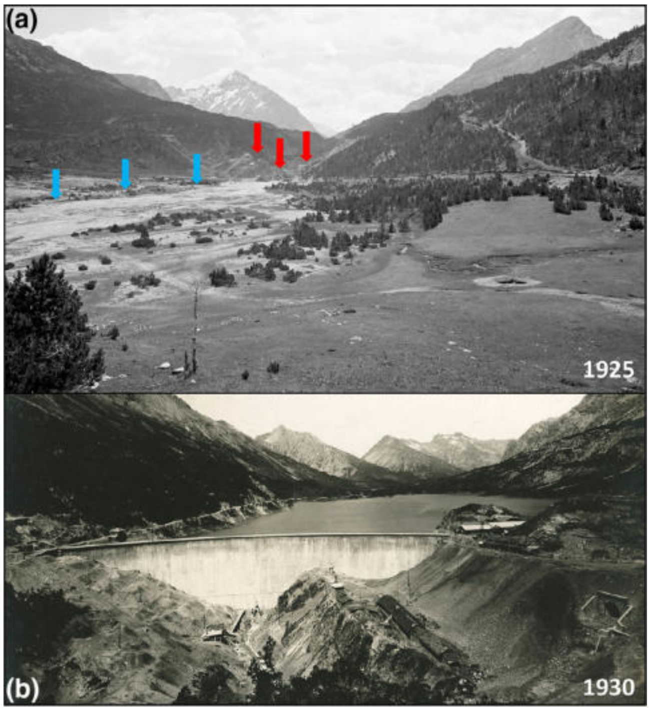

FIGURE 5 (A) The landscape of the Fraele Valley bottom in the proximity of the Cancano I dam site. The red arrows indicate the future dam site while the blue arrows indicate the Adda River watercourses. Notice the semi-confined valley setting to confined valley setting close to the dam site. (B) Panoramic view on the Cancano I dam after the construction. Notice the terraced slope and the waste materials fans accumulated at the floor valley (historical pictures source: © AEM historical photographic archive, Fondazione AEM – Gruppo A2A, Milan).

fans, extensive gravel riverbed streams that flowed in a semi-confined and confined valley setting (Figure 6A). In this context, the Adda River is represented over approximately 6 km, from its source area to its inflow within the Cancano reservoir. Based on old field photography, several Adda River reaches were detailed and analysed; the instream geomorphic fluvial features (Fryirs & Brierley, 2013). The first stream reach, at the entrance into the Fraele Valley (blue box in Figure 6A), the Adda River flows in a semi-confined valley setting, with a slight to moderate degree of sinuosity. The number of active channels varies according to the hydrological regime. A photograph taken in June 1937 captures the river in a transitional phase between high and low flow stages (Figure 6B). This hydrological variation results in the classification of the watercourse as a wandering (up to 3 channels) during low flow stages, with a possible transition to a braided (> 3 channels) during high flow conditions. The analysis of instream geomorphic features in the photograph enabled the identification of river behaviour. The active gravel riverbed is indicative of high-energy flow conditions, likely associated with snowmelt and seasonal discharge variations. The semi-confined valley setting, together with the presence of a wide braidplain dissected by multiple channels, exhibits a moderate degree of braiding. This braiding pattern is characterized by numerous fluvial bars and islands, some of which are classified as gravelly bars and lateral bars mainly vegetated. The presence of lateral bars along the margins suggests alternating periods of sediment deposition and erosion, driven by fluctuations in discharge and different areas of sediment source, with a seasonal thalweg shift. The gravelly bars, formed

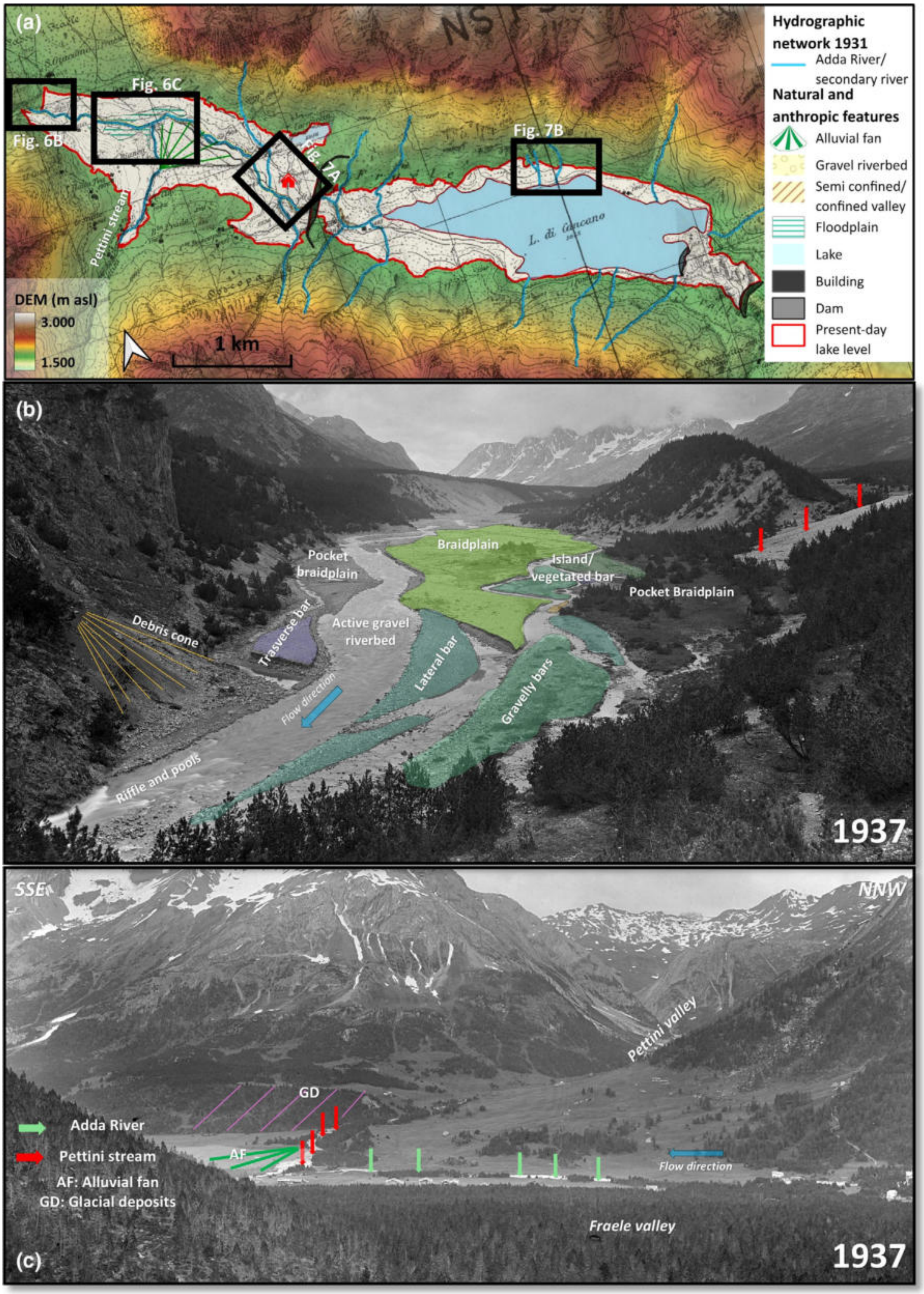

FIGURE 6 Geomorphological and fluvial characteristics of the Adda River before the construction of the San Giacomo Dam. (A) Hydrographic and geomorphological map from 1931, illustrating the course of the Adda River and its tributaries, highlighting alluvial fans, gravel riverbeds, semi-confined and confined valley sections, and the present-day lake level. (B) Historical photographs highlight the braided morphology of the river, with an active gravel riverbed, lateral bars and compound bars within a broad braidplain. (C) Overview of the valley showing the interaction between the Adda River and its tributaries, and the distribution of fluvial deposits shaped by episodic flooding (historical pictures B and C source: © AEM historical photographic archive, Fondazione AEM – Gruppo A2A, Milan).

by multiple episodes of sediment deposition, indicate a complex evolutionary history of sediment transport and accumulation that occurred in periods of high flow stage of the river. Many secondary streams originate from the valley margin, merging with the main course and, by transporting material, they produce joining and transverse bars or small alluvial fans; also, a large debris-flow fan (red arrows) is present to the left of the watercourse (Figure 6B). The river in this sector predominantly undergoes lateral course adjustments, where the main active channel splits into multiple threads due to the presence of islands and bars. Additionally, several slope processes were identified, including gravitational landslide, runoff and debris and grain flows with deposits subsequently reworked by the river (Figure 6B). Further downstream, the course of the Adda River is characterized by a notable change in its behaviour. The main river channel is fed by several smaller streams, which introduce additional sediment loads, contributing to changes in channel morphology and flow dynamics and direction. This is evident in the vicinity of the confluence with the Pettini Stream, where the Adda River undergoes a slight deflection in its flow direction. As illustrated in Figure 6C, the Adda River (light green arrows) exhibits a moderately meandering course within a flat area in the valley floor characterized by coarse sediments (mainly pebble and gravel) delivered by hillslope and fluvial processes. However, IGM cartographies (1885 and 1931) highlight that the Adda River channels carved the valley floor; close to the confluence with Pettini Stream (red arrows in Figure 6C), a slope gradient reduction occurred in an area in which the IGM charts reported an accumulation of finer material, suggesting an alluvial fan feature. The Pettini Stream, characterized by its torrential regime, flows within a narrow and confined valley, at times even a gorge, which subsequently merged into the Fraele Valley and cut Late Glacial Maximum glacial deposits (see present-day geomorphological map, and violet line in Figure 6C). The transport of material from the valley slopes to the valley outlet results in a transition from confined to semi-confined conditions, led to the formation of an alluvial fan. The Adda tributaries, entering from the valley sides, contribute to lateral sediment input, further influencing flow trajectory and channel morphology of the Adda River, causing a slight deviation of the flow direction to the east. Continuing further downstream, the Adda River flows through a landscape characterized by numerous trees and woods that make the course of the river very narrow and, in some cases, even straight. Field photographs from 1937 captured a reach of the Adda River flowing through a laterally semi-confined valley, with a low-sinuosity channel planform that closely follows the right margin of the Fraele Valley. The photograph in Figure 7A displays a gravel riverbed, smooth with several riffles and pools with very elongate longitudinal bars, locally vegetated and a small pocket floodplain. The left side of the Adda River is characterized by a swampy floodplain (or braidplain) in which there are several palaeochannels that testify to the thalweg shifts with a wandering to braiding channel planform according to the regime behaviour. The adjacent riparian vegetation in the floodplain and along the slope plays an important role in stabilizing sediments, reducing bank erosion and gravitative processes. Along the left banks of the Cancano reservoir, two main debris-flow fans are situated at the valley margins, where steep tributary channels transit into lower-gradient depositional environments (Figure 7B). These fans are formed by episodic sediment-laden flows originating from the surrounding mountain slopes. The yellow-marked sections indicate active depositional lobes, where recent sediment transport has occurred. The fans contribute by introducing coarse-grained material onto the artificial basin floor. Their extent and morphology indicate an ongoing interplay between hillslope processes, climate-driven runoff and sediment-transport efficiency.

5.3 | The landscape after the San Giacomo dam construction (1940–1950)

The construction of the San Giacomo Dam between 1940 and 1950 further reshaped an environment that had already undergone substantial changes in the previous decades. The historical aerial photograph from 1945 documents the Fraele Valley during the construction phase of the San Giacomo Dam, while the geomorphological sketch highlights three areas with distinct natural and anthropogenic characteristics. In the upstream section of the Adda River, near the village of San Giacomo di Fraele, a large portion of the settlement had not yet been submerged (Figure 8A). This landscape is shown more clearly in a 1939 field photograph, which offers a panoramic view of the valley and the Adda River floodplain, prior to inundation (Figure 8B). In the Cancano basin, the geomorphological map reveals numerous partially submerged debris-flow fans formed by gravitational mass transport from the surrounding slopes. These fans developed through episodic debris-flow events that transported a heterogeneous mixture of boulders, gravel, sand and fine sediments down steep channels, depositing them at the slope base and gradually prograding into the basin. Following the construction of the Cancano I Dam, the rise in water level led to the submersion of these deposits, modifying the lake's bathymetry and affecting internal sedimentary processes such as turbidity currents, subaqueous deposition and overall sediment dynamics (Lane et al., 2019; Kostaschuk, Aden, & Desloges, 2021). The central sector of the valley, especially in the immediate surroundings of the dam construction site, underwent the most intense anthropogenic modifications. The construction of the San Giacomo Dam involved a wide range of engineering operations, including excavation, foundation reinforcement and construction of the dam structure itself (AEM, 1997). Works also included the installation of surface spillways, intake structures and flow regulation mechanisms (AEM, 1997). Additionally, tunnels and pipelines were built to convey water to the downstream hydroelectric facilities. All these interventions contributed to reshaping the natural landforms well beyond the boundaries of the artificial basin. The most significant landscape changes occurred around the dam site, particularly along the valley margins, where large-scale excavation and slope reshaping were carried out. A major transformation took place around Cornaccia Lake, where extensive excavation and sediment backfilling radically modified the original morphology. The construction of artificial terraces, cut slopes, a quarry and the Braulio drainage canal substantially altered the pre-existing topography (Figure 8C–8D). Historical photographs from the construction phase (1938) provide crucial information on the fluvial dynamics of the Adda River in this segment. Specifically, the river (red arrows in Figure 8C and D) initially retained its natural braided and meandering morphology before undergoing a progressive process of channelization. Over time, engineering interventions confined the river within artificial embankments and diversion channels, prioritizing hydraulic efficiency over natural geomorphic equilibrium. The

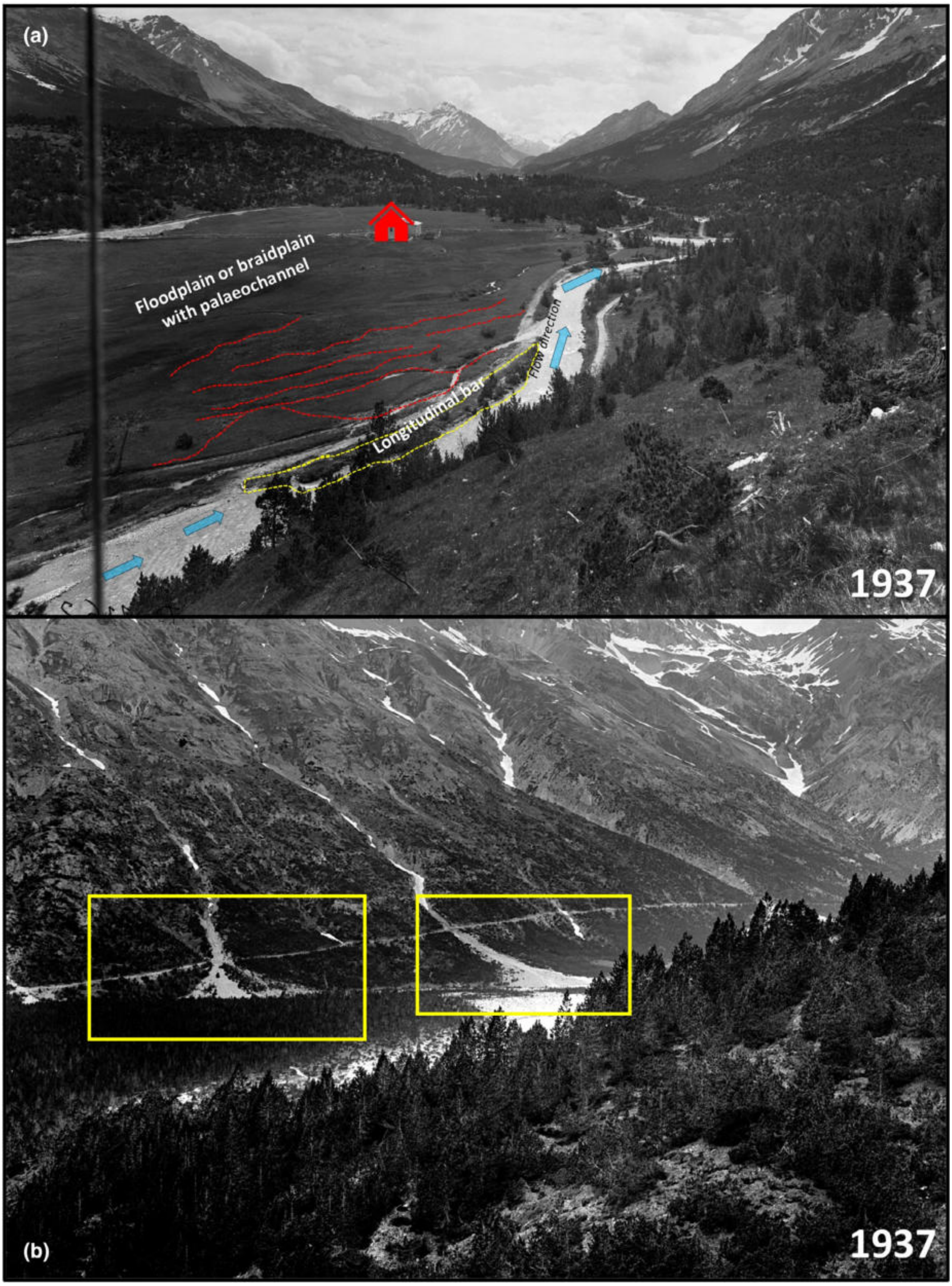

FIGURE 7 (A) Downstream perspective of the Adda River, showing its sinuous course, bordered by a floodplain and stabilized terraces, with riparian vegetation contributing to sediment stabilization before the dam's construction (red house was used as a fixed topographic reference point in the main geomorphological map in Figure 6, given its central location and long-standing presence in the landscape; red dotted lines represent the traces of paleochannels while the yellow ones are the boundary of longitudinal bar). (B) Image illustrating debris-flow fans at the valley margins (highlighted by the yellow polygon), where sediment-laden flows from steep tributary channels deposit material within the reservoir (historical pictures source: © AEM historical photographic archive, Fondazione AEM – Gruppo A2A, Milan).

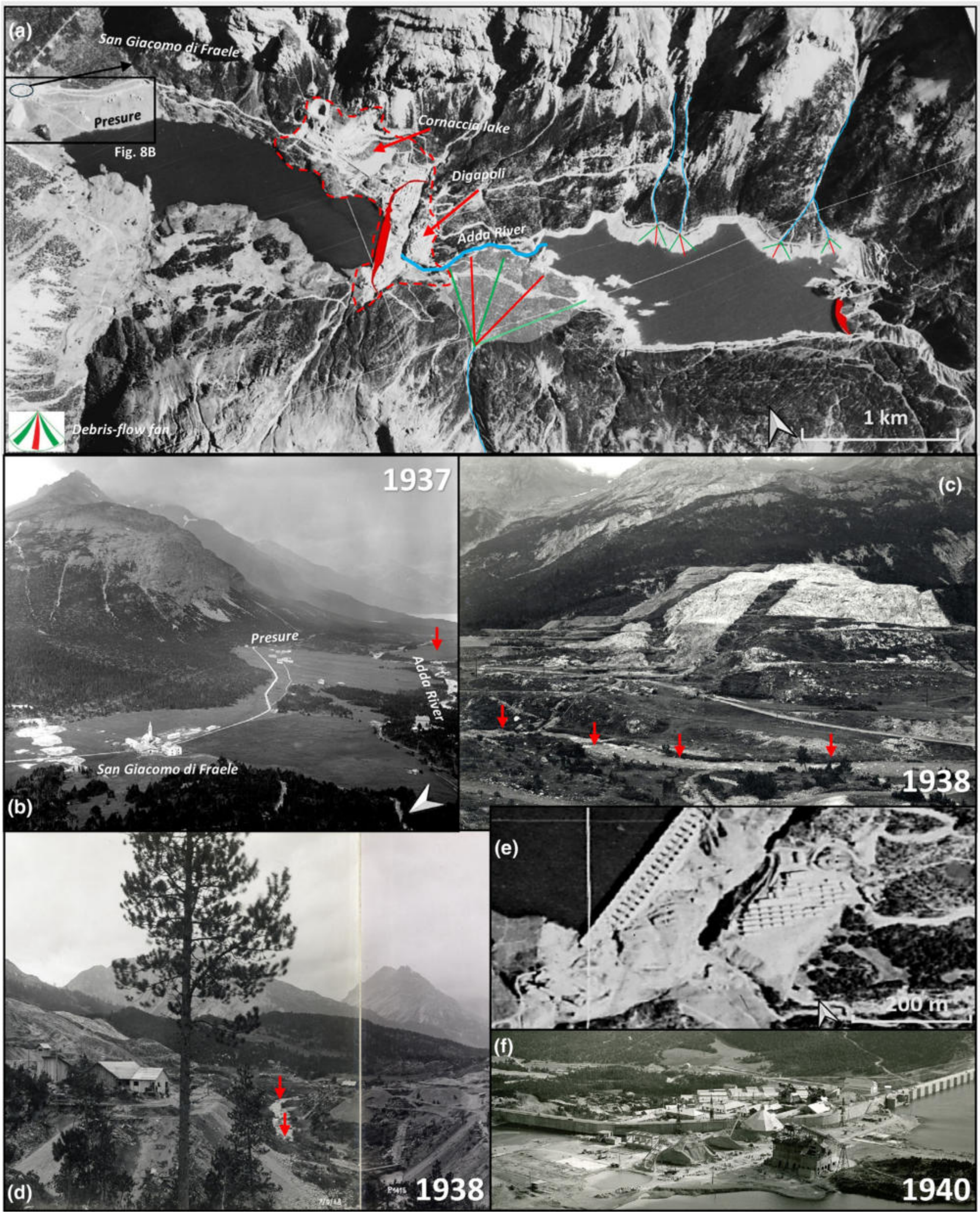

FIGURE 8 Historical and geomorphological overview of the Fraele Valley during the construction of the San Giacomo Dam (1938–1950). (A) 1945 IGM aerial imagery with a simplified geomorphological sketch highlighting natural and anthropogenic features (red dotted area). (B–D) Pre-inundation alluvial areas of the Adda River, showcasing excavation and reshaping activities for dam construction (the red arrows indicate the course of the Adda River). (E–F) Digapoli settlement, built to support dam construction, later submerged post-Cancano II development (historical pictures B, C, D, F source: © AEM historical photographic archive, Fondazione AEM – Gruppo A2A, Milan).

excavation phase resulted in massive sediment displacement, with large-scale removal of material from the valley floor and surrounding slopes. This significantly altered the sediment budget and the downstream sediment supply. The accumulation of excavated material in designated areas contributed to reshaping the local topography, forming stepped artificial terraces along the slopes adjacent to the dam site (Figure 8C and D). To support the workforce involved in construction, a dedicated settlement known as Digapoli was established near the dam site. Digapoli functioned as a self-sufficient village, equipped with infrastructure that included housing, medical facilities, storage areas and supply depots. The complex included dormitories, dining halls and communal spaces to accommodate the large number of workers and engineers engaged in the project (Figure 8E and F). The presence of this temporary urban core constituted another anthropogenic intervention that reshaped the topography and landforms near the dam site. These modifications are still visible today, as after the completion of the dam, the remnants of Digapoli were submerged without being fully dismantled (Figure 8F).

5.4 | The landscape after the Cancano II dam (1953–1956)

The construction of the Cancano II Dam, carried out between 1953 and 1956, represents the final major stage of human intervention in shaping geomorphological processes within the alpine system of the Fraele Valley. Located downstream of the existing Cancano I reservoir, the project was developed within a narrow gorge characterized by steep slopes and a confined setting, which offered a naturally suitable site for hydropower development (Figure 9A). During the initial

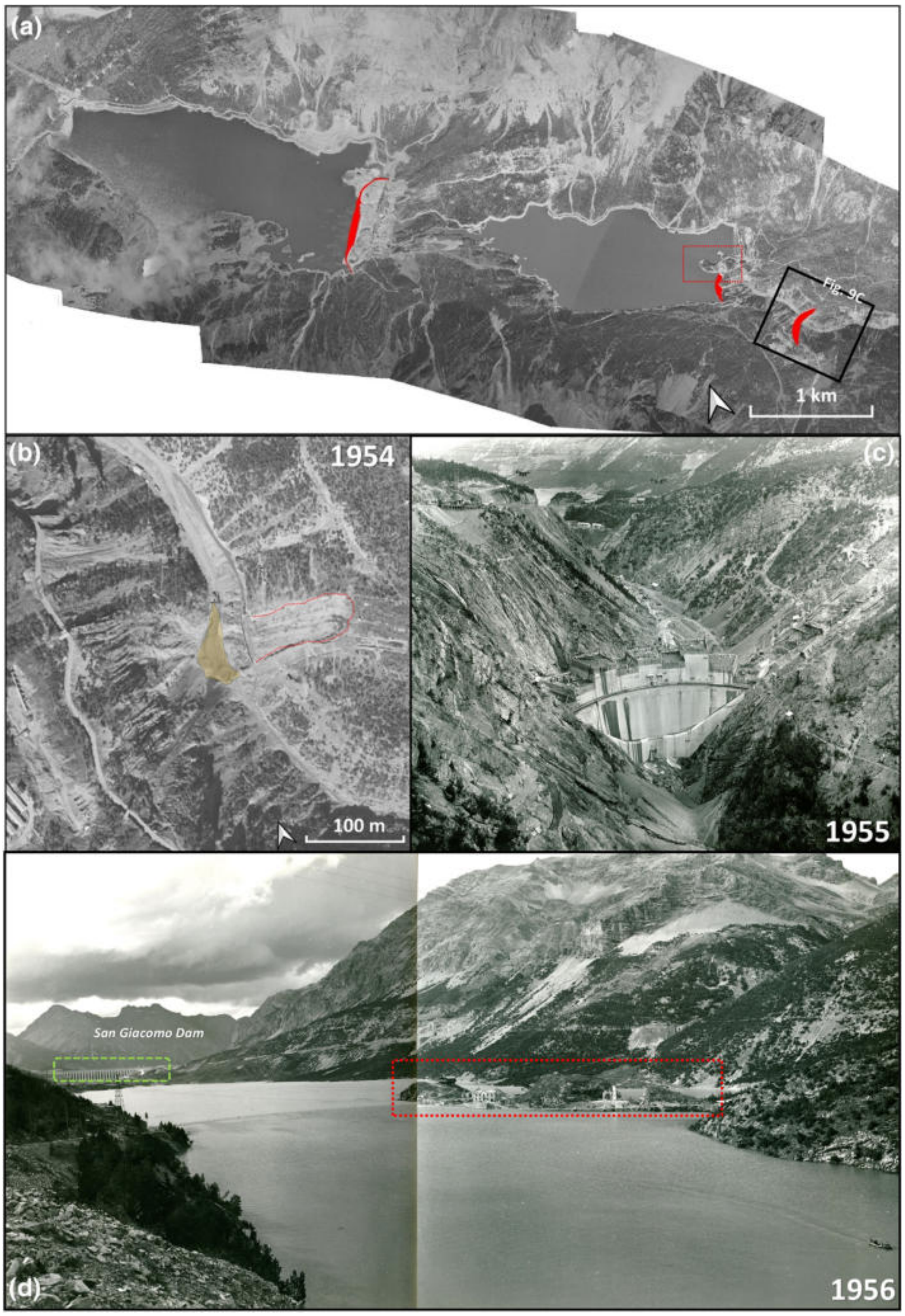

FIGURE 9 Construction of the Cancano II dam (1953–1956) and its geomorphological impacts. (A) 1953 IGM historical aerial imagery highlighting the three dams (black rectangle: plan-view position of the area shown in Figure 9C. Red dotted rectangles: locations of the submerged anthropogenic structures illustrated in Figure 9D). (B) 1953 imagery displayed the Cancano II excavation areas (red outline) and relocated debris deposits (orange polygon), shading with earthmoving activities formed debris talus at the valley base. (C) Partially constructed dam surrounded by infrastructure such as access roads and storage zones. (D) Reservoir inundation submerged the Cancano I dam and surrounding urban area (red dotted box) (images source C and D: © AEM historical photographic archive, Fondazione AEM – Gruppo A2A, Milan).

excavation phase, large-scale earthworks profoundly altered the natural morphology of the valley, exposing and modifying its margins. Establishing the foundations for the new dam required the removal of significant volumes of material, with the excavated area clearly delineated by sharp boundaries (Figure 9B). The excavated material was transported and deposited along the valley slopes, forming debris fans clearly visible at the base of the slopes (Figure 9B). These debris cones, composed of loose and heterogeneous material, were subject to slope processes such as gravitational settling, rill erosion and surface runoff-induced transport during rainfall events. These processes not only reshaped the morphology of the cones but also increased the sediment load into the downstream hydrological system, necessitating active engineering measures to mitigate sedimentation risks and ensure slope stability (AEM, 1997). As with Cancano I, the construction of Cancano II (Figure 9C) required numerous auxiliary works to support the project's implementation. These included access roads, temporary material storage areas, workers' accommodations and an aerial cableway. All these interventions led to changes in drainage pathways, exposure of bare soils and intensified surface runoff, further disturbing the natural sediment and water cycles. Following the completion of the dam, the valley underwent a great transformation during the filling phase of the newly formed reservoir (Figure 9D). The rising waters of the basin submerged the surrounding landscape, including both the infrastructure and the pre-existing Cancano I dam. The submergence of Cancano I had a significant impact on sedimentation dynamics within the reservoir. Fine sediments transported by tributaries and surrounding slopes began to settle in the still waters, forming stratified depositional layers on the reservoir floor (Lane et al., 2019; Carolli et al., 2023).

5.5 | Present-day active geomorphological processes

The present-day evolution of the study area is tuned by the interplay of multiple land-shaping processes, driven by a combination of controlling factors (Figure SI1). Running and channelized water, snow and seasonal ice, wind and gravity continue to shape the landscape. These active agents are evident in the frequent occurrence of debris flows and avalanches (Santilli & Pelfini, 2002; Pelfini et al. 2004; Pelfini & Santilli, 2008). Gravitational processes dominate the steep valley slopes, producing a variety of erosional and depositional landforms, such as debris flow channels and fans, debris cones and talus slopes (Figure 10). Talus cones and debris fans, originating between 2,300 and 2,700 m a.s.l., accumulate along the valley sides, particularly near the margins of the artificial lakes and in the downstream sector before the Cancano II dam (Figure SI2). These colluvial deposits are often connected to avalanche paths, and their proximity to the reservoirs suggests recurrent rolling and collapse events. Active degradation scarps, especially on the left slope close to the Cancano basin, indicate ongoing rockfall and toppling activity (Figure SI2). Water runoff, stream erosion and limestone dissolution also leave distinct imprints on both the natural landscape and anthropogenic deposits. Erosional features such as terraces and escarpments are particularly prominent downstream of the Cancano II dam along the Adda River. Fluvial processes, driven by the interaction between running water, sediment supply and valley morphology, play a fundamental role in shaping river and stream channels and their associated landforms from headwaters to downstream reaches. The Pettini Stream, a gravel-bed torrential tributary of the pristine Adda River, flowing within a narrow, locally gorge-like confined valley, cuts Late Glacial deposits and builds a submerged alluvial fan (see after chapter 6.2) within the San Giacomo reservoir, contributing coarse sediment supply to the basin (Figure 10 and Figure SI3). Further downstream (after the Cancano II dam), the regulated Adda River flows in a narrow gorge affected by slope processes such as debris cones and talus, reflecting enhanced vertical incision and modified fluvial dynamics in response to reservoir operation, highlighting how dam-related alterations propagate along the fluvial system (Figure SI2). Both concentrated rill erosion and diffuse sheet erosion affect the valley slopes, with more intense activity observed below the San Giacomo dam. Sediment deposition is equally significant, with alluvial cones and fans forming at stream confluences. Larger, now inactive alluvial fans are preserved in the upper sector of the first reservoir, whereas smaller and still active fans are developed along the left slope of the Cancano basin, becoming clearly exposed during low-water phases of the lake (Figure 10). These forms highlight the importance of sediment transport and deposition in shaping the valley's morphology. Karstic processes add further complexity to the area. Dissolution of carbonate rocks results in dolines and small depressions, which are mainly clustered downstream of the reservoirs, but also occur sporadically in the upper valley. The distribution of these karst features reflects both the local lithology and the role of CO_2-rich waters in enhancing carbonate dissolution. Although no active glacial processes are present today, glacial deposits remain a key source of material for mass movement (Pelfini & Santilli, 2008). Glacial erosion has carved cirques into the left slope near Cancano II, at approximately 2,900 m a.s.l., while extensive moraines and glacial sediments cover large portions of the upper right slope. Periglacial processes, although less dominant today, continue to influence the valley's evolution. A semi-permanent snowfield persists on the right slope between 2,600 and 2,800 m, reflecting current climatic conditions. Periglacial and nival processes generate landforms shaped by freeze–thaw cycles and slow sediment transport. Rock glaciers—indicative of past or present permafrost—are found on the right slope at elevations of 2,400–2,500 m (Figure SI2). Solifluction lobes, patterned ground and frost-shattered debris are widespread on the lower left slope, underscoring the continued influence of cryogenic processes on the valley landscape. Human activity has profoundly reshaped the geomorphological features of the area. Among the landscape-modelling agents, anthropogenic interventions, mainly related to reservoir management and road maintenance, have significantly modified the geomorphic setting (Pelfini et al., 2004). In terms of controlling factors, structural and tectonic elements play a crucial role in landscape evolution (Figure SI2). Major fault scarps define the valley, including a prominent fault running along the right slope between 2,600 and 2,400 m, and another parallel one on the left slope near 2,700 m. Other structural features, such as fractures, scarps and bedding-plane faults, are widespread and influence slope stability, erosion patterns and depositional setting of lacustrine sediments (Figure SI3). The alignment of scarps parallel to the valley axis, along with the presence of counter-slopes, further emphasises the role of tectonic processes in shaping the valley's morphology and drainage. Lithological variation governs rock weathering and the availability of debris for slope processes, while the presence of limestone also affects water infiltration and flow paths (Pelfini, Santilli, & Merlini, 2004). Topography, especially slope gradient, influences water

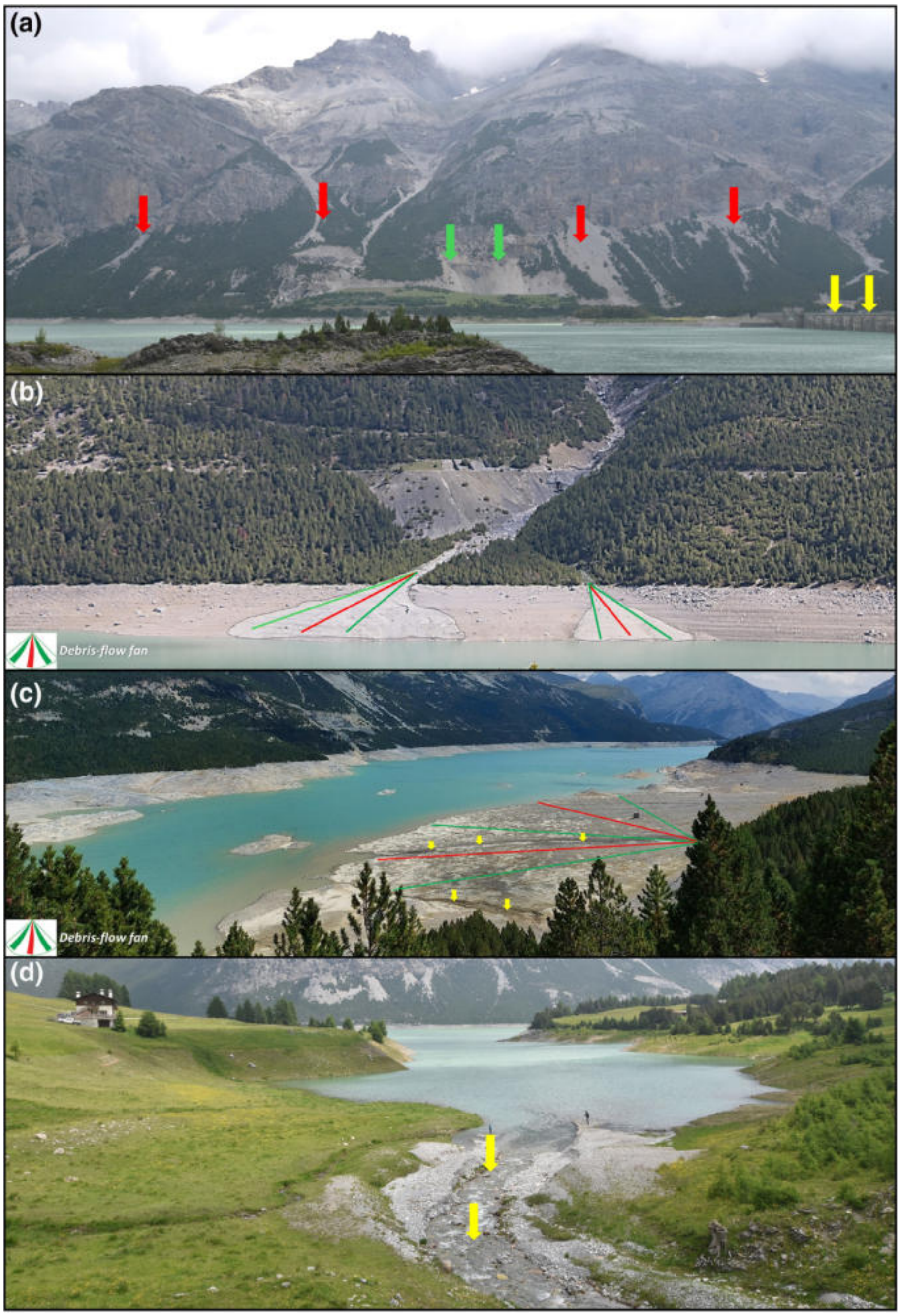

FIGURE 10 Field evidence of geomorphological processes around the artificial reservoirs. A) Panoramic view of the left side of the S. Giacomo reservoir showing several geomorphological features, including active slope processes (red arrows), the quarry area and associated slope reconfiguration (green arrows) and the terminal section of the S. Giacomo dam (yellow arrows). (B) Lowering phase of the Cancano reservoir water level (field 2023), highlighting two debris-flow fans (historical imagery in Figure 7B). (C) The 2023 lowering phase of the Cancano basin, highlighting the debris-flow fan and the reactivated drainage channels (yellow arrows) exposed during the lake drawdown. (C) Field view of the Pettini stream (yellow arrows), showing its gravel-riverbed and its inflow into the S. Giacomo reservoir.

flow velocity and the effectiveness of mass movements and sediment transport. In addition, slope aspect affects weathering intensity, while landform morphology interacts with climate and vegetation cover. Vegetation—particularly tree cover—serves as a valuable archive of both natural and anthropogenic events. Not only do trees record major disturbances such as debris flows and avalanches (Garavaglia et al., 2012; Pelfini & Santilli, 2008), but they also reflect more subtle processes like sheet flow (Pelfini, Leonelli, & Santilli, 2006), the deposition of fine anthropogenic materials such as mine waste (Pelfini et al., 2004), and climatic variability (Leonelli, Pelfini, & di Cella, 2009). The construction of the Cancano and San Giacomo reservoirs has had a profound impact on hydrological and sedimentary dynamics. Raised water levels have submerged parts of alluvial fans and debris cones, truncating their distal portions (Figure 10 and Figure SI2). Access roads running along the reservoir margins intersect debris flow paths and talus slopes, disrupting natural sediment fluxes and requiring constant maintenance. Additionally, a quarry on the left shore of the San Giacomo reservoir and the diversion of water from adjacent valleys further illustrate the extent of human-induced modifications (Figure 10 and Figure SI2). These interventions have reconfigured slopes, altered drainage networks and influenced sediment dynamics across the entire area.

6 | DISCUSSION

6.1 | Human impact on fluvial dynamics in the last century

The original fluvial landscape of the Adda River in the Fraele Valley, prior to the construction of large-scale infrastructures such as the Cancano I Dam (1920–1928), represents a key reference point for understanding subsequent geomorphological changes. Early cartographic sources (1855–1866) document a semi-confined to confined valley with a low-sinuosity to wandering stream channel, gravel bars and active sedimentary features. Fluvial and colluvial processes shaped alluvial zones, while debris-flow fans influenced the river's morphology and lateral behaviour. At the time, sparse settlements such as San Giacomo di Fraele village and minimal infrastructure represented the only anthropogenic modifications. Between 1920 and 1928, the construction of Cancano I pushed the first major human-induced geomorphological change. Located in a confined valley reach, the dam submerged debris flow fans, thus altering depositional processes and reducing the Adda River sediment flux. Upstream reaches are adapted by developing backwater configurations. Historical photos and maps highlight braided and wandering channels, shaped by seasonal hydrology, sediment cycles and emerging anthropogenic impacts. Tributaries like the Pettini stream contributed mainly coarse sediment via alluvial fans, while riparian vegetation stabilized the river's banks and controlled sediment transport. The San Giacomo Dam (1940–1953) marked a new phase of landscape transformation. Large-scale earthworks, submerged settlements, and disrupted fluvial dynamics. Aerial imagery and geomorphological mapping show excavation of valley margins, artificial canals construction and artificial terraces. Natural channel behaviour was replaced by embankments and controlled flow. During this phase, fluvial processes diminished significantly due to disrupted sediment transport and altered channel morphology, whereas slope processes, such as debris flows, became more evident as their deposits accumulated within the lake basins (Figure 10). The Cancano II Dam (1953–1956) exemplifies an intensive intervention in the alpine valley system. Excavation locally reshaped the valley margins, destabilizing the surrounding slopes and generating debris cones prone to rill erosion and to runoff-induced debris transport. These changes increased sediment load downstream, requiring engineering mitigation. Infrastructure such as roads and cableways supported work in this complex topography. After its completion, the filling of the Cancano II reservoir triggered significant geomorphological and hydrological changes. The rising water levels submerged pre-existing structures, including the earlier Cancano I reservoir, and altered sediment dynamics on the lakebed. Together, the Cancano and San Giacomo reservoirs regulate both water and sediment flow, partially stabilizing downstream hydrology. However, they have also profoundly changed the natural dynamics of the Adda River, particularly in the stretch immediately downstream of the dams.

6.2 | The effect of water level fluctuations

The analysis of historical images following the construction of the San Giacomo and Cancano II dams reveals that annual and seasonal fluctuations in reservoir water levels have played a fundamental role in reshaping the submerged fluvial landscape and landforms of the Adda River on the floor of the Fraele Valley. These fluctuations have significantly influenced geomorphological processes in the transition zone between land and water (e.g., hillslope processes). Swiss aerial photographs taken in 1947 over the San Giacomo reservoirs document the area surrounding the village of San Giacomo di Fraele, in close proximity to the confluence of the Pettini Stream with the Adda River. In this area, where the village once stood and where the Adda now flows within the reservoir (formerly within the valley), vast portions of the shore and lakebed are still exposed, highlighting the predominance of fluvial processes (Figure 11). Satellite imagery analysis shows that the Adda River largely follows its original course during low lake level phases, as does the Pettini Stream. To contextualize these observations, a geomorphological sketch derived from the 1885 IGM map was overlaid on the 1947 and 2016 satellite images. A strong correlation emerged between the landforms mapped in 1885 and those visible in 1947 and 2016 (Figure 11). The alluvial fan at the confluence of the Adda and Pettini rivers has retained its original geometry, shaped by deposition and erosion processes and by the nature of flow (e.g., hyperpycnal or hypopycnal). Changes in reservoir water levels have altered the natural flow regimes of the Pettini stream and the Adda River, producing backwater effects that modified the locally hydrodynamic equilibrium, induced intense in-channel sediment deposition, and drove progressive morphological adjustments to the riverbeds (Bao et al., 2021; Liro et al., 2020). A detailed analysis of the Adda River section in 2016 imagery shows the evolution of a delta plain toward a wave-dominated delta system (Figure 11B). The watercourse exhibits a torrential regime, marked by abrupt base-level drops that modify hydrodynamic conditions. This results in a weakly sinuous river system transitioning from braided to wandering, with the development of multiple river bars. The channel incises fine sediments before flowing over a gravel bed, such as the present-day riverbed of Pettini Stream (Figure 10D). The delta area, in contrast, displays a variety of bar types typical of deltaic environments (e.g., transverse bars, swash bars and ridges) (Nordstrom & Jackson, 2012) (Figure 11B). This geomorphological evolution is tied to the sudden lowering of the artificial reservoir. Different lake-level phases reconstructed from available satellite images (Figure 11B) show that when the lake reached its highest recorded level (2019), all geomorphological features and the shoreline were submerged. The subsequent water level drop exposed the shoreline and submerged forms. Images from 2016, 2022, and 2023 field evidence reveal numerous erosional and depositional features along the lake margins. The most evident landforms are lakeshore levels marked by alternating dark and light bands, which reflect fluctuations in water level and the action of wave processes (Figure 11C and 14). These dynamics have shaped small erosional niches (Figure 11C), which may also correspond to ridges and backshore terraces formed by shoreline migration (Nordstrom & Jackson, 2012; Pierce, 2004). Water level fluctuations have been recognized to strongly influence active erosional and depositional processes along the shores (Figure 11C and SI3C), including wind and water erosion and cryoturbation (Bao et al., 2021; Kaczmarek et al., 2016; Mazaeva, Babicheva, & Kozyreva, 2020; Vilmundardóttir et al., 2010). The main erosional process during the gradual drawdown of the water level was vertical incision, which contributed to the development of gullies. These features initially formed through surface runoff erosion but were subsequently enhanced by wave action and fluctuations in water level. During low water stages, vertical erosion intensified due to the increased base-level fall, leading to deeper incision into the fine-grained bank sediments. The lowering of the reservoir also favoured subsurface runoff within the shore massif, promoting linear gully development. Moreover, high reservoir water levels stimulate landslide activity: wave-cut notches and slope retreat reduce slope stability. These cyclic processes, driven by seasonal and annual water level changes, hinder the stabilization of shoreline erosion (Bao et al., 2021; Kaczmarek et al., 2016; Mazaeva, Babicheva, &

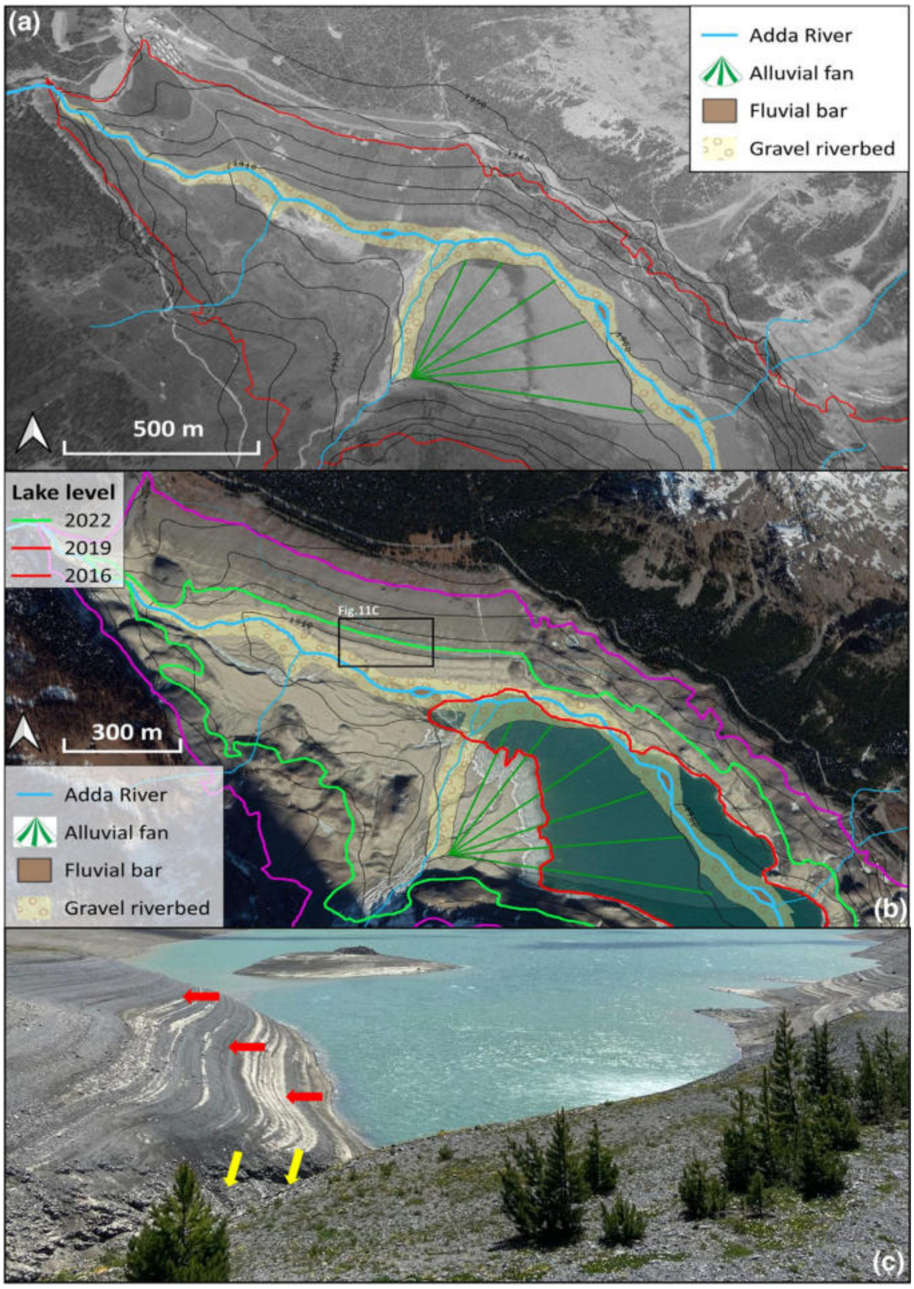

FIGURE 11 Geomorphological evolution of the Adda River in the Fraele Valley following reservoir construction. (A) Geomorphological map derived from the 1885 IGM map overlaid on a 1947 aerial imagery showing preserved and new submerged landforms (the red line represents the 2019 Lake level and black lines the contour lines). (B) Lake level variations (2016–2019-2022) highlighting shoreline and the Adda River submerged and subaerial geomorphic processes and landforms (black lines represent the contour line derived from 1885 IGM). (C) Field evidence (2023) of lake-level fluctuations, showing a shoreline sector, close to San Giacomo di Fraele village, affected by linear erosion (yellow arrows), sectors of the lakeshore reshaped by repeated lake-level rise and fall (red arrows).

Kozyreva, 2020; Vilmundardóttir et al., 2010) (Figure 11C). Although few studies have specifically addressed gully formation along reservoir shores, existing research agrees that continuous fluctuations in water levels prevent the stabilization of erosional processes. These cyclic changes significantly influence both gully development mechanisms and shoreline evolution, especially in areas with silty-sandy deposits. Understanding these dynamics is important for managing and mitigating the erosive impacts induced by artificial reservoirs. (Bao et al., 2021; Kaczmarek et al., 2016; Mazaeva, Babicheva, & Kozyreva, 2020; Petts & Gurnell, 2005).

6.3 | The evolution of debris flow fans in regulated reservoirs

The evolution of debris flow fans in the artificial basin environments of the Cancano and San Giacomo basins is a complex interplay of sediment transport processes, hydrodynamic interactions and anthropogenic influences. Debris flows play a crucial role in shaping the morphology of valley margins and influencing sediment dynamics within aquatic systems (Fan et al., 2020; Hutter, Svendsen, & Rickenmann, 1994). Historical analysis of the Cancano and San Giacomo reservoirs reveals the progressive transformation of debris flow fans over time, as captured in cartographic and photographic records. For instance, maps and images spanning from 1885 to 2022 and the 2023 field survey documented the dynamic nature of these depositional features, with marked changes in fan activity, shape and extent (Figures 10 and 11). The geomorphological interpretations with historical data and field survey illustrate the progression of active and inactive debris flow fans during key periods: 1882, 1931, 1945, 1953, 2016, 2019 and 2022–2023 (Figure 12A–E and 10B-C). These changes are further influenced by lake-level fluctuations and human activities due to the construction and operational activities related to the Cancano and San Giacomo dams. Notably, the position and activity of debris flow fans shifted due to sediment transport interruptions and variations in base level due to dam operations. The interaction between debris flows and lakes can lead to significant

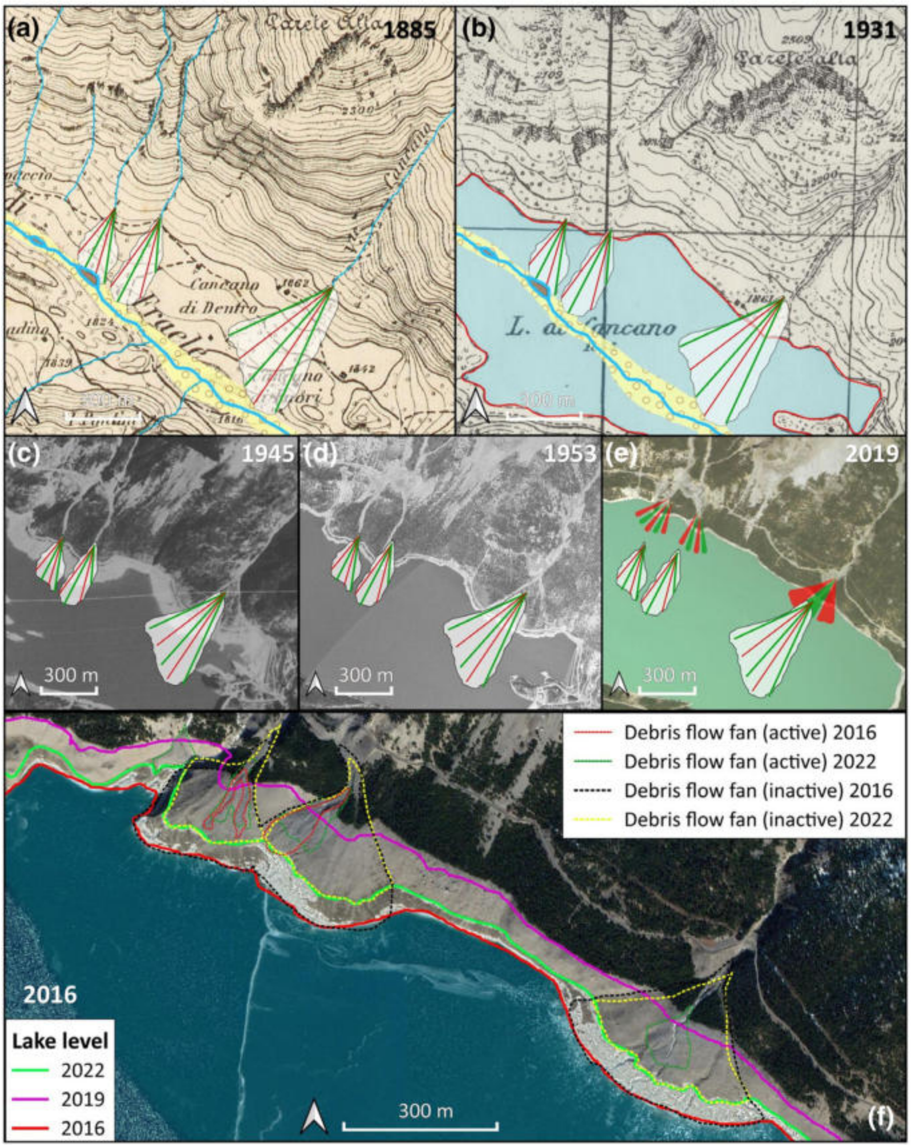

FIGURE 12 Evolution of debris flow fans in the Cancano and San Giacomo basins from 1885 to 2022. (A–B) Historical maps (1885, 1931) showing pre- and post-reservoir conditions. (C–E) Aerial and satellite imagery (1945, 1953, 2019) illustrating changes in fan activity and lake level variations. (F) 2016 satellite image with mapped active and inactive debris flow fans in 2016 and 2022, highlighting landform adjustments influenced by lake-level fluctuations (2023 field picture in Figure 10B).

morphological changes, including the formation of fan-deltas and sediment wedges, which are critical for understanding sediment delivery mechanisms in these environments (Figure 10B-C) (Słowik, Prekopová, & Budinský, 2024; Wei et al., 2012). For instance, under low lake-level conditions, as documented in the 2016 and 2022 satellite imagery and confirmed by the 2023 field survey (Figures 12F and 10B–C), extensive portions of the debris-flow fans surface become exposed, and the distributary channel is reactivated, revealing distinct patterns of sediment deposition and erosion. These conditions provide insights into how debris flows transition from terrestrial to aquatic environments, eroding and reshaping lakebeds to form sedimentary features such as channels, bars and wedges. The dynamics of debris flows entering lakes are influenced by various factors, including sediment composition and the hydrodynamic conditions of the receiving water body. Studies have shown that subaqueous debris flows can create distinct sedimentary features due to the interaction with existing lakebed topography (Kostaschuk, Aden, & Desloges, 2021). These morphological adjustments are detected in Figure 12E and F, which highlights how debris flow fans adapt to fluctuating hydrodynamic conditions induced by changes in lake levels (Figure 12E–F). Furthermore, the transition of debris flows into aquatic environments generates complex sedimentation processes (Schürch et al., 2016). The initial impact of these flows creates significant turbulence and sediment resuspension, while coarser materials settle to form fan deposits (Kostaschuk, Aden, & Desloges, 2021; Tsunetaka et al., 2022; Zaginaev et al., 2019). The 2019 satellite imagery (Figure 12E) highlights periods of high lake levels, during which debris flow fans are almost entirely submerged, allowing for sediment redistribution within the reservoir. Conversely, during periods of low water levels, vertical incision intensifies, exposing fans and activating gully formation along their edges (Schürch et al., 2016). The role of human activities, such as dam construction and land use change, further complicates sediment dynamics. Dams interrupt natural sediment transport pathways, modifying debris flow fan morphology. For example, the superimposed image from 1931 (Figure 12B) illustrates how the initial inundation of valleys by reservoirs modified fan structures. This intervention often results in sediment accumulation at river mouths while reducing sediment supply to downstream environments (Liro et al., 2020). Such changes are also evident in modern debris flow fans, which exhibit patterns of active deposition near stream mouths and progressive stabilization of distal areas (Harvey, 2012). Historical shifts in lake level, reconstructed through multitemporal analyses (Figure 12F) and field evidence (Figure 10B-C), underscore how periodic inundation and exposure of fan surfaces regulate depositional and erosional processes. For example, the progressive development of gully

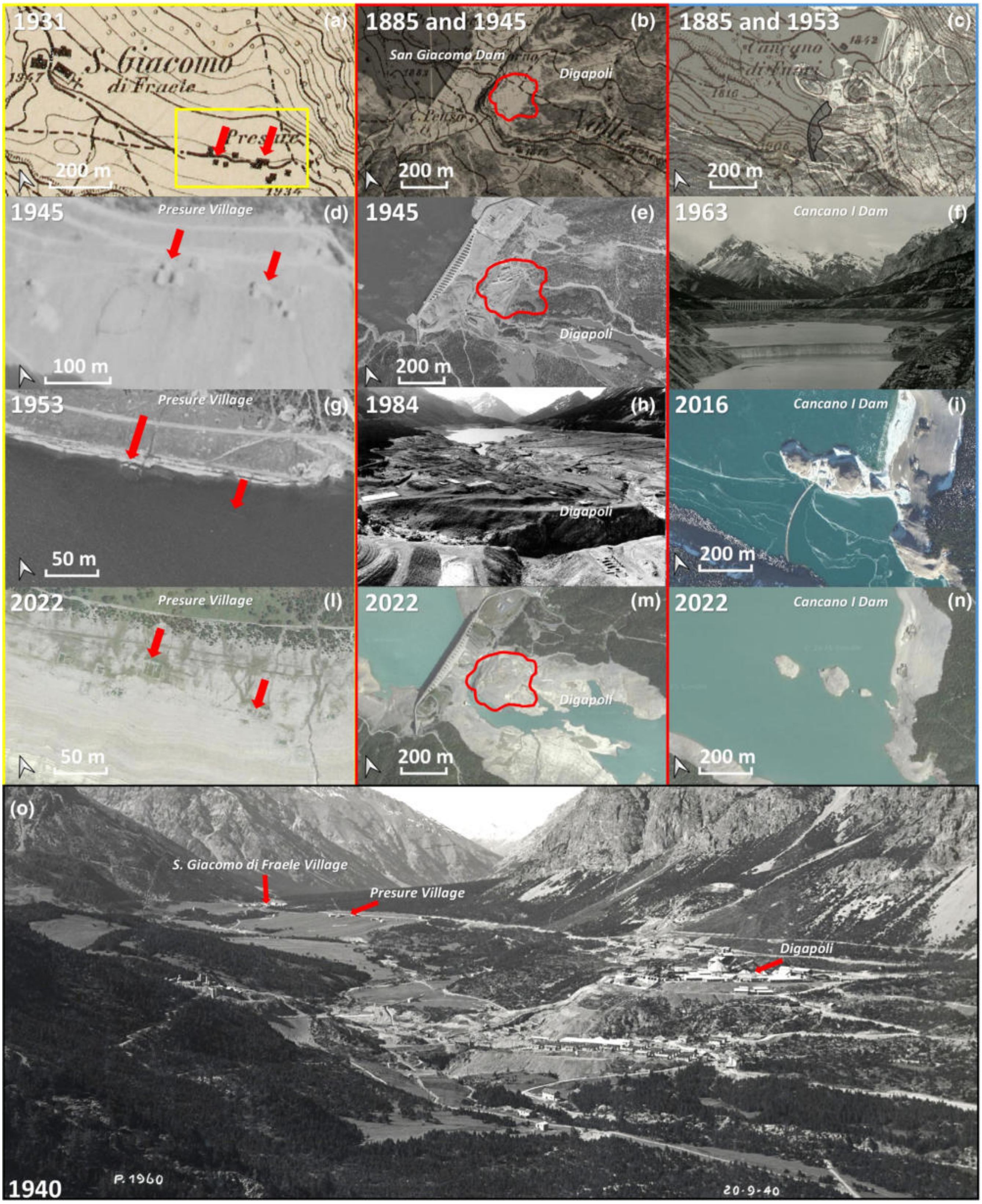

FIGURE 13 The transformation of the hydroelectric landscape in Alta Valtellina from 1885 to 2022. (A–C) Historical maps and aerial imagery of the sector close to the San Giacomo di Fraele Village, Digapoli and pristine Cancano I dam area. (D–F) 1945 and 1953 aerial photographs of Presure Village and its surroundings before the flooding related to S. Giacomo reservoir, and 1963 historical pictures of the Cancano I dam resurfaced. (G–N) photographs and aerial/satellite images documenting morphological and infrastructural changes from 1984 to 2022 in response to lake-level oscillations. (O) A 1940 photograph showed the San Giacomo di Fraele and Presure villages in their original state before extensive dam and reservoir modifications. Red arrows highlight key pristine and short-lived urban settlements (image source F, H, O: © AEM historical photographic archive, Fondazione AEM – Gruppo A2A, Milan).

systems along fan margins, driven by cycles of wave scouring, sediment saturation and groundwater fluctuations, reflects the dynamic response of these landforms to base-level changes (Bowman, 2019). Additionally, the influence of hillslope processes on debris flows is evident in the historical evolution of the Cancano and San Giacomo basins. The increase in hillslope processes during the late 19th and early 20th centuries contributed to the rapid formation and expansion of debris flow fans, as highlighted in the 1885 and 1945 datasets (Figure 12A,C). These features persisted through the 20th century, albeit with modifications caused by anthropogenic interventions, such as dam construction and regulated discharges. The ongoing evolution of debris flow fans in these contexts reflects the complex interplay of natural processes and human activities. The integration of historical imagery, geomorphological mapping and field validation into the image enables a detailed reconstruction of sedimentary and morphological changes, providing insights into sediment delivery, deposition patterns and shoreline dynamics. Understanding these processes is critical for managing and preserving the geomorphological and ecological integrity of lake systems in the face of climate change and increasing human pressures (Cui et al., 2010; Kafle et al., 2016; Koch, Clague, & Blais-Stevens, 2014; Schürch et al., 2016).

6.4 | Human geomorphology in the Cancano–San Giacomo di Fraele hydroelectric system

Large, dammed catchments represent some of the most emblematic Anthropocene landscapes, where human regulation has become the dominant driver of geomorphic processes, restructuring sediment pathways, altering hydrological regimes and reshaping connectivity across entire basins (Kelly et al., 2017; Skalak et al., 2013). In this perspective, rivers are increasingly conceptualized as disturbance-driven systems whose trajectories reflect the cumulative interaction of natural and anthropogenic drivers operating across multiple scales, often pushing fluvial environments beyond geomorphic thresholds and into

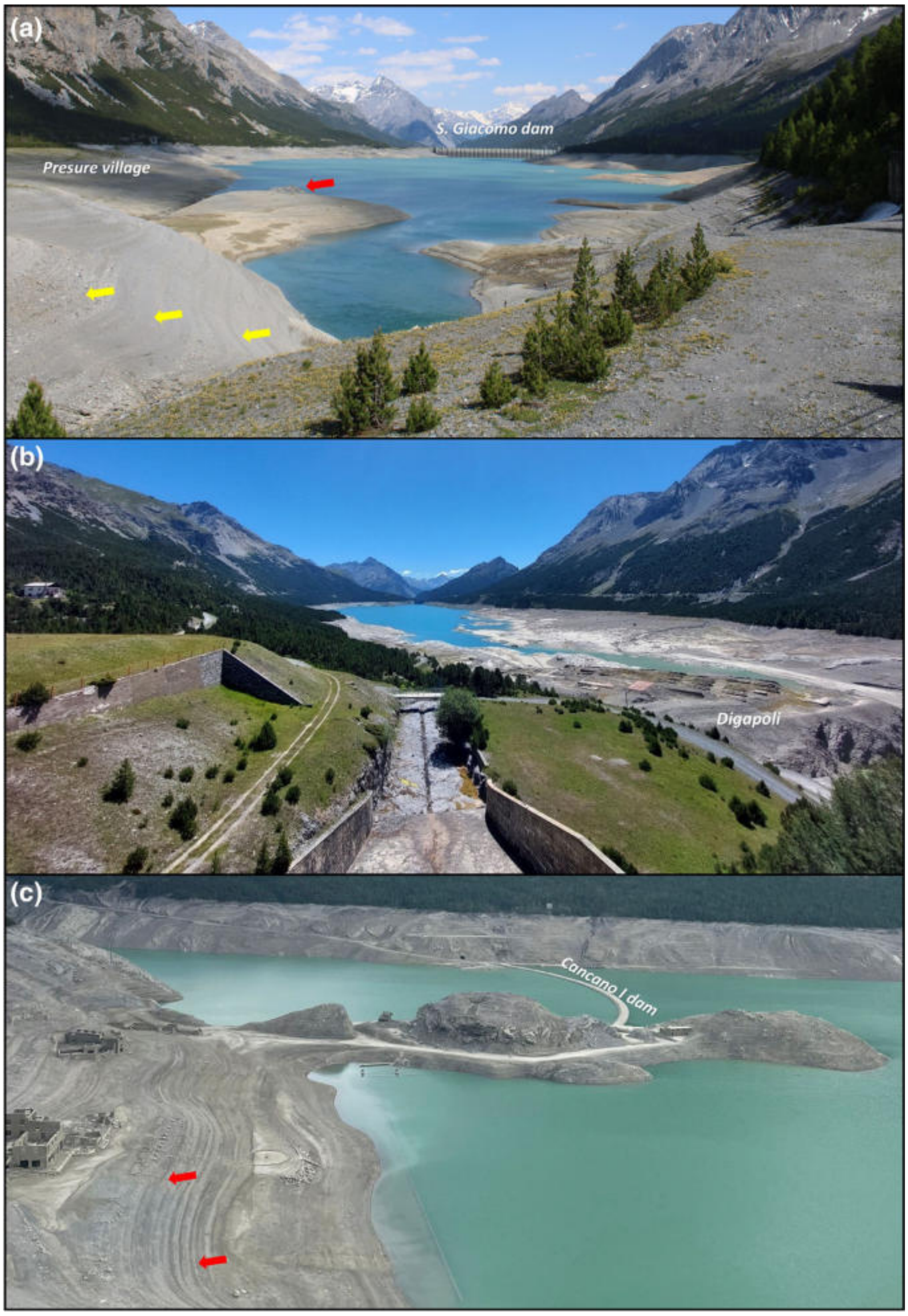

FIGURE 14 Field evidence recorded during the low-water phase observed in early summer 2023. (A) Panoramic view from the Adda River inflow area near the former village of San Giacomo di Fraele, where the remains of the Presure settlement are visible (stone piles, one indicated by the red arrow), together with shoreline reshaping in response to lake-level fluctuations (yellow arrows) (historical pictures in and 8B). (B) Detail of the central sector between the two reservoirs, showing the Viola drainage canal and, on the left, the re-emerging Digapoli valley (historical view in Figure 8E and F). (C) Low-water stage in the Cancano reservoir, where the former dam and workers' buildings re-emerge. Note the pronounced shoreline modelling associated with lake-level variations (red arrows) (historical pictures before the flooding in Figure 5B and 9D). The transformation observed from historical and present-day data of these three sector are represented in Figure 13.

new stability domains with reduced capacity for recovery. Recent advances in remote sensing and historical data integration provide a framework for diagnosing these trajectories, enabling multi-decadal reconstructions of channel change, shoreline evolution and sediment redistribution that cannot be captured through field observations alone (Piégay et al., 2020). The ability to combine historical aerial photography, cartography, satellite imagery and field evidence is particularly useful in highly regulated river systems, as it allows the identification of discontinuities, regime shifts and feedbacks associated with dam operation and shoreline adjustment, which represent key expressions of human geomorphology. (Piégay et al., 2020; Skalak et al., 2013). Within this broader framework, the Cancano–San Giacomo hydroelectric system provides a clear and well-documented example of reservoir-driven landscape transformation. Historical cartography and photographic evidence (Figures 13 and 14) illustrate the progressive transition from a natural alpine valley to a fully engineered hydropower landscape, marked by sediment redistribution, shoreline reconfiguration and the submergence and later re-emergence of former settlements. Comparable patterns have been documented in reservoirs affected by large water-level fluctuations, where repeated inundation and exposure phases promote bluff recession, gully development, shoreline erosion and redistribution of fine sediments (Figures 11, 12 and 14) (Forti et al., 2022; Mazaeva et al., 2013; Kaczmarek et al., 2016). Field observations in the Cancano–San Giacomo reservoirs during the 2023 low-water phase further reveal active shoreline erosion, reactivation of pre-existing drainage pathways and the exposure of submerged geomorphic features and former infrastructures, reflecting ongoing feedback between reservoir management, sediment dynamics and landscape connectivity (Figures 10, 11 and 14). The juxtaposition of historical and present-day satellite imagery with fieldwork underscores the persistence of human-induced geomorphic trajectories, where repeated water-level fluctuations and dam operations have established a new geomorphic regime controlled primarily by anthropogenic forcing (Kelly et al., 2017; Piégay et al., 2020). This case study highlights how large alpine reservoirs act as long-term geomorphic experiments, where anthropogenic forcing progressively overrides natural process–response systems, creating new, persistent landscape trajectories.

7 | CONCLUSION

This study demonstrates how large hydroelectric infrastructures in mountain areas significantly alter pristine geomorphological processes, modifying natural geomorphic dynamics, sediment connectivity and landform development. In the Fraele Valley, the construction of the Cancano I, San Giacomo and Cancano II dams led to the transformation of a dynamic fluvial system into a complex anthropogenic basin network. These interventions disrupted the Adda River's longitudinal continuity, submerged debris-flow fans and alluvial plains, and created new landforms such as fan deltas, subaqueous sediment wedges and gully networks along the reservoir margins. In such steep Alpine settings, dams function as geomorphic thresholds (Brandt, 2000; Lane, Gaillet, & Goldenschue, 2022), redefining sediment fluxes, altering valley-floor dynamics and creating a new scenario of slope instabilities exacerbated by fluctuating water levels. The Cancano dams, particularly Cancano II, exemplify how human activities may induce significant geomorphological feedback, including retrogressive erosion, local slope instabilities and sedimentation adjustments across a regulated hydro system.

In the context of ongoing climate change, these reservoirs may also serve a dual role: while they disrupt sediment continuity, they simultaneously act as sediment traps for debris flows (Cui et al., 2010; Fan et al., 2020), and as buffers against extreme discharge events that are expected to become more frequent due to increasing rainfall intensity (Duda & Bellmore, 2022; Poff et al., 2007).

The environmental reconstruction presented here outlines the importance of conducting detailed geomorphological studies in order to evaluate the effect of reservoir construction on the whole surrounding area, on the related natural processes and on the whole landscape. The change from a natural to a human reworked landscape also impacts the local geodiversity (Gordon, 2018) and geoheritage (Reynard, 2009) and on its human perception (Garavaglia et al., 2012). It is noteworthy to report how the prominent Italian Geologists Antonio Stoppani described the Fraele Valley in his Bel Paese (Stoppani, 1876): *Incisa tra due enormi pareti frastagliate di calcaree nere, ove si disegnano, con mille ondeggiature, contorsioni, mosse bizzarre, gli innumerevoli strati sovrapposti, la Val di Fraele è il tipo dello squallore. Quasi interamente chiusa, isolata dal mondo, può interessare il geologo che vi ammira nel loro più imponente sviluppo le calcaree alpine; ma è un regno di desolazione e di morte* [Carved between two enormous, jagged walls of black limestone—where with a thousand undulations, contortions and bizarre folds the countless overlaid strata are etched—the Val di Fraele is the very embodiment of desolation. Almost entirely enclosed and cut off from the world, it may captivate the geologist who admires there the Alpine limestones in their grandest development; yet it remains a realm of bleakness and death. Today, that same landscape is part of the Stelvio National Park and a well-frequented tourist destination thanks to its relevant aesthetic value, largely increased by the presence of artificial lakes. This transformation reflects an emerging recognition of anthropogenic landforms and hydroelectric heritage as integral components of Alpine geoheritage (Bollati et al., 2018; Reynard, 2009; Toso, 2014), with implications for territorial identity, conservation and landscape interpretation. The Cancano–San Giacomo area, with its intermittently exposed submerged landscapes and historical infrastructure and building remains, exemplifies the intersection between geoheritage and cultural heritage in transformed Alpine environments. The Fraele Valley thus offers a valuable example of how human activities reshape the high-mountain critical zone, with long-term consequences on geomorphic systems and landscape legacy (Leonelli et al., 2024). Recognizing the geomorphological, historical and geoheritage significance of such transformed environments is important to support informed and sustainable planning in the Alps.

AUTHOR CONTRIBUTIONS

Forti, Zerboni and Azzoni conceived the study. Azzoni acquired funding. Methodology was developed by Forti, Zerboni and Azzoni. Investigation was carried out by Forti, Azzoni and Zerboni. Data curation involved Forti, Azzoni, Zerboni, Morosini, Pelfini, Felletti, Zucali and Masseroli. Formal analysis was performed by Forti, Zerboni and Azzoni. Resources were provided by Forti, Trisoglio and Azzoni. Software was developed by Forti. Supervision was provided by Azzoni, Zerboni and Pelfini. Visualization was undertaken by Forti.

The original draft was written by Forti and Azzoni, and all authors contributed to reviewing and editing the manuscript.

ACKNOWLEDGEMENTS

We are particularly grateful to Fondazione AEM – Gruppo A2A, Milan, for granting access to its Historical Photographic Archive and for kindly authorizing the reproduction of historical photographs and technical sketches included in this study and the Stelvio National Park administration for granting permission and supporting the research. Funding was provided by the Italian Ministry of University and Research (Grant PRIN202223RAZZO, GEOTRes – Geoheritage threating and resilience: mapping the impact of geomorphic and human processes in sensitive morphoclimatic environments; entrusted to RSA). Part of the research was supported by the Italian Ministry of Universities and Research through the project “Dipartimenti di Eccellenza 2023–2027”, awarded to the Dipartimento di Scienze della Terra “A. Desio” of the Università degli Studi di Milano (WP2 and WP3) and by “Piano di sostegno alla ricerca: Linea 2, azione A anno 2023” (P.I. RSA). Open access publishing facilitated by Universita degli Studi di Milano, as part of the Wiley - CRUI-CARE agreement.

DATA AVAILABILITY STATEMENT

The data sets used and/or analysed during the current study are available from the corresponding authors on reasonable request.

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SUPPORTING INFORMATION

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How to cite this article: Forti, L., Pelfini, M., Masseroli, A., Zucali, M., Felletti, F., Morosini, S. et al. (2026) Reconstructing human-induced geomorphic changes through historical maps and multitemporal remote sensing data in the Cancano–San Giacomo di Fraele reservoirs (Central Alps, Italy). *Earth Surface Processes and Landforms*, 51(3), e70280. Available from: https://doi.org/10.1002/esp.70280