

Article

Large Dam Flood Risk Scenario: A Multidisciplinary Approach Analysis for Reduction in Damage Effects

Laura Turconi ^{1,*}, Fabio Luino ¹, Anna Roccati ², Gilberto Zaina ³ and Barbara Bono ¹

¹ National Research Council, Research Institute for Geo-Hydrological Protection, Strada delle Cacce 73, 10135 Turin, Italy; fabio.luino@cnr.it (F.L.); barbarabono@cnr.it (B.B.)

² Independent Researcher, Giuseppe Truffini 20, 21050 Lonate Ceppino, Italy; geolannaroccati@gmail.com

³ Independent Researcher, Via Albera 3, 25047 Darfo Boario Terme, Italy; gilbertozaina@geasncservizi.com

* Correspondence: laura.turconi@cnr.it

Abstract

Dam collapse is a catastrophic event involving an artificial reservoir usually filled with water for hydropower or irrigation purposes. Several cases of dam collapses have overwhelmed entire valleys, reconfiguring their geomorphology, redesigning their landscape, and causing several thousand casualties. These episodes led to more careful regulations and the activation of more effective monitoring and mitigation strategies. A fundamental tool in defining appropriate procedures for alert and risk scenarios is the Dam Emergency Plan (PED), an operational document that establishes the actions and procedures required to manage potential hazards (e.g., geo-hydrological and seismic risk). The aim of this study is to describe a reference methodology for identifying geo-hydrological criticalities based on historical and geomorphological data, applied to civil protection activities. A further objective is to provide a structured inventory of Italian reservoirs, assigning each a potential risk index based on an analytical approach considering several factors (age and construction methodology of the dam, morphological and environmental settings, anthropized environment, and exposed population). The approach identifies that the most significant change in risk over time is not only the dam itself but also the transformation of the territory. This methodology does not incorporate probabilistic forecasting of flood or climate change; instead, it objectively characterizes the exposed territory, offering insights into existing vulnerabilities on which to base effective mitigation strategies.

Keywords: dam emergency plan; large dam; historical flood; flood risk scenario; Italy



Academic Editor: Tiago Miguel Ferreira

Received: 13 August 2025

Revised: 1 October 2025

Accepted: 9 October 2025

Published: 11 October 2025

Citation: Turconi, L.; Luino, F.; Roccati, A.; Zaina, G.; Bono, B. Large Dam Flood Risk Scenario: A Multidisciplinary Approach Analysis for Reduction in Damage Effects. *GeoHazards* **2025**, *6*, 65. <https://doi.org/10.3390/geohazards6040065>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Dams have played an essential role in the management of water resources and have become fundamental to the development of modern societies. Their significance extends beyond hydropower generation, contributing to the regulation of water supplies for agriculture, industrial use, flood control, and recreational activities. The construction and use of dams have evolved over time, and their global spread can be traced through key periods of human history, with their importance peaking in the 20th and 21st centuries.

The world's largest dams are located in countries with significant water resources and growing demand for electricity, as well as flood protection. In many of these areas, dam construction is also linked to political, economic, and social reasons, such as transboundary water management or drinking water supply.

A dam is a structure built to hold back or control the flow of water, typically in a river or a stream, creating a reservoir. The primary purpose of a dam is to store water, and its

uses can be varied depending on the region (geology and geomorphology), technology, and the needs of the population. Dams have been constructed for centuries, evolving from simple earth and stone barriers to massive concrete structures that can hold back millions of cubic meters of water. The function of dams is multifaceted, with the most commonly recognized purposes being the generation of hydropower, flood control, irrigation, and potable water supply. More recently, the role of dams has expanded to include water recreation, ecosystem restoration, and climate change mitigation efforts [1–3]. Despite their benefits, dams are often subject to scrutiny due to their potential environmental impacts, including ecosystem disruption and displacement of communities. However, their role in water management remains indispensable in many parts of the world.

There are numerous cases in the world of flooding events with fatalities and extensive damage along rivers, due to the failure of large reservoir dams. The damage has often been underestimated, because entire valleys, villages, people, histories, monuments, productive activities have been wiped out by the floods. Italy is a major producer of hydroelectricity in Europe. Europe's geographical features, including its many rivers, valleys, and mountain ranges, make it ideal for large dams.

Italy, too, which has witnessed these anthropogenic floods, has undertaken management, organizational, urban and spatial planning initiatives with the intention of improving risk management and awareness. Large-scale civil protection systems and procedures have been adopted for risk mitigation. In Italy alone, numerous cases of large dam break and related damages are cited [4], such as the Gleno dam (1923, 356 fatalities) [5,6], Molare dam (1935, 111 fatalities) [7,8], Pontesei (1959, 1 fatalities) [9], Vajont (1963, 1917 fatalities) [10–12] and, Stava dam (1985, 268 fatalities) [13–15]. In these cases, where nearby settlements were razed, bridges and roads destroyed, pouring a wave of mud and debris down entire valleys.

The scientific community has been called upon to highlight the critical issues associated with the presence of large dams and for analyzing the risk associated with the damaging effects of a large dam collapse. The scientific literature proposes different analytical approaches based on geo-hydrological and hydraulic data, and different numerical models, e.g., [16–21]. These studies typically require large and detailed datasets, which are both scarcely available and subject to rapid temporal variations. A comprehensive assessment of the territory hosting a dam, together with the morphological and anthropogenic changes that have occurred since the reservoir's construction (often spanning more than a century), can significantly contribute to a more informed understanding of actual dam-related risk. The National Research Council, Research Institute for Geo-Hydrological Protection (CNR-IRPI) [22] has examined a significant number of large dams, proposing a simplified approach to support the development of Dam Emergency Plan (PED), aimed at capturing and providing meaningful interpretation of the factors contributing to risk amplification. The aim of this study is to highlight strategies for mitigating the risk of damage linked to the collapse of dams or incorrect maneuvers of the operating bodies connected to them, through a several factors analysis. The focus of the research was to evaluate the natural and anthropical variations (occurred in a mid-term period) along the river corridor and riverine areas down-stream a large dams. This is functional to correct planning of scenarios for the occurrence of geo-hydrological events, based on the history of the territory and geo-morphological evolution, through an index of potential factors of damage of dam failure (e.g., population increasing, infrastructures development, urban sprawl, historical floods, relative occurrence, etc.).

To describe the importance of prevention activities for dam risk, the development of initiatives was examined in an area that has historically been subject to damaging flood events caused by geomorphological and climatic factors. The case study of Valcamonica (Oglio River Valley, Lombardy Region, Italy) [23–27] is proposed. This alpine area, in

which many large dams are located, is representative of a touristic area and an intensely productive reality also due to the presence of hydroelectric power, which represents a rather high percentage of the national GDP of Italy [28].

2. General Settings

2.1. Damage and Benefits of Large Dams

The history of dam construction extends back to ancient civilizations. One of the earliest examples is the Sadd el-Kafara dam in Egypt (2700–2600 BC), an embankment dam built to retain floodwaters, today recognized as the world's oldest large dam (14 m high, 113 m long) [29]. Early dams, also built by Mesopotamians, Egyptians, and Romans, were relatively simple structures of earth and stone, designed primarily to support irrigation and agriculture. Despite their simplicity, they played a critical role in societies whose survival depended on crop production. The modern era began in the 19th century with the industrial revolution, when the use of concrete and advances in engineering enabled larger and more durable structures [29]. This period marked the beginning of large-scale construction in Europe and the United States, with notable examples such as the Niagara Falls Power Company Dam (1881) and the Assouan Dam in Egypt (1902). The 20th century witnessed an unprecedented expansion of dam projects worldwide, driven by industrial growth and energy demand. The Hoover Dam (1936) [30] became emblematic of this phase, serving millions in the southwestern United States. Later, large-scale projects, often supported by international organizations such as the World Bank, proliferated in developing countries to foster irrigation, agriculture, and electricity supply. The Aswan High Dam (1970) and the Three Gorges Dam in China (2012) stand as milestones of this era. While construction continues, recent decades have seen a shift in emphasis. Large projects remain common in developing economies, yet greater attention is now paid to sustainability and social impacts [31], reflecting tensions between proponents and opponents [32,33]. Dams today are central not only to hydropower but also to water management, ensuring agricultural productivity in arid and semi-arid regions, supporting industrial processes, and supplying urban centers. Systems such as the Indus Basin in Pakistan [34], and cities like Los Angeles and Cape Town [35], highlight their strategic importance. Dams also mitigate floods by regulating reservoir releases during extreme precipitation and snowmelt, as demonstrated in South Asia, Bangladesh, and parts of the United States. Nonetheless, large dams raise profound ecological and social concerns. Reservoir creation often submerges forests, wetlands, and habitats, resulting in biodiversity loss [36–38]. Major projects displace populations, as in the case of the Three Gorges Dam, which forced the relocation of over one million people [39]. Failures in karst terrains, cumulative environmental degradation, as observed in Iran, where ca. 500 dams have caused deforestation and disrupted indigenous communities [40], further underline the challenges. Climate change compounds these issues, exposing dams to altered precipitation regimes, glacial retreat, permafrost degradation, landslides, and outburst floods, which can accelerate sedimentation, reduce storage capacity, and threaten dam stability [41,42]. In the 21st century, priorities in many developed countries have shifted from building new dams to maintaining and upgrading existing infrastructure, alongside ecological restoration projects aimed at mitigating negative impacts. Dams remain emblematic of 20th-century large-scale engineering, yet their high hazard potential, capable of generating catastrophic downstream floods in case of failure, continues to fuel public sensitivity and concern. Their dual role, as essential infrastructure for water and energy security and as potential sources of risk, underscores the urgent need for sustainable design, management, and monitoring.

Actually, dams are classified based on height, purpose, and construction material. According to the World Commission on Dams (WCD), large dams can be over 15 m in height

and generally involve significant alterations to the environment, including the displacement of populations and changes in ecosystems [43]. The International Commission on Large Dams (ICOLD) [44] defines a large dam as a structure that holds back water to create a reservoir for various purposes such as hydropower generation, flood control, irrigation, or water supply. In total, there are over 50,000 large dams worldwide, with many being key drivers of industrialization and urbanization, particularly in developing nations. Dams are constructed along some of European major rivers, including the Rhine, Danube, Seine, and Volga. However, Europe is generally less reliant on large dams compared to other continents due to the availability of other water management systems and regulations on environmental impacts. In Europe, the primary purpose of dams tends to be hydropower, flood control, and navigation.

2.2. Global Dam Safety Legislation

Historically, dam safety regulation has often been reactive, emerging in response to catastrophic accidents that revealed critical gaps in engineering and risk management [45,46]. Today, most countries have adopted legal frameworks, although approaches vary depending on geography, governance, and industrial priorities.

In the United States, the Federal Energy Regulatory Commission (FERC) oversees dam safety, supported by the Dam Safety Program (1967) and the National Dam Safety Program Act (1996), which institutionalized a risk-based inspection regime [47,48]. States complement federal standards; for example, California requires inspections of all dams at least every five years [49]. China, which has the largest number of dams globally, introduced the Law on the Safety of Dams in 2007, mandating five-year evaluations with emphasis on flood risk and structural integrity, and expanding regional monitoring systems [50]. India's Dam Safety Act (2019) created a central authority to harmonize inspection standards across states, supported by the National Committee on Dam Safety [51].

In Europe, dam legislation has been shaped by cross-border risks. The EU Water Framework Directive (2000/60/EC) promotes sustainable water management and integrates dam safety into flood risk planning [52], while the Seveso III Directive (2012/18/EU) extends to reservoirs involving hazardous substances [53]. The EU Dam Safety Guidelines (2009) [54], although non-binding, provide best practices on design, monitoring, hazard classification, and emergency planning. National legislations build on this framework: the UK Reservoirs Act (1975, revised 2010) [55] mandates risk assessments for reservoirs >25,000 m³; France's Water Code (1964) [56] requires regular inspections and classifies dams by hazard potential.

Overall, dam safety regulation has evolved from reactive to increasingly proactive frameworks, reflecting growing recognition of dam-related risks in water management and environmental policy [57–64].

2.3. The Role of Dam Disasters in Shaping Legislation in Italy

The Gleno, Molare, Vajont, and Stava disasters in Italy [4–15,65–71], in particular, served as pivotal moments that shaped national and international policies. This article delves into the legislative responses to dam safety, with a focus on Europe and Italy, examining how these events often influenced policy and law.

On 1 December 1923, the structural failure of the Gleno Dam triggered a catastrophic flood event that severely impacted the Scalve Valley (Province of Bergamo, Lombardy, Northern Italy). The breach released an estimated 6×10^6 m³ of water, sediment, and debris from the reservoir located at ca. 1500 m a.s.l. The flood wave propagated downstream to Lake Iseo within approximately 30 min, causing widespread destruction along the valley floor. The event resulted in 356 confirmed fatalities. Failure occurred when the

central section of the dam collapsed, initiating a rapid outflow. The advancing flood was preceded and intensified by a high-magnitude air displacement wave, further increasing the destructive potential [65].

On 13 August 1935 the Molare Dam (maximum capacity of 855 m³/s) following a prolonged drought an extreme rainstorm (364 mm in <8 h with peak of 554 mm; 182 mm in 2 h) struck the upper Orba Valley, in Alessandria Province (Piedmont, Italy). This rainfall data are equivalent to 30% of the annual average [65]. Rapid reservoir filling prompted emergency opening of the bottom discharge valves, which soon failed due to mud and debris accumulation. Discharge capacity was then limited to 650 m³/s via the spillway and siphons, while inflow peaked at 1800–2200 m³/s. The overtopping began at both dams, causing severe erosion of jointed rock at Sella Zerbino's saddle. Successively, the secondary dam collapsed under hydrostatic pressure and rock destabilization. The Molare Dam in Italy experienced a significant safety issue, where cracks in the dam's structure raised concerns about its integrity [66,67]. While the dam did not collapse, it resulted in major investigations and a renewed focus on the safety of existing reservoirs. It spurred additional regulatory oversight for dam structures, particularly those that had been in place for a long time. The Italian government implemented more stringent safety guidelines for the operation and monitoring of dams, including better protocols for emergency preparedness.

The Vajont Dam disaster is one of the most infamous dam failures in history [68–70]. Located in northern Italy, the Vajont Dam was overtopped on 9 October 1963, by a massive landslide into the reservoir, which generated a 250 m high flood wave. The resulting flood devastated the valley below, killing nearly 2000 people. This disaster highlighted serious flaws in dam design, construction, and management. Subsequently, Italy passed laws aimed at improving the safety of dams and the regulation of reservoirs. The Law 1/1964, which came into effect shortly after the Vajont tragedy, required more stringent safety assessments for dams and better management practices for reservoirs. The Vajont disaster remains a milestone event that shaped Italy's dam safety legislation and prompted further international scrutiny of dam safety standards.

The Stava dam failure occurred on 19 July 1985 when two tailings dams of fluor used for mining operations collapsed in the Stava Valley, releasing a torrent of water and debris [65,71,72]. Though technically not a traditional water reservoir failure, it had a similar impact in terms of catastrophic loss of life and property. The Stava disaster prompted further review of industrial dams and tailings facilities in Italy. It led to the implementation of stronger safety standards for industrial reservoirs and greater attention to the risk of water-related accidents from mining operations.

In Italy, dam safety is regulated by Decree 156/2014, which aligns national legislation with EU directives and establishes a comprehensive framework for dam risk management [73]. The law applies to all large dams, requiring systematic risk assessments, regular inspections, and maintenance protocols. It also created the National Dam Safety Authority (NSDA), responsible for enforcing standards and ensuring uniform compliance across the country. Under this decree, dam owners must conduct periodic inspections and report on structural integrity, with particular emphasis on risks to human life, property, and the environment under extreme weather scenarios.

The current framework was strongly shaped by past catastrophic events which exposed serious safety deficiencies and catalyzed legislative reforms. As a result, three core principles underpin Italy's dam safety regime: (i) stronger inspection standards, with increased frequency and depth; (ii) risk mitigation focused on the potential consequences of dam failure, particularly loss of life; and (iii) centralized oversight through the NSDA, which harmonizes safety practices nationwide. This evolution reflects a broader European trend toward proactive risk governance, combining lessons from past tragedies with ad-

vances in monitoring technology and civil protection strategies. Current Italian regulations emphasize not only structural evaluation but also the development of detailed mitigation and emergency planning measures to ensure human safety.

A proven methodological approach from CNR IRPI (National Research Council, Research Institute for Geo-Hydrological Protection) [22] is proposed for the preparation of Dam Emergency Plan (PED). The approach is applied also where are multiple dams in a single river basin, with potential “cascading” effects according to scenarios of possible occurrence.

3. Materials and Methods

3.1. The Large Dams Census in Italy

In Italy, of the large dams, 530 of them [74], the majority are built for hydroelectric power generation, but they also serve other purposes, including flood control and agricultural irrigation (Figure 1). Italy, characterized by its mountainous terrain and extensive river networks, hosts numerous significant large dams, particularly concentrated in the northern regions such as Piedmont, Lombardy, and Trentino-Alto Adige. The country is among the leading producers of hydroelectric power in Europe.

Reservoirs could store water during periods of abundance and allow producers to use it in times of scarcity, thus regulating river flows independently from climatic and meteorological conditions. After World War I, reservoirs received increasing attention from producers because they could store water during periods of water abundance and allow it to be used in times of scarcity. In fact, a severe drought in the early 1920s highlighted the hydrological vulnerability of the hydroelectric energy regime. In the following years, the number of hydroelectric reservoirs increased considerably. By the end of the 1950s, there were over 140 dams on many tributaries of the Po River. Of Italy’s 530 dams, more than 71% were built before 1965 (Figure 1). The analysis reveals that 26.4% of Italian dams are used for irrigation purposes, while those dedicated to hydroelectric power generation account for 58.1%, of which 35% are located in northern Italy, benefiting from the favorable morphology of the Alpine regions. The remaining 15.5% of dams are distributed among other purposes, including water reservoirs, flood attenuation (lamination), industrial use, or multiple functions (Figure 1).

With regard to dam construction types, the dataset indicates that flow-regulating barriers (weirs) are predominant in central and southern Italy. In contrast, gravity and arch dams are more common in the Apennine regions and parts of the Italian Alps (northern Italy) (Figure 1), generally reflecting the altitudinal and morphological features of the Italian territory.

The territory has undergone profound transformations over the decades, particularly in the period following the construction of large dams. Significant financial investments have been directed toward the expansion of productive, industrial, residential, and tourist areas. The river sections downstream of the reservoirs have been heavily anthropized, to the extent that they are no longer capable of conveying flood discharges comparable to design flows, nor those predicted by original dam break scenarios and/or operational procedures of the facilities. This analysis highlights the existing issues in early warning, planning, and prevention procedures, which are often based on a static view of the territory, frozen in a geomorphological interpretation that reflects the conditions at the time the infrastructures were built, in some cases dating back to the early 20th century. These aspects are crucial for a proper assessment of the risk associated with the presence of large hydraulic reservoirs and can be effectively updated using appropriate approaches, such as PEDs. Today, these areas are also highly frequented by tourists, who are often unaware of the potential geo-hydrological events that may occur and the related risks due to the

presence of dams. A thorough analysis of the environmental context in which the structure is located, its current condition, and the transformations of the surrounding territory, along with an assessment of the exposed population and assets, can therefore provide an updated and realistic perspective of the risk associated with dams.

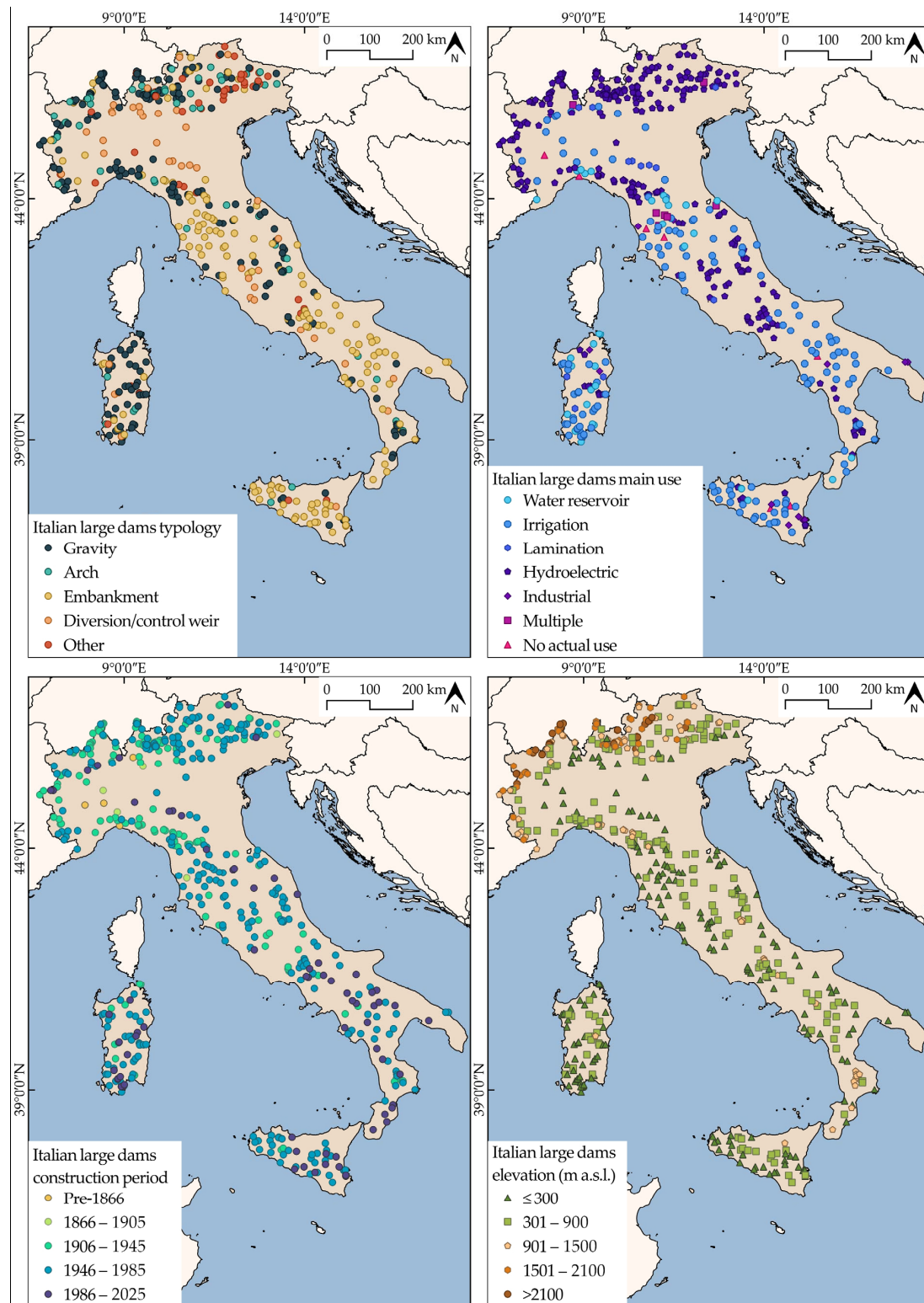


Figure 1. A multi-panel figure illustrating the 530 large Italian dams [74] classified and geolocated within a GIS software (3.40.11). These dams are categorized based on construction type (**top left**), main use (**top right**), construction period without further temporal specifications regarding maintenance/expansions (**bottom left**), and their elevation location (**bottom right**).

A simplified method is proposed, complementary to existing approaches (e.g., [58]) and not intended to be exhaustive, which does not include specific studies on probabilistic flood forecasting or climate change projections, factors that certainly and often exponentially increase risk. The method relies on the assignment of indices to factors considered significant in aggravating risk, which can be easily obtained through historical and cartographic analyses. Therefore, it can be applied even with limited resources and with information that is relatively simple to obtain. The main factors considered most significant for assessing exposure to Dam Break risk, for which specific indicators have been developed, are: (i) increase in population; (ii) tourism pressure; (iii) expansion of built-up areas; (iv) road infrastructure density; (v) degree of anthropization of the riverine area; (vi) artificiality of the main stream; (vii) presence of strategic structures. These aspects are complemented by analyses concerning the recurrence of flood events, the presence of relict and obsolete morphologies associated with former fluvial patterns, the role of tributaries, the land-use changes, and the environmental context of the site where the dam is located. These latter components have been deliberately assigned a quali-quantitative evaluation, in order to integrate both measurable and interpretative dimensions into the overall assessment framework.

3.2. The Analysis of Dams-Location Potential Failure

Based on the national inventory of large dams in Italy [74], a classification system has been developed to identify a reference index representing the intrinsic criticality of the context in which each dam is situated. This index incorporates multiple variables, including the dam's construction age, structural typology, geomorphological setting, slope instability characteristics, and seismicity of the area. The construction age is important in the stability analysis of the structure in relation to the natural degradation of construction materials and/or the lack of maintenance of the facilities [75]. These factors influence the overall stability of the structure. Each parameter was weighted using a three-level numerical scale, with values ranging from 1 to 3, where 3 corresponds to the most adverse condition. The cumulative score defines a qualitative failure index for the territory influenced by the dam, categorized into three classes: low, medium, and high. A higher overall score suggests the need for more detailed investigations into potentially critical environmental factors. Such cases should be prioritized for continuous and targeted monitoring, in order to prevent the aggravation of geo-hydrological and geomorphological hazards that could ultimately compromise the structural stability of the dam itself (Table 1).

Table 1. Context-Based Evaluation of Criticality Factors for Hydraulic Reservoir Structures.

Description	1	2	3
Geomorphological and Topographic Setting	Floodplain regions	Hilly regions	Mountainous regions
Slope failures and drainage network instability	Localized minor shallow instabilities near the dam (e.g., rockfalls, soil slips); minimal tributary presence with negligible sediment transport; no recorded avalanche activity	Widespread small-scale landslides near the reservoir; lateral tributaries show low to moderate torrential sediment supply. No recent avalanche activity recorded.	Fractured rock slopes with active deep and shallow landslides, tributaries delivering debris flow, and frequent avalanche activity
Seismic zoning of the municipality(ies) where the dam is located [76–78]	Zone 4	Zone 3	Zone 1–2

Similarly, to the classification-based assessment of the area surrounding the hydraulic retention structure, a specific set of considerations is proposed to evaluate the downstream river reach, based on a range of factors (Table 2). This analysis aims to contextualize the increasing severity of potential adverse impacts resulting from dam-break scenarios or flood events triggered by operational maneuvers, particularly in a territory that has undergone substantial transformation since the dam was originally constructed.

Table 2. Critical factors downstream of a large dam articulated on three class of severity.

Factor	Description	1	2	3
A	Increase in the population	<100%	101–150%	>151%
B	Tourism pressure	<3	4–10	>10
C	Increase in the built-up areas	<2	3–5	>6
D	Road infrastructure density	<2	3–5	>6
E	Anthropized riverine area	<25%	26–50%	>51%
F	Main stream artificiality	L	M	H
G	Strategic structures	L	M	H

Key factors include land-use changes, the expansion of urban centers, the development of transportation infrastructure [79], and the general increase in public services. Significant attention is also given to the transformation of fluvial and riverine areas, which has led to substantial modifications in the river regime [80–82]. In addition to demographic growth, increased territorial usage is also driven by heightened tourism demand. Many mountainous regions now represent year-round tourist destinations, leading to the establishment of numerous accommodation facilities within alpine valleys (see Figure 1). The increase in population is particularly important as a factor exacerbating risk conditions in a territory that has been significantly altered since the time of reservoir construction. To evaluate this population growth, recent data [83] was compared with the one at the time of dam construction [84], referring to the period immediately preceding the construction of each individual dam (Table 2).

Population increase was classified into three ascending categories: Class 1 (increase < 100%), Class 2 (101–150%), and Class 3 (>151%) (Table 2, letter A). Moreover, increasing tourism pressure in recent decades has led to the widespread accessibility of areas previously characterized by predominantly agricultural or pastoral use. These areas are now frequently reached via excursion trails; cycle routes; unpaved roads; and, in some cases, cableways and vehicular roads. This enhanced accessibility has facilitated the development of tourist infrastructures such as campgrounds and hospitality facilities, especially along valley floors and alluvial fans. To assess tourist pressure in Italian municipalities, particularly within the Alpine Region, the number of tourist arrivals in 2023 was normalized by the resident population for the same year [85]. This ratio was then classified into three categories (1 to 3) reflecting the relative increase in population exposed to potential risk (Table 2, letter B): Class 1 (<3 times the resident population), Class 2 (4–10 times), and Class 3 (>10 times).

The increase in population and demand for accommodation facilities has led to a corresponding expansion of built-up areas. To quantify this growth, the extent of current built-up areas (CORINE Land Cover, CLC 2021) [86] was compared to that of 1954 (CLC 1954) [86]. This parameter was categorized into three classes of increasing impact (Table 2, letter C): Class 1 (increase < 2 times), Class 2 (3–5), and Class 3 (>6 times).

The presence of artificial lakes has further contributed to the recreational appeal of these areas, particularly in the summer months, as they are often easily accessible via an extensive network of trails and secondary roads. Road infrastructure density was estimated as the total length of roads (in kilometers) [86] per square kilometer of area (Table 2, letter

D). This factor was classified into three categories: Class 1 (density $< 2 \text{ km/km}^2$), Class 2 ($3\text{--}5 \text{ km/km}^2$), and Class 3 ($>6 \text{ km/km}^2$).

To assess the degree of anthropogenic impact on the riverine area, a 500 m buffer was applied on both sides of the median axis of the Oglio River, resulting in a total river corridor width of 1 km. For this purpose, the CLC 2021 dataset [86] was used. From this dataset, the areal extent of impervious surfaces was extracted, yielding variable percentages, which were then classified into three categories of increasing severity: Class 1 ($<25\%$), Class 2 ($26\text{--}50\%$), and Class 3 ($>51\%$) (Table 2, letter E).

Of particular relevance is the assessment of river channel artificialization, due to the presence of various longitudinal and transversal hydraulic structures that constrain the watercourse and limit its lateral mobility. This artificialization is evaluated along the entire channel length and its banks, with specific reference to the disruption of river continuity with floodplains and tributaries [80,81,87]. The entire stretch of the main watercourse is in the highest class of artificialization (Class H) [81,88]. This value is reported with letter F in Table 2. In the assessment of territorial vulnerability associated with the presence of large dams, several additional factors must be considered. Among these are the recurrence and severity of major flood events, the expansion of urbanized areas since the dam's construction, and the degree of anthropogenic alteration of the river corridor. This factor has a significant impact on the floods, especially in areas where longitudinal and transversal structures interrupt the natural connectivity of the river system and its tributaries.

The transformations have stimulated local economic activity, contributing to a rise in resident populations and the proliferation of second homes. Consequently, these developments have amplified the potential socio-economic impacts of flood events and the associated risks linked to hazardous processes originating from upstream reservoirs (Table 2). Among the exposed structures, greater weight was given to the presence of schools, healthcare facilities, high-risk industrial plants, gathering places, military areas, airports, and railway stations, assigning them a higher risk class. The current presence of these elements was compared to their original distribution within the same area, based on conditions in 1954. Three classes of increasing severity were identified: Class 1 (no increase in sensitive elements), Class 2 (up to a twofold increase in the number of initial elements), and Class 3 (increases exceeding this threshold) (Table 2, letter G). For each factor, a score of zero was assigned in cases where the analyzed data could not be assessed.

The integrated assessment of these factors allows for the classification of downstream areas, encompassed within the updated scenarios of the PED, according to levels of territorial criticality (Table 3). Classifications ranging from medium to high reflect a progressively worsening condition in terms of stability, particularly in zones potentially subject to dam failure and downstream flooding processes.

Table 3. Assignment of criticality classes occurs based on the total score calculated using Table 2.

Class	Low	Medium	High
Total score	<7	8–14	$>15\text{--}21$

3.3. The Dam Emergency Plans in Italy

PEDs are documents that define the operational phases and activities that the Italian Civil Protection system must undertake to manage any dangers related to dams in a coordinated and planned manner. PEDs are required by specific national legislation, represented by the Directive of the Italian President of the Council of Ministers of 8 July 2014 “Operational guidelines relating to civil protection activities within basins where large dams are present” [73]. The coordination between the PED and the Civil Protection Plans (PPC) of the municipalities where the dam is located or that are affected by its potential

risk is fundamental. The PPCs must contain all the risk scenarios present in the territory, including those outlined in the PED, with the related intervention models. A municipality could, among other things, be affected by more than one large dam; in this case, its PPC, in relation to this specific risk, must consider all the dams whose effects affect the municipal territory. In Italy, there is a considerable number of large dams for which the relative PED must be drawn up, pursuant to the Italian Directive 08/07/2014 [73]. The Directive also establishes that the PEDs incorporate the Civil Protection Documents (DPC) approved by the competent Prefecture–Territorial Government Office (UTG) as well as the Lamination Plans (PL) if prepared. The PED refers to the downstream hydraulic risk and the dam break risk: the first is related to the flood wave originated by the maneuvers of the discharge organs, the second by the collapse of the barrier (as reported in the studies of the propagation of flood waves referred to, e.g., in Lombardy Region Circular DSTN/2/2280/1995) [89]. The complexity of some PEDs also concerns the potential domino effect of one dam on another due to their position in cascade within the same hydrographic basin. For each dam, the PED is prepared and approved by each interested Region, in coordination with the Prefectures-UTG competent for the territory: the Region in whose territory the dam is located and the Region whose territories could be affected by the effects of the artifact. For the drafting of the PEDs, the Lombardy Region has set up a multidisciplinary Working Group, in consideration of the contents required by the Directive 08/07/2014. These contents are in fact the responsibility of various regional Directorates General and Bodies of the enlarged regional system, as well as Bodies external to the regions, such as the Ministry of Infrastructure and Transport—Directorate General for Dams and Water and Electricity Infrastructure, Prefectures-UTG, Provinces, Municipalities, Mountain Communities, Land Reclamation Consortia, Dam Managers, Interregional Agency, District Basin Authority, Bodies managing essential services and infrastructures. The working methodology adopted therefore includes meetings of the aforementioned Working Group for the sharing of the structure and contents of the PEDs as well as for the mutual exchange of information and specific documents. Technical inspections are also organized in the territories with the Prefectures-UTG, the reference Provinces and the Municipalities involved to define risk scenarios, intervention models, and the areas for gathering rescuers at provincial/regional level, following the criteria dictated by the Operational Guidelines relating to “the determination of the general criteria for identifying the Operational Coordination Centre and Emergency Areas” issued by the Italian Head of the Civil Protection Department on 31 March 2015. Once the Working Group approves the individual PED, the approval process for the same is carried out by the Regional Council. The development of PEDs has required close coordination with the Department of Civil Protection, particularly in addressing several key issues. These include: (1) the analysis of artificial flood wave propagation scenarios, both for controlled releases and hypothetical dam failures, conducted by dam operators. Although approved by the Ministry of Infrastructure and Transport, these studies, including floodplain shapefiles, are considered preliminary and must be validated through site-specific inspections and updated using current cartographic data; (2) the presence of geo-hydrological hazards affecting reservoirs and associated infrastructure, representing a multi-risk context (geo-hydrological, hydraulic, and dam-related) that necessitates an integrated analytical and planning approach, especially in cases involving potential domino effects among dams; (3) the involvement of multiple adjacent administrative regions sharing exposure to dam-related risks from the same infrastructure; and (4) the aging of dam structures and ongoing extraordinary maintenance works authorized by the Ministry, which require corresponding updates to existing PEDs during and after completion of the interventions.

Consequently, multiple approval acts will be necessary for the same PED. In addition, some regions have approved the list of reservoirs on which the evaluation of a Lamination Plan is a priority and a document of “Guidelines on flood lamination actions and plans” that completes the hydraulic study.

3.4. The Valcamonica Dams: A Case Study in an Vulnerable Area of Italian Central Alps

3.4.1. The Features of the Oglio River Valley

The Oglio River, originating from the Stelvio (Ortles-Cevedale) mountain group (3905 m a.s.l.), represents the primary fluvial axis of the Oglio River Valley (also known as Valcamonica) extending ca. 80 km and draining a 1500 km² basin with an average elevation of 1535 m. This Alpine valley encompasses three major structural domains, Austroalpine and South Alpine crystalline basements, and the South Alpine sedimentary unit, intersected by the regionally significant Insubric Tectonic Line. Valcamonica is shaped by intense glacial and post-glacial geomorphic processes, including extensive moraine systems, thick alluvial deposits, and slope instability phenomena. Deep-seated gravitational slope deformations (DGPVs), active alluvial fans, and gorges significantly influence the morphology of the river and hydrodynamics. These features act as both sediment sources and natural retention structures but also as potential triggers for mass movement hazards. Geo-hydromorphological hazards are concentrated in steep tributaries, where frequent debris flows, high sediment yields, and torrential regimes pose risks to downstream floodplains and infrastructure. The Oglio River exhibits a stepped longitudinal profile typical of glaciated valleys, punctuated by hydroelectric dams and natural or artificial impoundments. Downstream of Oglio River, the floodplain becomes increasingly vulnerable to debris flows from lateral catchments, with natural damming and floodplain constriction intensifying geo-hydrological risk. Urban expansion, particularly since the mid-20th century, has substantially altered floodplain morphology through channelization, embankments, and infrastructure development, reducing the natural flood of the river attenuation capacity and increasing exposure to flooding, bank erosion, and sediment accumulation [90]. In the lower valley, the Oglio River transitions to a low-gradient system characterized by braided, meandering channel dynamics. Fluctuations in Lake Iseo water level also influence flood behavior, potentially causing backwater flooding of adjacent lowlands during high lake stages. Climatically, Valcamonica ranges from an alpine to Insubric mesoclimate, with significant seasonal and altitudinal variation in temperature and precipitation. These conditions, coupled with snowmelt-driven runoff, contribute to flash flood and debris flow susceptibility, especially in high-relief areas. Precipitation peaks locally at ca. 2000 mm/year, further enhancing geo-hydrological instability.

Although population density remains moderate, the presence of settlements, critical infrastructure, and industrial activities within the floodplain heightens the potential consequences of geo-hydrological events. By the late 19th and early 20th centuries, before the arrival of large-scale electric utility companies, small cooperative societies emerged to provide electricity for public and private lighting in various municipalities through small hydroelectric plants. Systematic exploitation of water resources in Valcamonica began with the establishment of major corporations in the early 20th century, leading to large-scale hydropower projects. Despite challenges such as the two World Wars and harsh environmental conditions (e.g., construction sites in Oglio River basin were over 2000 m a.s.l.), hydroelectric expansion continued, culminating in major infrastructure developments by the late 1950s. Historical exploitation of hydropower resources led to widespread dam construction and water regulation infrastructure, which, while crucial for energy production, also interacts with natural hazard processes. Therefore, the Oglio River basin is characterized by high geomorphological complexity and multiple, interacting geo-

hydrological hazards, including debris flows, landslides, flooding, sediment overloading, and riverbed instability. These processes are driven by a combination of geological setting, steep morphologies, climatic forcing, and anthropogenic pressures, necessitating integrated hazard assessment and mitigation strategies across the basin.

3.4.2. Large Dams in Valcamonica Area

In Valcamonica area ten large dams are located, most of which were completed between 1930 and 1960 (Table 4) [74]. All of them are currently operational and primarily used for hydroelectric power generation. The dams of Lago Benedetto, Lago d’Avio, Pantano d’Avio, Vasca di Edolo, and Venerocolo belong to the same system (Avio System). The remaining dams are part of the Poggia-Remulo hydroelectric system (Lago Baitone, Lago d’Arno, Lago Salarno, Poggia) and the “La Rocca” hydroelectric plant (Lago di Lova) (Figure 2).

Table 4. Technical details and the extent of the area potentially affected by the individual failure of large dams located in Valcamonica [74].

Dam	Finishing (Year)	Typology	Elevation (m a.s.l.)	Structural Height (m)	Impounded Volume (10 ⁶ m ³)	Area at Risk (km ²)	Main Use
Lago Baitone	1930	Gravity	2291	37.90	10.65	27	Hydroelectric
Lago Benedetto	1940	Gravity	1929	31.00	6.96	33	Hydroelectric
Lago d’Arno	1927	Gravity	1817	36.85	22.80	25	Hydroelectric
Lago d’Avio	1929	Gravity	1902	39.55	12.38	30	Hydroelectric
Lago di Lova	1935	Embankment	1302	18.00	0.46	2	Hydroelectric
Lago Salarno	1928	Gravity	2084	38.4	11.34	23	Hydroelectric
Pantano d’Avio	1956	Gravity	2376	59.00	12.67	36	Hydroelectric
Poggia	1950	Gravity	626	49.40	0.50	4	Hydroelectric
Vasca di Edolo	1984	Embankment	640	23.90	1.32	24	Hydroelectric
Venerocolo	1959	Gravity	2529	26.90	2.55	34	Hydroelectric

3.4.3. Geo-Hydrological Hazard in Valcamonica

Geo-hydrological risk factors in Valcamonica, analyzed by historical research, are linked to both natural elements (such as geological structures, geomorphology, landslide- and flood-prone areas) and human-induced factors (including urbanization, land-use changes, land management practices, dam and reservoir construction, infrastructure development on unstable slopes, and the alteration of natural drainage systems). All these factors contribute to an increased probability of geo-hydrological hazards. Furthermore, changes in precipitation patterns and rising temperatures can exacerbate these hazards, leading to more frequent and severe events.

The earliest known records of flood events of the Oglio River date back to the year 1204. However, these accounts are generic and of limited reliability, providing limited information on the affected areas. More detailed data, even if still referring generally to damages within municipal territories and lacking exact spatial references, have been available since the 16th century, becoming progressively more numerous and detailed over time, reported in Table S1 [91–95]. In most cases, flood events were triggered by intense or prolonged rainfall and localized severe thunderstorms that affected only specific areas, either in the upper basin or in the mid-to-lower sections of Valcamonica. In other cases, flooding impacted only a limited number of municipalities, often spread along the valley and sometimes far apart. These were linked to hydrometeorological events concentrated in certain lateral sub-basins, which caused sudden tributary floods and led to hydraulic issues along the main Oglio River floodplain.

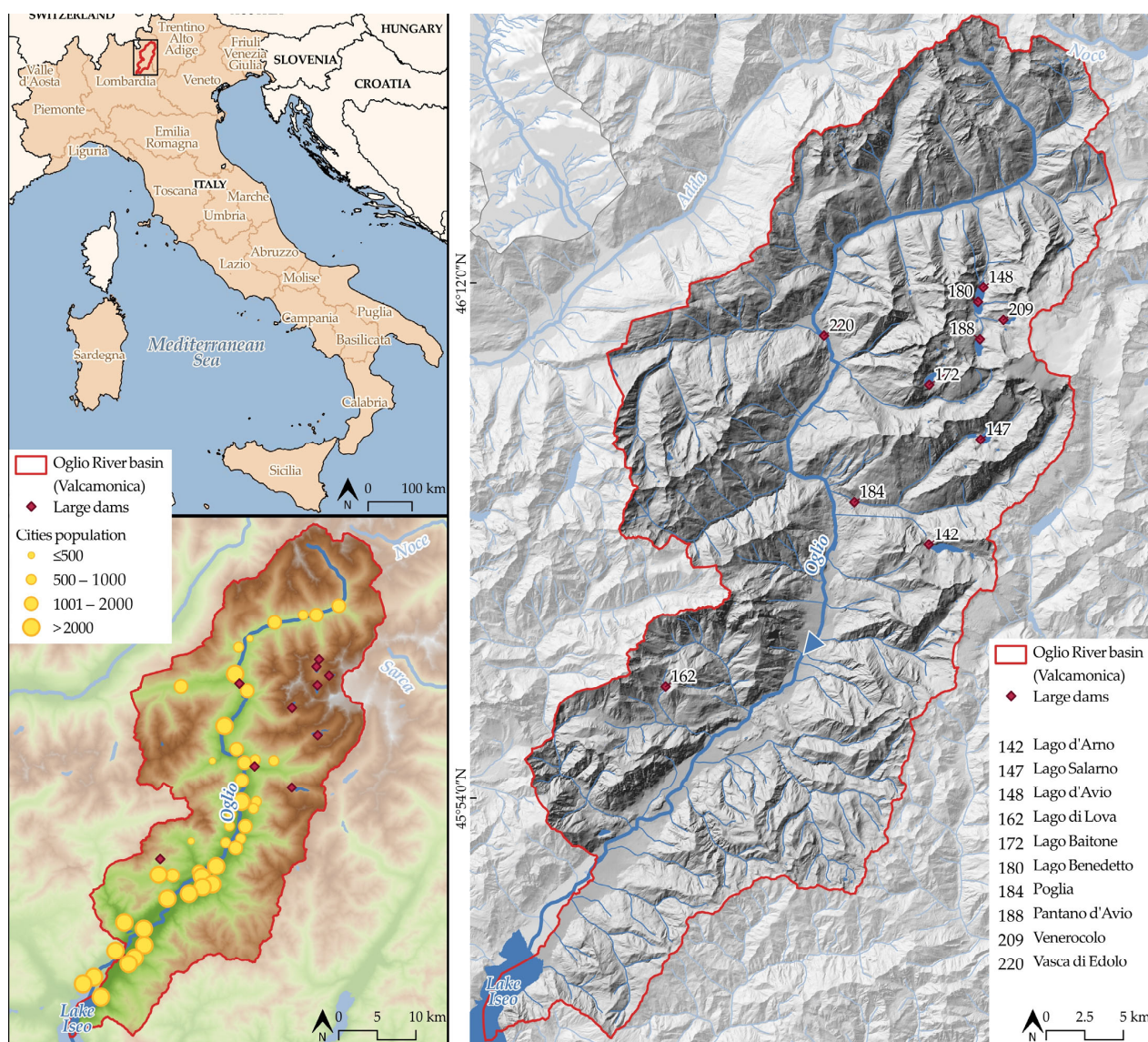


Figure 2. Large dams in Valcamonica and their corresponding national census number [74]. The blue arrow indicates the Oglio River flow direction.

Following this historical analysis, the municipal territory was classified into zones with different levels of flood occurrence. Specifically, five classes were defined based on the frequency of flood-related reports in each municipality during the period 1506–2023 (Table 5, Figure 3): Low (0–5 occurrences), Medium (6–15), High (16–25), Very High (>26), and No Data (N.D.).

Table 5. Flood events and relative frequency occurrences (period: 1506–2023) affecting the municipalities of Valcamonica [91–96].

Municipalities	Abbreviation	Flood Events (No)	Flood Frequency Occurrence
Artogne/Gianico	AR/GN	5	Low
Berzo Demo	BD	13	Medium
Braone	BRA	13	Medium
Breno	BRE	15	Medium
Borno/Ossimo	BO/OS	5	Low
Capo di Ponte	CDP	13	Medium
Cedegolo	CG	20	High

Table 5. *Cont.*

Municipalities	Abbreviation	Flood Events (No)	Flood Frequency Occurrence
Cerveno/Ono San Pietro	CR/OSP	13	Medium
Ceto	CE	16	High
Cevo/Saviore dell'Adamello	CO/SA	6	Medium
Cividate Camuno	CC	20	High
Costa Volpino	CV	1	Low
Darfo Boario Terme	DBT	46	Very High
Edolo	ED	17	High
Esine	ES	21	High
Incudine	IN	11	Medium
Losine	LO	4	Low
Lovere	LV	1	Low
Malegno	ML	1	Low
Malonno	MA	13	Medium
Monno	MO	6	Medium
Niardo	NR	4	Low
Paspardo	PA	N.D.	N.D.
Pian Camuno/Pisogne	PC/PS	2	Low
Piancogno	PI	1	Low
Ponte di Legno	PDL	19	High
Rogno	RO	1	Low
Sellero	SE	N.D.	N.D.
Sonico	SO	20	High
Temù	TM	20	High
Vezza d'Oglio	VDO	14	Medium
Vione	VI	27	Very High

The 16–17 September 1960 flood event was considered as the main flood event in 20th century for Valcamonica, causing over 205 million euros in damages [96] (corresponding at 13 billion Italian Lire of 1960 [97]). This flood event has damaged almost half of the Valcamonica municipalities (18 over 37), the majority of them situated in the floodplain (Figure 4).

3.4.4. Planning and Civil Protection Strategies for Geo-Hydrological Risk in Valcamonica

In Italy, protection plans often overlap with various territorial planning instruments (e.g., urban planning, land-use, landscape planning) and risk representation frameworks (e.g., seismic, avalanche, and geo-hydrological hazards) [98]. To date, no standardized multi-hazard tool exists that is uniformly adopted across all Italian regions. For the Lombardy Region, the territorial planning instruments reviewed include the landslide and flood hazard map (Inventory of Landslide in Italy, IFFI) [99], the Hydrogeological Structure Plan (PAI) [100], the Flood Risk Management Plan (PGRA) [101], and the avalanche hazard map. In Valcamonica, these regulatory references are further complemented by dam risk scenarios proposed by the Ministry of Infrastructure and Transport. In the same area, Civil Protection instruments also identify additional risk zones (e.g., seismic, wildfire). The Valcamonica territory may simultaneously be affected by geo-hydrological processes, defined through geomorphological or, in some cases, historical criteria. The PED, as previously described, delineates potential flood-prone areas based strictly on hydraulic modeling, considering various dam failure mechanisms or operational scenarios.

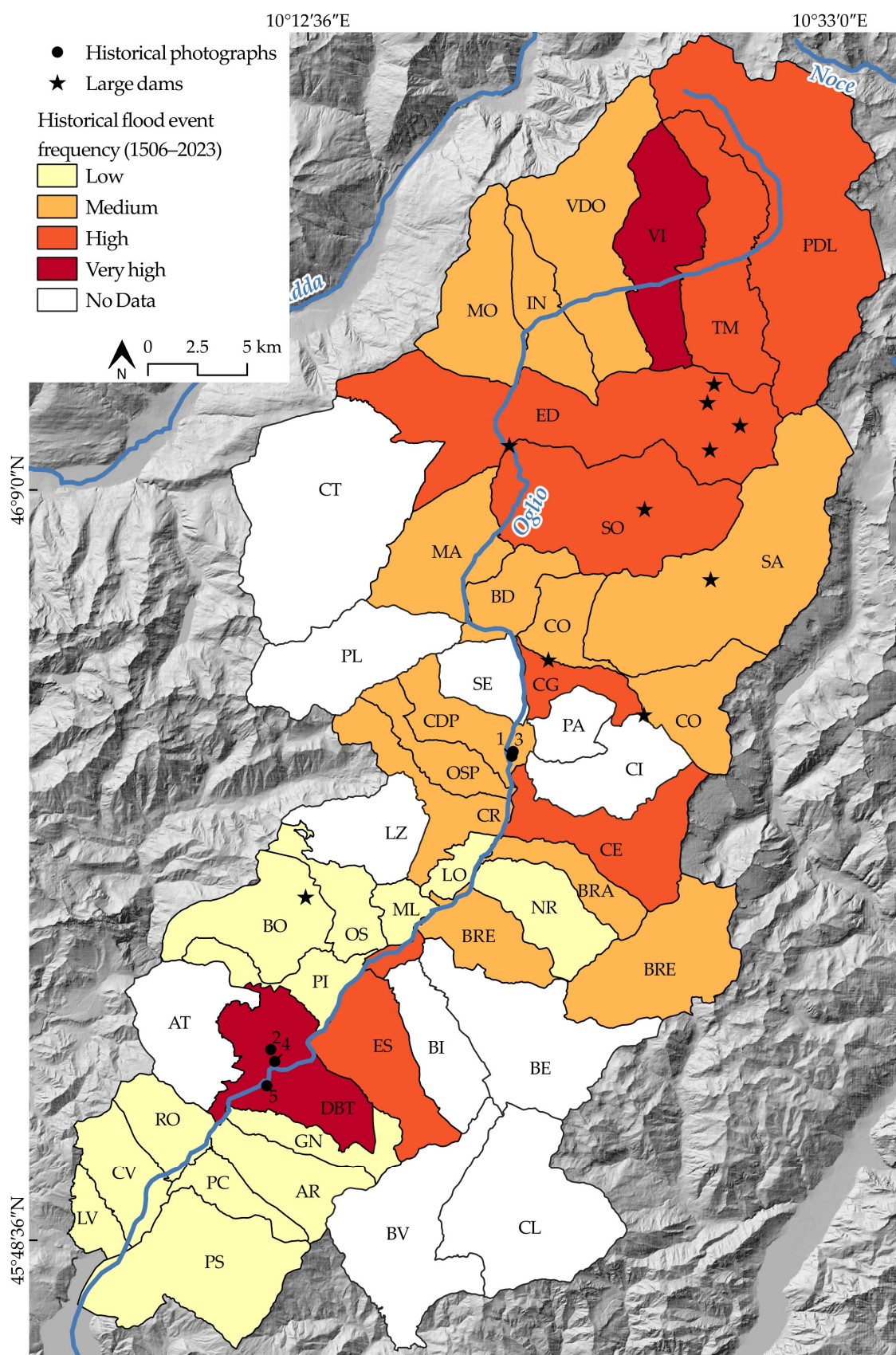


Figure 3. Valcamonica municipalities affected by damaging torrential and fluvial events since the 16th century. The color gradient, with increasing intensity, highlights the areas most impacted by such events (see Table 5). Black dots indicate sites affected by the 1960 flood event, with historical photographs presented in historical images reported in the text [92]. Dams located in this area are marked with black stars.



(a)



(b)

Figure 4. Historical images of Valcamonica area, respectively (a) Capo di Ponte and (b) Darfo Boario Terme, affected by the 1960 flood. For their location, refer to Figure 3. The historical flooded areas were used as a reference for the improving of dam break scenarios, in addition to other data [92].

The spatial representations of these overlapping hazard frameworks do not always coincide perfectly across the territory (see Figure 5).

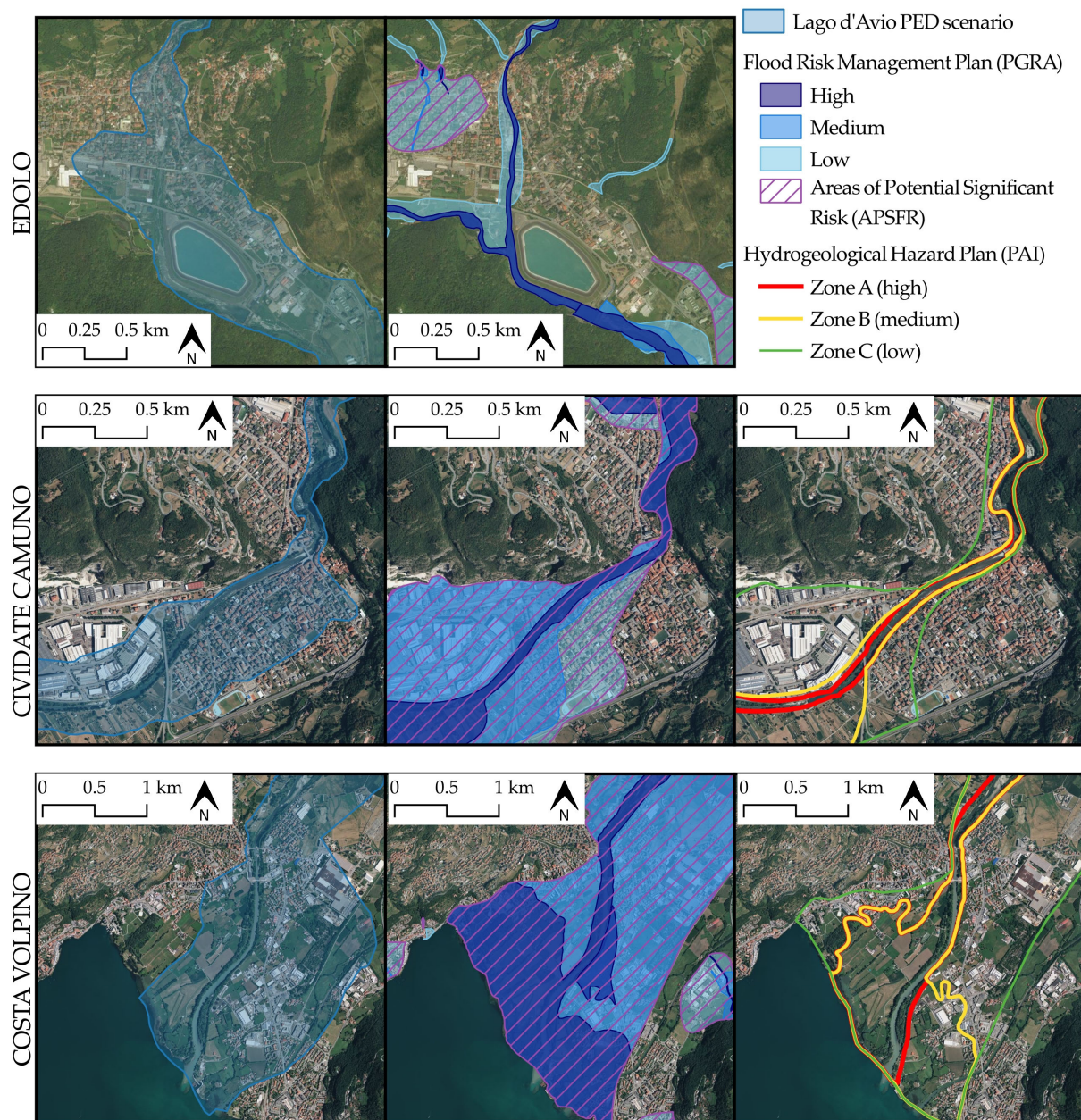


Figure 5. Three areas in Valcamonica (Edolo, Cividate Camuno, and Costa Volpino, respectively, ED, CC, CV in Figure 3) where differences in the application of current planning instruments (PED, PGRA, and PAI) [100,101] are evident.

The CNR-IRPI, responsible for drafting the technical aspects of the PED, structured the document to provide the relevant authority (Lombardy Region) with a consolidated operational tool addressing geo-hydrological hazards (floods, landslides, avalanches), seismic risks, and incorporating historical flood events through integrated historical reconstruction using complementary and diachronic methods. Often, the reference to areas affected by the damaging effects of historical events serves as the starting point for analyzing territorial vulnerabilities to refine the PED's collapse scenario maps, which are not based on a single actual event but rather on the maximum documented flood levels. This approach has highlighted portions of territory potentially involved in dam collapse scenarios that were not included in the original version provided by the Ministry of Infrastructure and Transport. The methodology considers current morphologies, relict features, and evidence of obsolete flow directions of watercourses. Each river section is described in detailed sheets specify-

ing critical issues, past events, scenario integration, and identification of sensitive areas. The PED also places particular emphasis on standardizing alert and emergency response strategies according to municipal Civil Protection plans, which must be integrated.

4. Results

4.1. Population Exposed to Dam-Related Risk in the Study Area

The population exposed to dam-related risk was estimated by considering the increase in the number of residents within the area affected by the dam collapse scenario over the period 1861–2021 (Figure 6) [83,84]. The observed trend indicates a continuous growth, particularly pronounced during the first decade of the 1900s, the post-World War II period through the 1980s, and the early 2000s. For each PED, the increase was calculated relative to the most recent census conducted prior to the construction of the dam.

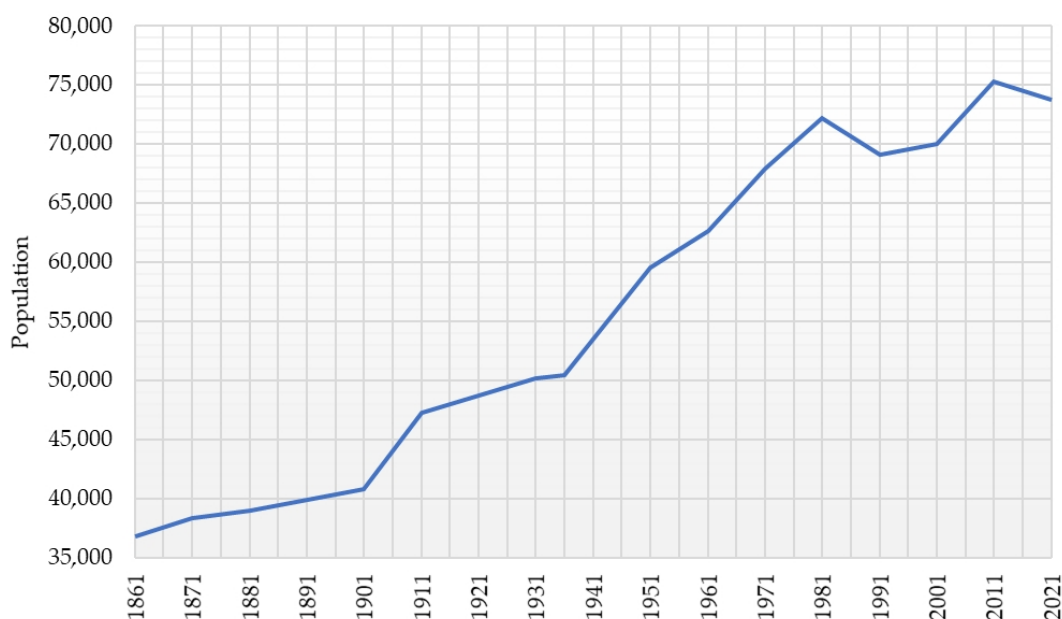


Figure 6. Trend of the resident population in Valcamonica (period 1861–2021) [83,84].

In addition to the resident population, the analysis also takes into account the number of tourists present in the area during the year 2023 (Figure 7), as a further component of the population potentially exposed to dam-related risk. The inclusion of tourism data provides a more comprehensive assessment of exposure, particularly in areas with significant seasonal population fluctuations [85].

The data concerning both the resident population exposed to dam-related risk and the annual tourist presence have been analyzed as indicators of territorial criticality. The combined analysis allows for a more comprehensive understanding of the population potentially at risk and contributes to more informed risk management and emergency planning. The results of this analysis are summarized in Table 6.

The values presented in Table 6, analyzed according to the criteria outlined in Table 2, lead to the analytical results summarized in Table 7.

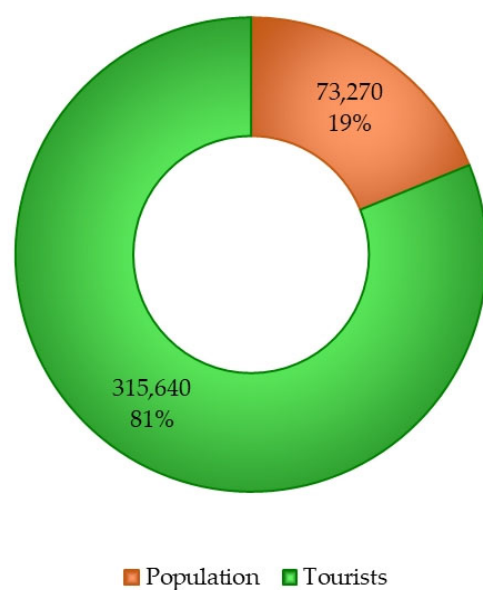


Figure 7. Resident population and tourist presence according to the most recent available data, for the year 2023 [83,85].

Table 6. Percentage increase in population, calculated by comparing the latest census conducted prior to dam construction with the resident population in 2023. The tourism pressure index is also reported, expressed as the ratio between the number of tourists in 2023 and the resident population in the same year (see Section 3.2).

Dam Area	Increase in Population	Tourism Pressure
Lago Baitone	151%	4.31
Lago Benedetto	145%	4.31
Lago d’Arno	180%	4.31
Lago d’Avio	151%	4.31
Lago di Lova	151%	4.31
Lago Salarno	155%	4.31
Pantano d’Avio	145%	4.31
Poglia	145%	4.31
Vasca di Edolo	108%	4.31
Venerocolo	123%	4.31

Table 7. Criticality indices related to the factors “increase in population” and “tourism pressure”.

Dam Area	Increase in Population	Tourism Pressure
Lago Baitone	3	2
Lago Benedetto	2	2
Lago d’Arno	3	2
Lago d’Avio	3	2
Lago di Lova	3	2
Lago Salarno	3	2
Pantano d’Avio	2	2
Poglia	2	2
Vasca di Edolo	2	2
Venerocolo	2	2

4.2. Land-Use Changes

The Valcamonica has undergone significant transformations over time, resulting in substantial changes in land-use and a reduction in natural areas. By comparing the 1954 CLC dataset with that of 2021 [86], it was possible to quantify the extent of these changes

(Figure 8). The most notable variations include not only a decrease in natural areas (from 44% to 27%), but, more significantly, an increase in urbanized areas (from 3% to 15%) and industrial and commercial areas (from 1% to 12%), largely at the expense of the former.

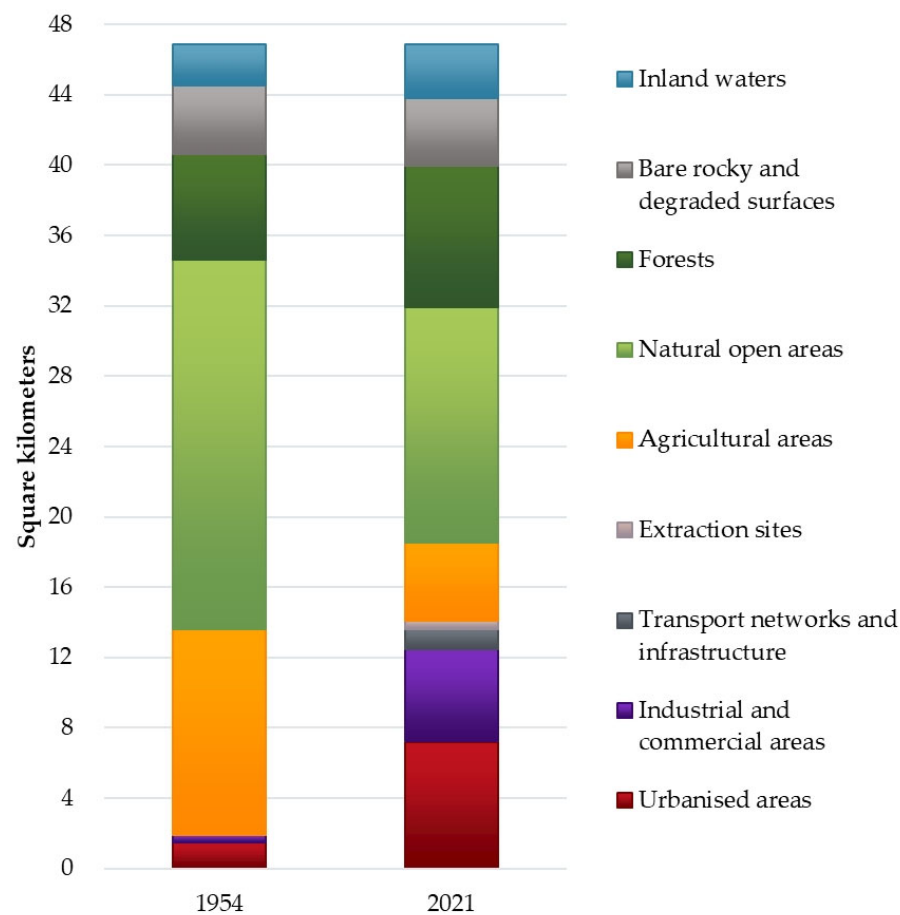


Figure 8. Comparison of 1954 CLC and 2021 CLC [86].

Specifically, for the areas identified by the PED dam collapse scenarios, the increase in built-up areas was assessed relative to the situation at the time when construction works began, based on the earliest available CLC dataset from 1954 [86] (Figure 9, Table 8). This analytical assessment also includes transportation networks, considered as the linear development of the entire road system, without distinction between municipal, regional, highway roads, and railways (Table 8).

The indices reported in Table 8 were analyzed following the methodology and criteria outlined in Table 2. This analysis led to the derivation of the values summarized in Table 9, providing a comprehensive assessment of the critical factors considered.

4.3. Riverine Area Transformations

The riverine area along the main course of the Oglio River within the dam collapse scenario zones was analyzed in terms of the urban sprawl and the degree of artificialization. Regarding the latter, reference was made to specific studies [88]: for each geomorphologically homogeneous river stretch of the Oglio River, anthropogenic elements constraining natural flow laterally and transversely were evaluated, influencing the trend and dynamics river. The entire Oglio riverbed was classified as having a high to very high degree of artificialization [88]. For the calculation of impermeable surfaces within the riverine area, the most recent 2021 CLC dataset was used within a 500 m buffer from the median line of the current Oglio River [86] (Table 10).

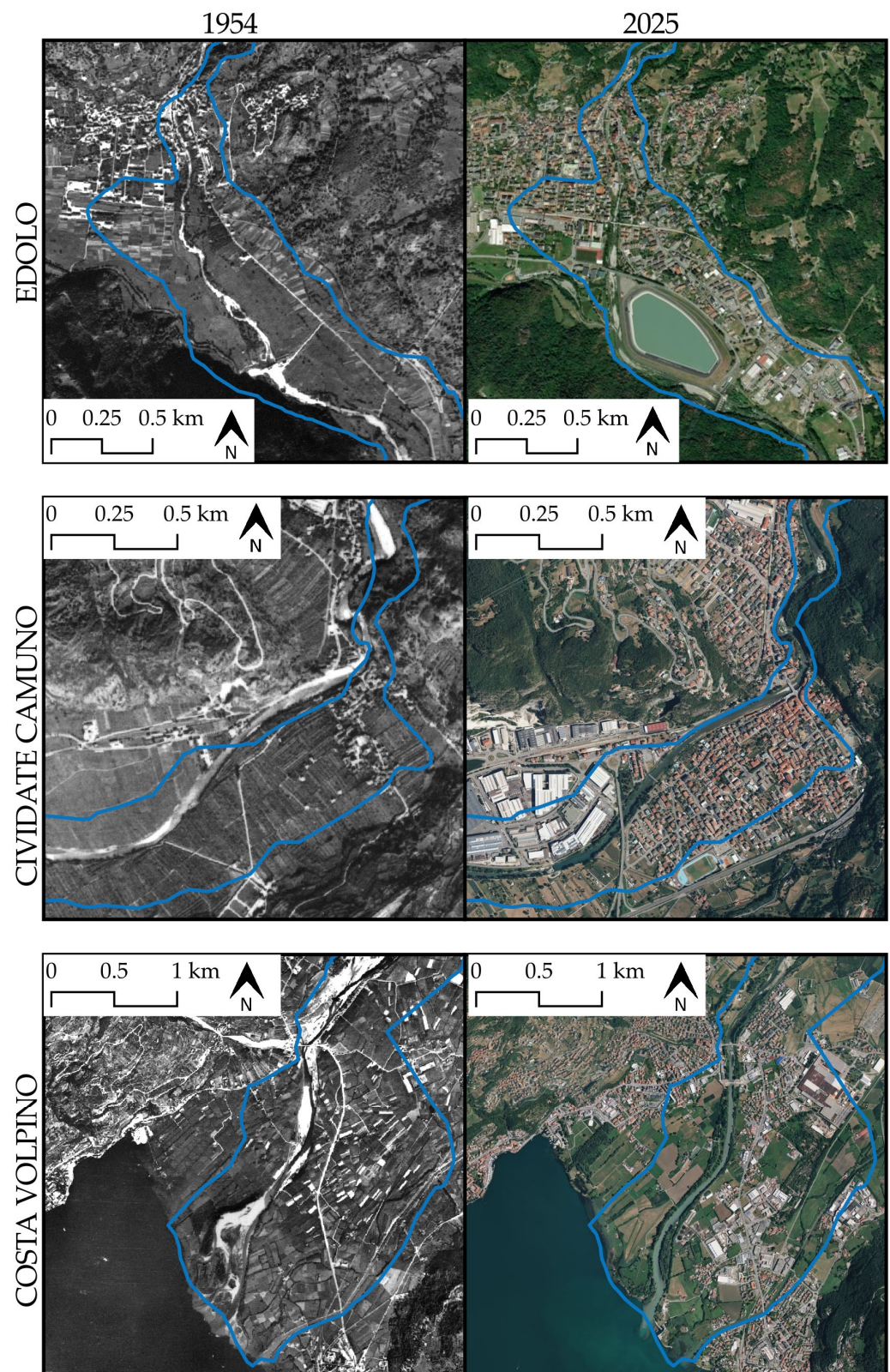


Figure 9. Comparison of aerial images from 1954 [92] and satellite imagery (Bing Aerial® 2025) for selected areas in Valcamonica (municipalities of Edolo, Cividate Camuno, and Costa Volpino, respectively, ED, CC and CV in Figure 3). The images are overlaid with the PED collapse risk scenario area with the blue outline. The results reveal a highly anthropized current landscape, with significant expansion of built-up and impermeabilized surfaces, and a drastic reduction in riverine areas. Consequently, the overall exposure to risk has substantially increased.

Table 8. Indices related to the increase in built-up areas and infrastructure density, calculated as described in Section 3.2.

Dam Area	Increase in Built-Up Areas	Road Infrastructure Density (km/km ²)
Lago Baitone	7.3	3.1
Lago Benedetto	7.0	3.7
Lago d’Arno	7.2	3.5
Lago d’Avio	7.1	3.5
Lago di Lova	4.6	0.8
Lago Salarno	7.3	3.3
Pantano d’Avio	6.9	3.8
Poglia	8.5	3.1
Vasca di Edolo	7.5	3.5
Venerocolo	7.0	3.5

Table 9. Criticality indices assigned to the factors “increase in built-up areas” and “road infrastructure density”.

Dam Area	Increase in Built-Up Areas	Road Infrastructure Density (km/km ²)
Lago Baitone	3	2
Lago Benedetto	3	2
Lago d’Arno	3	2
Lago d’Avio	3	2
Lago di Lova	2	1
Lago Salarno	3	2
Pantano d’Avio	3	2
Poglia	3	2
Vasca di Edolo	3	2
Venerocolo	3	2

Table 10. Values related to the anthropized riverine area and main stream artificiality, calculated as described in Section 3.2.

Dam Area	Anthropized Riverine Area	Main Stream Artificiality
Lago Baitone	26%	H
Lago Benedetto	26%	H
Lago d’Arno	30%	H
Lago d’Avio	26%	H
Lago di Lova	31%	H
Lago Salarno	30%	H
Pantano d’Avio	26%	H
Poglia	30%	H
Vasca di Edolo	26%	H
Venerocolo	26%	H

The values reported in Table 10 were used to calculate the indices presented in Table 11, following the criteria and methodology outlined in Table 2.

Table 11. Criticality indices assigned to the factors “anthropized riverine area” and “main stream artificiality”.

Dam Area	Anthropized Riverine Area	Main Stream Artificiality
Lago Baitone	2	3
Lago Benedetto	2	3
Lago d’Arno	2	3
Lago d’Avio	2	3
Lago di Lova	2	3
Lago Salarno	2	3
Pantano d’Avio	2	3
Poglia	2	3
Vasca di Edolo	2	3
Venerocolo	2	3

4.4. The Improvement of the Riks Analysis in the PED Scenario

The study area revealed the presence of elements at risk in the event of dam failure. The PEDs have contributed to the geomorphological adaptation of collapse scenarios based on the current configuration of the territory, which has often changed significantly since the time the dams were originally constructed. This has enabled the mapping of both natural and anthropogenic criticalities. The PEDs are designed to identify and document all critical structures potentially vulnerable to dam-break scenarios. This includes institutional facilities, operational headquarters, emergency management centers, strategic infrastructure, access points, sports complexes, sensitive recreational and accommodation facilities, educational institutions, civic and public buildings, industrial and production sites, road networks, and public utility distribution systems. Additionally, the plans encompass architecturally and artistically significant structures, as well as environmental heritage sites that may be exposed to dam-related risks.

To highlight the significance of the analysis, the current state of the territory was compared with its condition at the time of the dam installations, using historical aerial imagery from 1954 [92], the 1954 CLC dataset [86], the most recent CLC 2021 data [86], and satellite imagery such as Google Earth®. The comparison clearly shows an increase in the number of strategically important structures currently exposed to dam-related risk (Figure 10, Table 12).

The relevant anthropogenic increase has led to a substantial amplification of structures potentially at risk across all PEDs associated with the dams under study. This intensification is clearly reflected in the data reported in Table 12, which results in a worsened classification of risk, also from an analytical perspective, as detailed in Table 13.

4.5. Integrated Risk Evaluation of Large Dams in the Valcamonica

The critical issues assessment, conducted by CNR-IRPI, in support of risk management planning for large dams in the Valcamonica, was developed through a comprehensive territorial analysis integrated within the framework of the PED. This methodological approach enabled the identification and characterization of the complex interplay of geo-hydrological and anthropogenic factors influencing potential downstream risk scenarios. Importantly, the analysis focuses exclusively on areas potentially impacted by dam-break events, intentionally excluding the geotechnical and structural conditions of the dam infrastructure itself (Table 1). The study highlights how land-use changes, increased exposure due to urban expansion, and growing density of critical infrastructure have substantially altered the territorial vulnerability of downstream areas. This is particularly evident in the spatial overlap between flood propagation scenarios and regions of high anthropogenic concentration, including residential, industrial, and service-related structures. Through the integration of

geomorphological observations, historical reconstruction, and updated geospatial data, the PEDs provide a robust framework for translating potential consequences of dam failure into quantifiable indicators. These indicators, derived from the analytical synthesis of multiple risk components, are presented in Table 14, offering a numerical representation of the severity and extent of impacts in the event of a dam collapse.

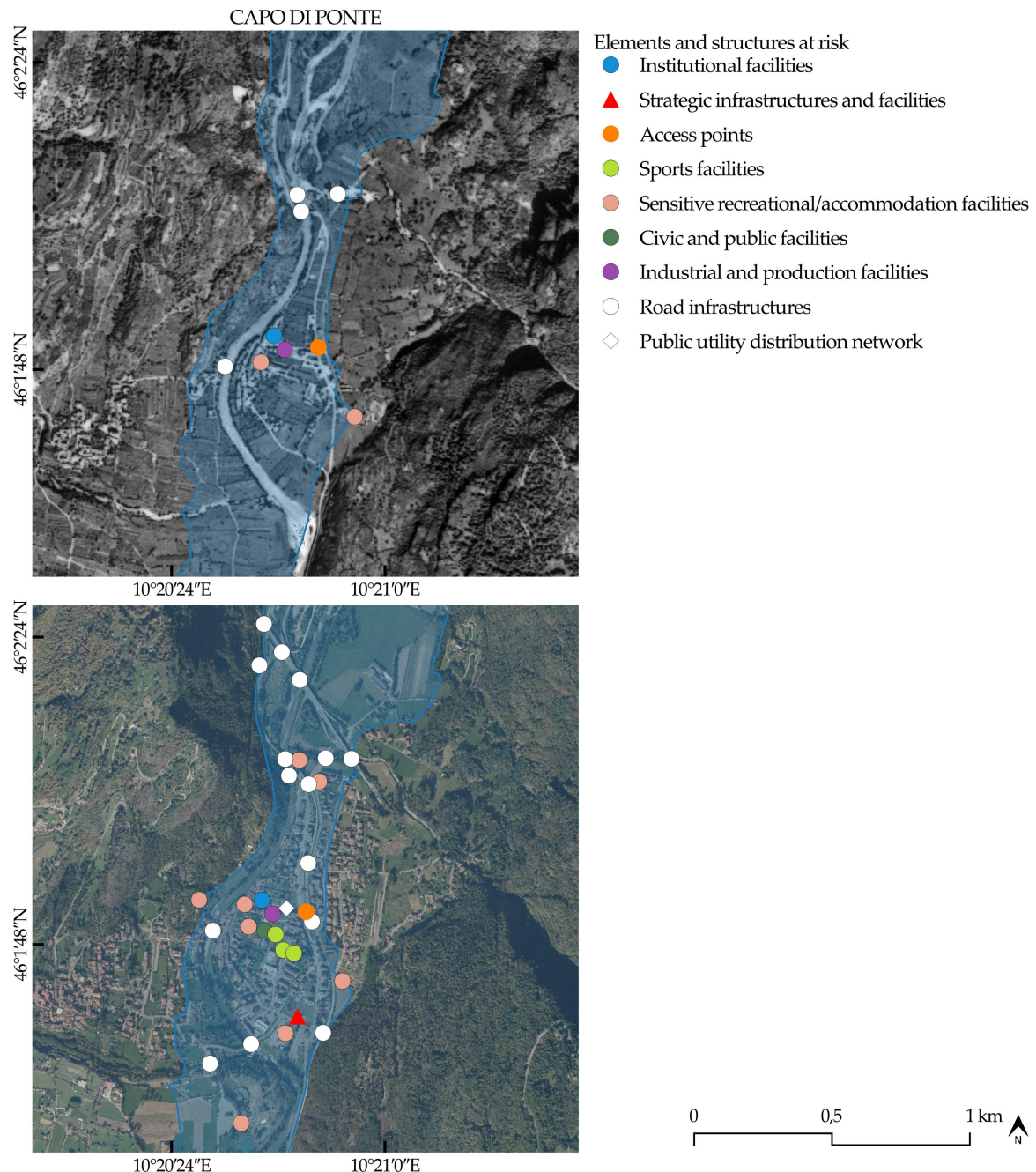


Figure 10. Example of the numerical increase in the structures exposed to dam-related risk scenario (light blue area), divided by categories, comparing the situation at the time of dam construction (1954 aerial imagery [92], **top**) with the current state (Bing Aerials 2025, **bottom**) in Capo di Ponte municipality (CDP in Figure 3).

Table 12. Values assigned to the factor “strategic structures” as described in Section 3.2.

Dam Area	Strategic Structures
Lago Baitone	H
Lago Benedetto	H
Lago d’Arno	H
Lago d’Avio	H
Lago di Lova	H
Lago Salarno	H
Pantano d’Avio	H
Poglia	H
Vasca di Edolo	H
Venerocolo	H

Table 13. Criticality indices assigned to the factor “strategic structures”.

Dam Area	Strategic Structures
Lago Baitone	3
Lago Benedetto	3
Lago d’Arno	3
Lago d’Avio	3
Lago di Lova	3
Lago Salarno	3
Pantano d’Avio	3
Poglia	3
Vasca di Edolo	3
Venerocolo	3

From Table 14, an integrated classification was derived based on the cumulative scores assigned to each territorial scenario downstream of the large dams in Valcamonica. The final score, calculated as the sum of the values assigned to indicators A through G, provides a synthetic measure of the overall level of exposure and criticality. The resulting final scores and the corresponding overall evaluations are presented in Table 15.

Table 14. Summary of all indicators used to evaluate increased exposure to dam-related risk in Valcamonica for each PED.

Dam Area	A	B	C	D	E	F	G
Lago Baitone	3	2	3	2	2	3	3
Lago Benedetto	2	2	3	2	2	3	3
Lago d’Arno	3	2	3	2	2	3	3
Lago d’Avio	3	2	3	2	2	3	3
Lago di Lova	3	2	2	1	2	3	3
Lago Salarno	3	2	3	2	2	3	3
Pantano d’Avio	2	2	3	2	2	3	3
Poglia	2	2	3	2	2	3	3
Vasca di Edolo	2	2	3	2	2	3	3
Venerocolo	2	2	3	2	2	3	3

The integrated analysis reveals that all dam-break scenarios associated with the large reservoirs studied are classified as high-risk. This outcome underscores the significant alteration and development of downstream areas over time, particularly during the early 20th century. Since then, these regions have experienced substantial urban growth, including the construction of residential buildings, infrastructure, and public services. Such transformations have not only fueled local economic development, especially through tourism,

but have also led to an increase in the population and accommodation facilities exposed to dam-related risks. Concurrently, these changes have exacerbated the extent of risk-prone areas by reducing the land's natural capacity for infiltration and runoff. More critically, they have diminished the availability of natural floodplain areas, which are essential for the unhindered flow and dissipation of floodwaters, whether triggered by extreme meteorological events or the potential failure of dam structures. Although this analysis does not explicitly address the aggravating role of climate change and the increasing frequency of extreme weather events, especially in mountainous regions [102–104], it implicitly incorporates the issue by documenting the reduction in fluvial space available for peak discharge events. This spatial constriction increases both exposure and vulnerability, and highlights the need to reassess historical flood scenarios in the context of modern land-use configurations. Furthermore, the study underscores the importance of deepening historical analyses of past damaging events. Such events not only enhance the understanding of recurrence patterns and territorial susceptibility but also allow for indirect estimation of event magnitude. In the absence of direct records of dam-break incidents, this retrospective approach becomes crucial. It offers a reference framework to assess potential impacts by interpreting the consequences of past floods in an area now heavily modified by anthropogenic activity, an area where current hazard conditions have significantly worsened. This retrospective evaluation supports more realistic and precautionary risk assessments for present and future dam-related scenarios (Figure 11).

Table 15. Final score and integrate value obtained from the analytic methodology.

Dam	Final Score	Integrate Value
Lago Baitone	18	H
Lago Benedetto	17	H
Lago d'Arno	18	H
Lago d'Avio	18	H
Lago di Lova	16	H
Lago Salarno	18	H
Pantano d'Avio	17	H
Poglia	17	H
Vasca di Edolo	17	H
Venerocolo	17	H



(a)



(b)

Figure 11. *Cont.*



(c)



(d)



(e)



(f)

Figure 11. Example of flood damage event occurred in 1960 in Capo di Ponte (a) and Darfo Boario Terme (c,e) (respectively CDP and DBT in Figure 3) and comparison to recent images of the same locations [92]: Capo di Ponte (b) and Darfo Boario Terme (d,f). Historical images of the 1960 flood event, which represents one of the most significant historical floods in Valcamonica in terms of damage, are compared with recent images as they provide valuable information on the water levels reached and the extent of the inundated areas.

5. Discussion

Most of the reservoirs in Valcamonica (approximately 80%) were constructed prior to the mid-20th century. In the decades since, regular and extraordinary maintenance interventions have been necessary, occasionally involving structural modifications aimed at enhancing the safety of the installations. However, in all the cases analyzed, the surrounding territory has undergone profound transformations, including those affecting the fluvial environment. The need to identify criticalities related to flood risk has led to alarming considerations regarding the current territorial configuration, which is also subject to dam-related risk. This condition is further exacerbated by the often irrational and uncontrolled use of alpine valley floors downstream of large dam infrastructures. In Italy, a true awareness of territorial risk has only emerged in recent decades, as repeated damaging events began to threaten regional and national economies. Fortunately, both public awareness and the implementation of regulations aimed at mitigating such risks have

increased. Today, spatial planning and risk management tools (including PEDs) represent a fundamental safeguard for limiting potential damages, though they must be continuously updated to meet the immense challenge posed by a rapidly evolving environment. The project that supported the development of PEDs (still ongoing for all large Italian reservoirs despite European regulatory pressures) was carried out with significant involvement of local authorities. Inclusive working groups were established, with public presentations and direct engagement with residents. A substantial portion of documentation was derived from informal exchanges with citizens and local associations, deeply rooted in their communities. This approach has promoted a process of resilience that should be further expanded through locally supported knowledge-building initiatives. An in-depth understanding of the territory, including its transformation over time and its history of flood events, enabled the identification of strategic infrastructure and vulnerable sites potentially impacted by dam failures or operational releases. The geometry of flood-prone areas was refined through targeted field inspections and analysis of past event zones, supported by on-site working teams tasked with addressing territorial complexities.

In many cases, PEDs were based on geomorphological references and hydraulic studies concerning flood propagation scenarios that are now outdated. Moreover, most of the original studies related to dam-break flood scenarios did not consider the role of sediment transport. This represents a significant underestimation of fluvial dynamics, as transported debris is often a key factor in amplifying damage during extreme events (Figures 12 and 13).

Hydraulic models alone are insufficient for risk assessment. More complex analyses are required, incorporating updated digital elevation models (DEMs), digital surface models (DSMs), and continuously revised urban development data. This need has been highlighted in multiple technical meetings, and further evaluations are currently underway.

The frequency and severity of hydrometeorological disasters in Valcamonica and across Italy, often with considerable socio-economic consequences, underscore the importance of historical memory. Understanding past events and their associated damages provides an essential foundation for forecasting future scenarios and defining effective strategies for risk prevention and mitigation. In the case of flood hazards, many areas currently at risk from river overflows are the same as those that have historically experienced flooding and damage, often exacerbated by urban expansion and anthropogenic alterations to riverbeds (e.g., channelization, embankments, structural interventions). Collecting information on past flood events and their impacts on infrastructure is thus crucial for building a comprehensive understanding of expected dynamics and ground effects in similar future contexts [106,107]. A comparison between existing technical and regulatory plans, e.g., [99–101], and official dam-break scenarios provided by the Italian Ministry of Infrastructure reveals significant discrepancies in spatial coverage and land-use designations (Figures 8 and 9).

In the case study of Valcamonica, where Emergency Management Plans (PEDs) have been completed for all major dams, it has been possible to identify key regional and supra-municipal assets that may be exposed to potential dam-break or operational failure scenarios. These assets have been classified according to their typology. The application of the analytical methodology developed in this study highlights a general increase in the exposure to dam-related risks (Table 15). These risk assessments should be further complemented by considerations of the region's susceptibility to flood events (Table S1). Additionally, the historical analysis provided a comprehensive chronological framework, enabling the classification of the territory into frequency-based event categories, which serve to enhance the understanding of vulnerability across the studied areas [108–110].

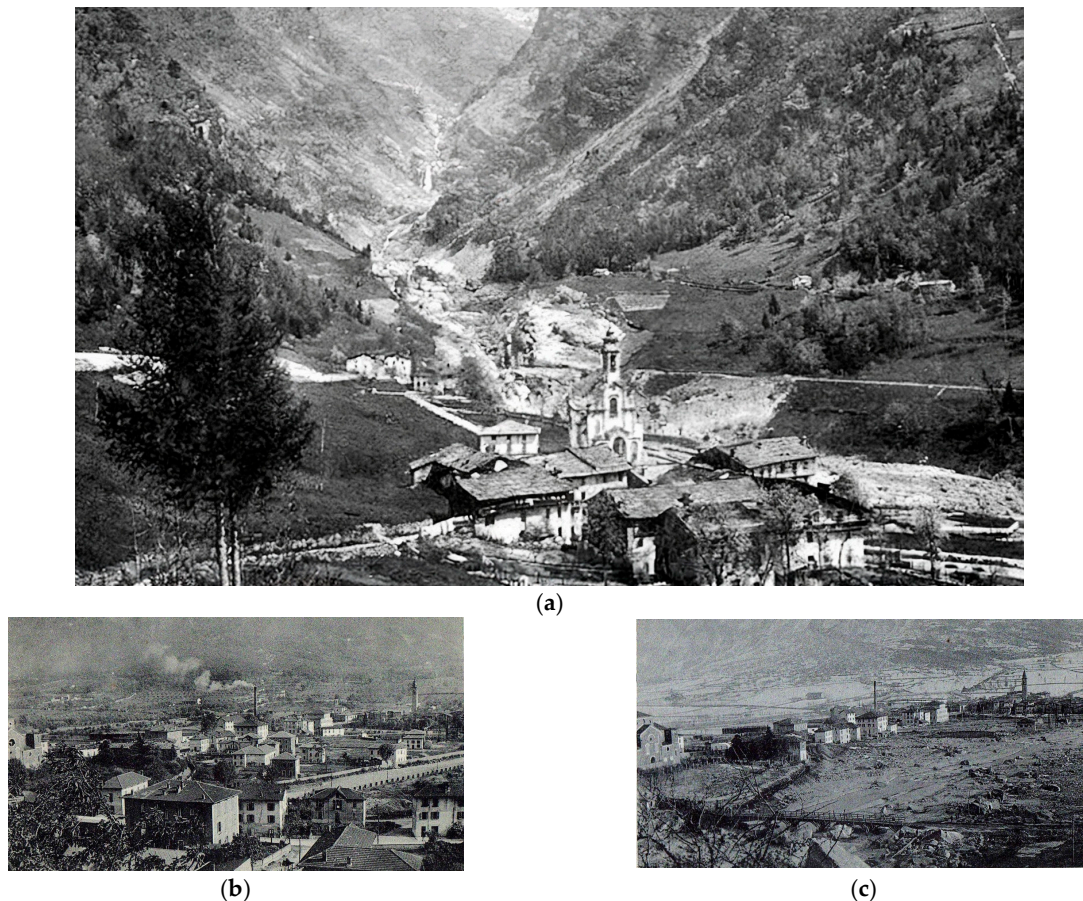


Figure 12. Damage effects of the Gleno Dam collapse (Valcamonica, 1 December 1923), which caused 356 fatalities. The flood wave's impact was intensified by large volumes of debris. Effects visible in Bueggio ((a), Vilminore di Scalve municipality) [105] and in Corna hamlet (Darfo Boario Terme municipality), before (b) and after (c) the event [65].

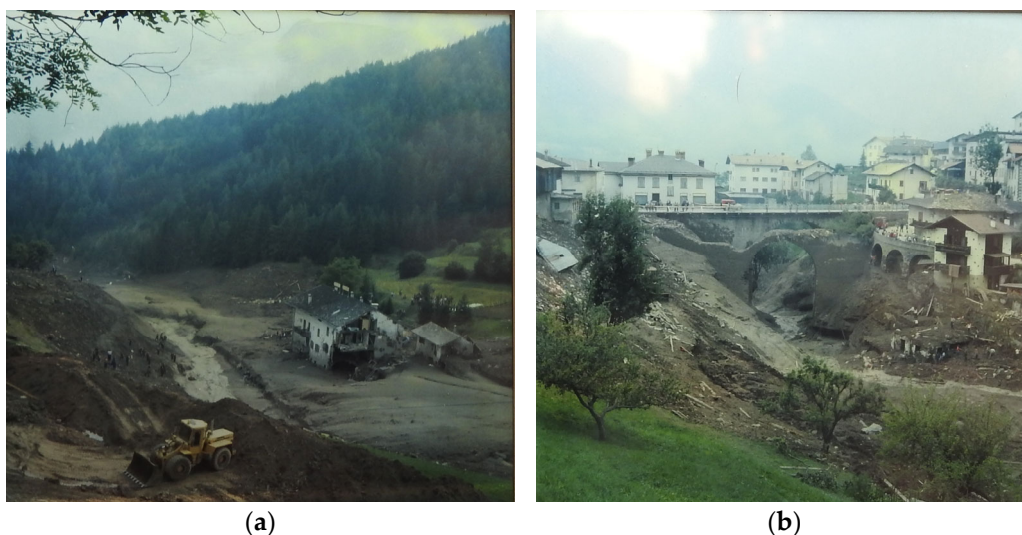


Figure 13. Flooding caused by the failure of two dams (19 July 1985), which, with its substantial volume of mobilized solid material (a), destroyed the municipality of Tesero, especially Stava locality (Trentino, Northeastern Italy), resulting in the death of 268 people [92]. In Tesero (b), the effects of the flood can be seen, which reached about 18 m from the riverbed on the left riverbank, and 8 m on the right, destroying a number of buildings.

As a preventive measure, these insights should also be applied when planning new dam sites, or evaluating existing ones (Table 1). Integrating geomorphological, hydrological, historical, and infrastructural perspectives is essential to better define current and future risk scenarios in mountainous regions undergoing rapid transformation.

Population increase, infrastructure density, tourism pressure, and long-term alterations of river systems and riparian areas were quantified to obtain a synthetic indicator of changes in the exposure component of risk. Since risk is directly proportional to exposure, this approach provides a quantitative measure of risk variation over time. Historical data were incorporated to better capture anthropogenic transformations of the territory: flood event chronicles and geomorphological evidence of fluvial dynamics were analyzed to assess the current condition of rivers and riverine areas. Within the PEDs, these data support the reconstruction of temporal sequences necessary to develop scenarios of potential dam damage, despite the lack of precise forecasts concerning magnitude and recurrence intervals. In particular, evidence from past floods, obsolete channels reconstructions, and evolutionary trend analyses contribute to a more objective assessment of uncertainties related to dam failure impacts.

PEDs also include specific sections for community involvement, both for resident and seasonal populations. These are implemented through communication strategies and awareness-raising initiatives, supported by widely accessible information systems such as the IT-Alert [111], recently deployed at the national scale in Italy within a multi-hazard framework.

6. Conclusions

Despite the numerous positive aspects associated with the presence of reservoirs, the global record of incidents caused by partial or total dam failures remains high, often resulting in substantial human, economic, and social losses. The collapse of dams or accidents involving large reservoirs has long been a source of global concern. The consequences of dam failures can be catastrophic, leading to loss of life, environmental damage, and significant economic costs. These tragic events have prompted the development of comprehensive dam safety legislation across the globe, with particular emphasis in regions such as Europe and Italy.

The in-depth studies conducted within the framework of the PEDs highlight the value of detailed technical information that goes beyond the reliance on hydraulic simulations, often based on two-dimensional models, commonly used to define flood scenarios. These models, while essential, must be periodically updated and integrated to reflect both anthropogenic and natural changes in the territory. Beyond assessing territorial vulnerability in relation to anthropogenic transformations affecting river corridors, historical research should also encompass the collection of pluviometric data and, where available, hydro-metric and discharge records. These are crucial for reconstructing past rainfall and flood events, and for comparing them with recorded water volumes. The identification of critical boundary conditions near the dam structures and the current state of river systems, in conjunction with evolving exposure levels and the increasingly fragile conditions of the territory, constitute the basis for evaluating future risk scenarios. The proposed analysis, based on indices related to both natural and anthropogenic changes in downstream areas potentially exposed to damage effects associated with large dams, provides additional information on current risk exposure elements, allowing for a preliminary assessment in a simple and rapid analysis. No considerations are introduced regarding hydraulic discharge evaluations or analyses of rainfall regime variations associated with climate change; rather, the method offers indicative insights into territorial transformations with respect to the original conditions at the time of dam construction. The approach provides indices that

can be periodically updated to monitor changes in dam-related risk and ensure consistency with exposure levels. In this way, the proposed framework can complement hydraulic assessments and modeling, making the respective outcomes mutually reinforcing.

Spatial planning tools, both urban and civil protection, must be conceived as dynamic instruments, subject to regular updates, to ensure that risk mitigation strategies can be effectively applied in evolving contexts. Equally significant is the local response to growing awareness of hazards and vulnerabilities. This awareness translates into greater community resilience, as well as more proactive behavior by local authorities and land managers. Effective actions include the sharing of risk information and the implementation of early warning systems and operational protocols aimed at reducing the impacts of future events.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/geohazards6040065/s1>, Table S1: Flood events affecting the municipalities of Valcamonica (period 1506–2023). References [92,94] are cited in the supplementary materials.

Author Contributions: Conceptualization, B.B. and L.T.; methodology, B.B., A.R., L.T. and G.Z.; software, B.B. and L.T.; validation, B.B. and L.T.; formal analysis, B.B., F.L., A.R., L.T. and G.Z.; investigation, B.B., F.L., A.R., L.T. and G.Z.; resources, F.L. and L.T.; data curation, B.B. and L.T.; writing—original draft preparation, B.B. and L.T.; writing—review and editing, B.B., F.L., A.R. and L.T.; visualization, B.B. and L.T.; supervision, B.B., F.L., A.R. and L.T.; project administration, F.L. and L.T.; funding acquisition, F.L. and L.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by DEBRIS FLOW Valcamonica CNR IRPI Project, supported by Lombardy Region (Italy) Project CNR Number DTA.AD003.599; Hydropower Large Dam Lombardy Region Projects (EC Directive Dam Break and Flood Scenarios), Project CNR Number DTA.AD003.877.

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors thank Antonella Belloni, Marco Chiera, Massimo Compagnoni, Chiara Dell’Orto, Sara Elefanti, Paolo Fassi, Robert Ribaud, Andrea Zaccone, Claudia Zugliani; also thanks to all municipalities of Valcamonica, Gianbattista Sangalli (Comunità Montana della Valcamonica), Marco Gavazzeni (Protezione Civile, Provincia di Bergamo) and dam hydroelectric managers of Valcamonica (EDISON S.P.A., ENEL Green Power, Sistemi di Energia S.P.A.).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Karakatsanis, D.; Patsialis, T.; Kalaitzidou, K.; Kougias, I.; Ntona, M.M.; Theodossiou, N.; Kazakis, N. Optimization of Dam Operation and Interaction with Groundwater: An Over-view Focusing on Greece. *Water* **2023**, *15*, 3852. [CrossRef]
2. Fayaed, S.S.; El-Shafie, A.; Jaafar, O. Reservoir system simulation and optimization techniques. *Stoch. Environ. Res. Risk Assess.* **2013**, *27*, 1751–1772. [CrossRef]
3. Busico, G.; Ntona, M.M.; Carvalho, S.C.P.; Patrikaki, O.; Voudouris, K.; Kazakis, N. Simulating future groundwater recharge in coastal and inland catchments. *Water Resour. Manag.* **2021**, *35*, 3617–3632. [CrossRef]
4. Panizzo, A.; De Girolamo, P.; Di Risio, M.; Maistri, A.; Petaccia, A. Great landslide events in Italian artificial reservoirs. *NHESS* **2005**, *5*, 733–740. [CrossRef]
5. Migliorati, L. The Gleno Dam Disaster (1923). Cultural Trauma and Collective Memories of an In-Depth Mountain Community in Italy a Century Later. *Ital. Sociol. Rev.* **2024**, *14*, 51–70. [CrossRef]
6. Belluco, E. 1923–2023: The centenary of the Gleno dam’s failure (Po basin, Bergamo-Northern Italy). In Proceedings of the ICIRBM—44th Italian Conference on Integrated River Basin Management, Calabria, Italy, 22–23 July 2023; pp. 135–146. Available online: <https://hdl.handle.net/11577/3507140> (accessed on 10 September 2024).
7. Petracchia, G.; Lai, C.G.; Milazzo, C.; Natale, L. The collapse of the Sella Zerbino gravity dam. *Eng. Geol.* **2016**, *211*, 39–49. [CrossRef]

8. Petaccia, G.; Natale, L. 1935 Sella Zerbino Dam-Break Case Revisited: A New Hydrologic and Hydraulic Analysis. *J. Hydraul. Eng.* **2020**, *146*, 0502000. [CrossRef]
9. French Ministry for Sustainable Development DGPR/SRT/Barpi, Lyon, France, 2010. Release of 50 Million m³ of Water at the Vajont Dam. 9 October 1963. Erto e Casso (PN) Italy. Available online: https://www.aria.developpement-durable.gouv.fr/wp-content/files_mf/A23607_ips23607_002.pdf (accessed on 3 March 2024).
10. Margitta, M.R.; Onorati, B. The Hydrological Characteristics of the Vajont Valley. *Ital. J. Eng. Geol. Environ.* **2013**, *1*, 567–572. [CrossRef]
11. Barla, G.; Paronuzzi, P. The 1963 Vajont Landslide: 50th Anniversary. *Rock Mech. Rock Eng.* **2013**, *46*, 1267–1270. [CrossRef]
12. Paronuzzi, P.; Bolla, A.; Pinto, D.; Lenaz, D.; Soccac, M. The clays involved in the 1963 Vajont landslide: Genesis and geomechanical implications. *Eng. Geol.* **2021**, *294*, 106376. [CrossRef]
13. Pirulli, M.; Barbero, M.; Marchelli, M.; Scavia, C. The failure of the Stava Valley tailings dams (Northern Italy): Numerical analysis of the flow dynamics and rheological properties. *Geoenviron. Disasters* **2017**, *4*, 3. [CrossRef]
14. Simeoni, L.; Tosatti, G.; Lucchi, G.; Longo, M. The Stava catastrophic failure of 19th July 1985 (Italy): Technical-scientific data and socioeconomic aspects. *CSE J.* **2017**, *1*, 17–30. [CrossRef]
15. Boaretto, M.; Lucchi, G.; Tosatti, G.; Zorzi, L. The Stava Valley Tailings Dams Disaster: A Reference Point for the Prevention of Severe Mine Incidents. *Environ. Sci. Eng. B* **2018**, *7*, 234–241. [CrossRef]
16. Wang, J.; Feng, J.; Sun, B.; Guo, J.; Hu, S.; Zhang, M. Characterization of dam failure flooding in an urban reservoir under different rainfall conditions. *Sci. Rep.* **2024**, *14*, 27560. [CrossRef]
17. Ferrari, A.; Vacondio, R.; Mignosa, P. High-resolution 2D shallow water modelling of dam failure floods for emergency action plans. *J. Hydr.* **2023**, *618*, 129192. [CrossRef]
18. Aureli, F.; Maranzoni, A.; Petaccia, G. Review of historical dam-break events and laboratory tests on real topography for the validation of numerical models. *Water* **2021**, *13*, 1968. [CrossRef]
19. Gaagai, A.; Aouissi, H.A.; Krauklis, A.E.; Burlakovs, J.; Athamena, A.; Zekker, I.; Boudoukha, A.; Benaabidate, L.; Chenchouni, H. Modeling and Risk Analysis of Dam-Break Flooding in a Semi-Arid Montane Watershed: A Case Study of the Yabous Dam, Northeastern Algeria. *Water* **2022**, *14*, 767. [CrossRef]
20. Zhou, X.; Chen, Z.; Zhou, J.; Guo, X.; Du, X.; Zhang, Q. A quantitative risk analysis model for cascade reservoirs overtopping: Principle and application. *Nat. Hazards* **2020**, *104*, 249–277. [CrossRef]
21. Marangoz, H.O.; Anilan, T. Two-dimensional modeling of flood wave propagation in residential areas after a dam break with application of diffusive and dynamic wave approaches. *Nat. Hazards* **2022**, *110*, 429–449. [CrossRef]
22. CNR IRPI (National Research Council, Research Institute for Geo-Hydrological Protection). Available online: <https://www.irpi.cnr.it/en/> (accessed on 3 April 2024).
23. Luino, F.; Belloni, A.; Padovan, N.; Bassi, M.; Bossuto, P.; Fassi, P. Historical and geomorphological analysis as a research tool for the identification of flood-prone zones and its role in the revision of town planning: The Oglio basin (Valcamonica—Northern Italy). In Proceedings of the 9th Congress of the International Association for Engineering Geology and the Environment, Durban, South Africa, 16–20 September 2002; pp. 191–200. Available online: <https://www.researchgate.net/publication/305303889> (accessed on 13 October 2023).
24. Tropeano, D.; Govi, M.; Mortara, G.; Turitto, O.; Sorzana, P.; Negrini, G.; Arattano, M. *Eventi Alluvionali e Frane Nell'Italia Settentrionale. Periodo 1975-81*; CNR-IRPI GNDICI: Turin, Italy, 1999; pp. 240–243. (In Italian)
25. Castellarin, A.; Magnini, A.; Kyaw, K.K.; Ciavaglia, F.; Bertola, M.; Blöschl, G.; Volpi, E.; Claps, P.; Viglione, A.; Marinelli, A.; et al. Frequency of Italian Record-Breaking Floods over the Last Century (1911–2020). *Atmosphere* **2024**, *15*, 865. [CrossRef]
26. Claps, P.; Evangelista, G.; Ganora, D.; Mazzoglio, P.; Monforte, I. FOCA: A new quality-controlled database of floods and catchment descriptors in Italy. *Earth Syst. Sci. Data* **2024**, *16*, 1503–1522. [CrossRef]
27. Luino, F.; Turconi, L. *Eventi di Piena e Frana in Italia Settentrionale nel Periodo 2005–2016*; SMS: Moncalieri, Italy, 2017; p. 478. ISBN 8890302380/9788890302381. (In Italian)
28. ISTAT. Italian GDP. Available online: <https://www.istat.it/tag/pil/> (accessed on 10 March 2025).
29. Angelakis, A.N.; Baba, A.; Valipour, M.; Dietrich, J.; Fallah-Mehdipour, E.; Krasilnikoff, J.; Bilgic, E.; Passchier, C.; Tzanakakis, V.A.; Kumar, R.; et al. Water Dams: From Ancient to Present Times and into the Future. *Water* **2024**, *16*, 1889. [CrossRef]
30. Forsythe, K.W.; Schatz, B.; Swales, S.J.; Ferrato, L.-J.; Atkinson, D.M. Visualization of Lake Mead Surface Area Changes from 1972 to 2009. *ISPRS Int. J. Geo-Inf.* **2012**, *1*, 108–119. [CrossRef]
31. Hariri-Ardebili, M.A.; Mahdavi, G.; Nuss, L.K.; Lall, U. The role of artificial intelligence and digital technologies in dam engineering: Narrative review and outlook. *Eng. Appl. Artif. Intell.* **2023**, *126*, 106813. [CrossRef]
32. Angelakis, A.N.; Valipour, M.; Ahmed, A.T.; Tzanakakis, V.; Paranychiakis, N.V.; Krasilnikoff, J.; Drusiani, R.; Mays, L.; El Gohary, F.; Koutsoyiannis, D. Water Conflicts: From Ancient to Modern Times and in the Future. *Sustainability* **2021**, *13*, 4237. [CrossRef]
33. Haftendorn, H. Water and international conflict. *Third World Q.* **2000**, *21*, 51–68. [CrossRef]

34. Qureshi, A.S. Water Management in the Indus Basin in Pakistan: Challenges and Opportunities. *Mt. Res. Dev.* **2011**, *31*, 252–260. [CrossRef]
35. Brühl, J.; le Roux, L.; Visser, M.; Köhlin, G. Decision-Making in a Water Crisis: Lessons from the Cape Town Drought for Urban Water Policy. Oxford Research Encyclopedias Environmental Science. 19 November 2020. Available online: <https://oxfordre.com/environmentalscience/view/10.1093/acrefore/9780199389414.001.0001/acrefore-9780199389414-e-706> (accessed on 7 June 2024).
36. Pess, G.R.; McHenry, M.L.; Beechie, T.J.; Davies, J. Biological Impacts of the Elwha River Dams and Potential Salmonid Responses to Dam Removal. *Northwest Sci.* **2008**, *82*, 72–90. [CrossRef]
37. Elagib, N.A.; Basheer, M. Would Africa's largest hydropower dam have profound environmental impacts? *Environ. Sci. Pollut. Res.* **2021**, *28*, 8936–8944. [CrossRef]
38. Li, B.; Chen, N.; Wang, W.; Wang, C.; Schmitt, R.J.; Lin, A.; Daily, G.C. Eco-environmental impacts of dams in the Yangtze River Basin, China. *Sci. Total Environ.* **2021**, *20*, 774–145743. [CrossRef]
39. Carney, T.M. China's Three Gorges Dam: Development, Displacement, and Degradation. *Neb. Anthropol.* **2021**, *29*, 20–27. Available online: <https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1193&context=nebanthro> (accessed on 24 March 2025).
40. Zafarnejad, F. The contribution of dams to Iran's desertification. *Int. J. Environ. Stud.* **2009**, *66*, 327–341. [CrossRef]
41. Boulange, J.; Hanasaki, N.; Yamazaki, D.; Pokhrel, Y. Role of dams in reducing global flood exposure under climate change. *Nat. Comm.* **2021**, *12*, 417. [CrossRef]
42. Li, D.; Lu, X.; Walling, D.; Zhang, T.; Steiner, J.K.; Wasson, R.J.; Harrison, S.; Nepal, S.; Nie, Y.; Immerzeel, W.W.; et al. High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nat. Geosc.* **2022**, *15*, 520–530. [CrossRef]
43. Moore, D.; Dore, J.; Gyawali, D. The World Commission on Dams + 10: Revisiting the Large Dam Controversy. *Water Altern.* **2010**, *3*, 3–13. Available online: <https://www.water-alternatives.org/index.php/volume3/v3issue2/79-a3-2-2/file> (accessed on 15 June 2025).
44. ICOLD International Commission on Large Dams. Constitution Status. Available online: https://www.icold-cigb.org/userfiles/files/CIGB/INSTITUTIONAL_FILES/Constitution2011.pdf (accessed on 5 May 2025).
45. Adamo, N.; Al-Ansari, N.; Sissakian, V.; Laue, J.; Knutsson, S. Dam Safety: Sediments and Debris Problems. *Earth Sci. Geotech. Eng.* **2021**, *11*, 27. [CrossRef] [PubMed]
46. Contreras, R.J.; Escuder-Bueno, I. Dam Safety History and Practice: Is There Room for Improvement? *Infrastructures* **2023**, *8*, 171. [CrossRef]
47. Federal Energy Regulatory Commission (FERC). Available online: <https://ferc.gov/> (accessed on 15 December 2024).
48. National Dam Safety Program Act (NDSPA). Dam Safety in the United States: A Progress Report on the National Dam Safety Program. Available online: <https://www.fema.gov/grants/mitigation/learn/dam-safety/progress-report> (accessed on 3 March 2025).
49. California Has Its Dam Safety Program. Available online: <https://water.ca.gov/programs/all-programs/division-of-safety-of-dams> (accessed on 13 January 2025).
50. China Law on the Safety of Dams. Available online: <http://www.lawinfochina.com/display.aspx?id=29508&lib=law&EncodingName=gb2312> (accessed on 7 July 2024).
51. India Dam Safety Act. Available online: <https://www.indiacode.nic.in/bitstream/123456789/17002/1/A202141.pdf> (accessed on 3 September 2024).
52. Council Directive 2000/60/EC (Water Framework Directive). Available online: https://environment.ec.europa.eu/topics/water/water-framework-directive_en (accessed on 17 October 2024).
53. Council Directive 2012/18/EU (Seveso III Directive). Available online: https://environment.ec.europa.eu/topics/industrial-emissions-and-safety/industrial-accidents_en (accessed on 25 November 2024).
54. Europe Dam Safety Guidelines. Available online: <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:163:0001:0140:EN:PDF> (accessed on 8 June 2024).
55. UK Reservoirs Act. Available online: <https://www.legislation.gov.uk/ukpga/1975/23> (accessed on 15 June 2025).
56. French Water Code and the Dam Safety Regulations. Available online: <https://www.barrages-cfbr.eu/Surveillance.html> (accessed on 8 April 2025).
57. International Commission on Large Dams. *Dam Failures Statistical Analysis*; ICOLD: Paris, France, 1995.
58. International Commission on Large Dams. *Risk Assessment in Dam Safety Management: A Reconnaissance of Benefits, Methods and Current Applications*; ICOLD: Paris, France, 2005.
59. CAN/CSA-Q850-97; Risk Management: Guideline for Decision-Makers. Canadian Standards Association: Toronto, ON, Canada, 1997.
60. World Commission on Dams. *Dams and Development, A New Framework for Decision-Making; The Report of the World Commission on Dams*; Earthscan Publications Ltd.: London, UK, 2000; Available online: https://awsassets.panda.org/downloads/wcd_dams_final_report.pdf (accessed on 10 May 2025).

61. Australian National Committee on Large Dams. *Guidelines on Risk Assessment*; ANCOLD: Hobart, Australia, 2022; Available online: <https://ancold.org.au/product/ancold-guidelines-on-risk-assessment-july-2022/> (accessed on 6 February 2025).
62. Spanish National Committee on Large Dams. *Risk Analysis as Applied to Dam Safety. Technical Guide on Operation of Dams and Reservoirs*; Professional Association of Civil Engineers, 1st ed.; Spancold: Madrid, Spain, 2012.
63. Canadian Dam Association. *Dam Safety Guidelines*; CDA—ACB: Markham, ON, Canada, 2013.
64. New Zealand Society on Large Dams. *New Zealand Dam Safety Guidelines. Professional Engineers New Zealand*; New Zealand Society on Large Dams: Christchurch, New Zealand, 2015.
65. Luino, F.; Tosatti, G.; Bonaria, V. Dam failures in the 20th century: Nearly 1000 avoidable victims in Italy alone. *J. Environ. Sc. Eng.* **2014**, *3*, 19–31. Available online: <https://hdl.handle.net/20.500.14243/257940> (accessed on 3 April 2022).
66. Bonaria, V.; Tosatti, G. 13th august 1935: A catastrophic dam failure in the Orba valley (Piedmont, Italy). *Ital. J. Eng. Geol. Environ.* **2013**, *6*, 383–391. [\[CrossRef\]](#)
67. Abbate, A.; Frigerio, A. Molare tragedy: The secondary dam collapse induced by a heavy rainfall event. In *Twenty-Eighth International Congress on Large Dams/Vingt-Huitième Congrès International des Grands Barrages*, 1st ed.; CRC Press: London, UK, 2025; Volume 1, pp. 296–316. [\[CrossRef\]](#)
68. Bolla, A.; Paronuzzi, P.; Pinto, D.; Lenaz, D.; Del Fabbro, M. Mineralogical and Geotechnical Characterization of the Clay Layers within the Basal Shear Zone of the 1963 Vajont Landslide. *Geosciences* **2020**, *10*, 360. [\[CrossRef\]](#)
69. Müller, L. The rock slide in the Vajont Valley. *Rock. Mech. Eng. Geol.* **1964**, *2*, 148–212.
70. Bianchizza, C.; Frigerio, S. Domination of or adaptation to nature? A lesson we can still learn from the Vajont. *Ital. J. Eng. Geol. Environ.* **2013**, *6*, 523–530. [\[CrossRef\]](#)
71. Luino, F.; De Graff, J.V. The Stava mudflow of 19 July 1985 (Northern Italy): A disaster that effective regulation might have prevented. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 1029–1044. [\[CrossRef\]](#)
72. Alexander, D.E. Northern Italian dam failure and mudflow, July 1985. *Disasters* **1986**, *10*, 3–7. [\[CrossRef\]](#)
73. Italian National Dam Safety. Available online: https://www.dighe.eu/normativa/allegati/2014_D_Min_IITT_26-06.pdf (accessed on 2 March 2025).
74. Italian Large Dam Census. Available online: https://www.dighe.eu/dati/grandi_dighe_italiane.htm (accessed on 11 November 2024).
75. Perera, D.; Smakhtin, V.; Williams, S.; North, T.; Curry, A. Ageing water storage infrastructure: An emerging global risk. *UNU-INWEH Rep. Ser.* **2021**, *22*, 11–25. [\[CrossRef\]](#)
76. Stucchi, M.; Meletti, C.; Montaldo, V.; Akinci, A.; Faccioli, E.; Gasperini, P.; Malagnini, L.; Valensise, G. Pericolosità Sismica di Riferimento per il Territorio Nazionale MPS04 [Data Set]. INGV 2004. Available online: <https://doi.org/10.13127/sh/mps04/ag> (accessed on 27 January 2025).
77. Italian Sismic Areas Webgis. Available online: <http://zonesismiche.mi.ingv.it/> (accessed on 6 April 2024).
78. Italian Sismic Areas. Available online: <https://www.testo-unico-sicurezza.com/classificazione-sismica-comuni-italiani.html> (accessed on 3 February 2025).
79. Turconi, L.; Bono, B.; Genta, R.; Luino, F. The Effects of Flood Damage on Urban Road Networks in Italy: The Critical Function of Underpasses. *Land* **2024**, *13*, 1493. [\[CrossRef\]](#)
80. Turconi, L.; Bono, B.; Faccini, F.; Luino, F. Anthropic Constraint Dynamics in European Western Mediterranean Floodplains Related to Floods Events. *Remote Sens.* **2023**, *15*, 4798. [\[CrossRef\]](#)
81. Turconi, L.; Casazza, M.; Bono, B.; Luino, F. Increasing geohydrological instability in a valley of the Italian Central Alps: A study in the Anthropocene. *J. Maps* **2022**, *19*, 2145917. [\[CrossRef\]](#)
82. Mandarino, A.; Faccini, F.; Luino, F.; Bono, B.; Turconi, L. Integrated Approach for the Study of Urban Expansion and River Floods Aimed at Hydrogeomorphic Risk Reduction. *Remote Sens.* **2023**, *15*, 4158. [\[CrossRef\]](#)
83. ISTAT (Italian Institute of National Statistics) Dataset. Available online: <https://demo.istat.it/app/?i=POS> (accessed on 21 March 2024).
84. ISTAT (Italian Institute of National Statistics) Census. Available online: https://ebiblio.istat.it/digibib/Censimenti%20popolazione/Censimentipopolazioneresidentedal1861/RML0050288Pop_res_cens_1861_1991.pdf (accessed on 7 June 2024).
85. ISTAT (Italian Institute of National Statistics) Tourism—Movimento Dei Clienti (Arrivi/Presenze) Negli Esercizi Ricettivi per Tipologia Ricettiva e Comune di Destinazione. Available online: http://dati.istat.it/DownloadFiles.aspx?&DatasetCode=DCSC_TUR&Lang=IT (accessed on 21 March 2025).
86. Lombardy Region Geoportal. Available online: <https://www.geoportale.regione.lombardia.it/en-GB/home> (accessed on 12 April 2024).
87. Rinaldi, M.; Surian, N.; Comiti, F.; Bussettini, M. *IDRAIM—Sistema di Valutazione Idromorfologica, Analisi e Monitoraggio dei Corsi d’Acqua*; ISPRA: Rome, Italy, 2014. Available online: <https://www.isprambiente.gov.it/it/pubblicazioni/manuali-e-linee-guida/idraim-sistema-di-valutazione-idromorfologica-analisi-e-monitoraggio-dei-corsi-dacqua> (accessed on 22 December 2016).

88. Gestione dei Sedimenti Fluviali (Ge.Se.Flu) CNR IRPI Project. 2014. Available online: <http://www.irpi.cnr.it/project/geseflu/> (accessed on 4 September 2020).
89. Lombardy Region Circular DSTN/2/2280/1995. Available online: <https://www.regione.lombardia.it/wps/wcm/connect/f03628d3-a9ea-4e4f-971c-ab65d1b92442/nota-tecnica-approfondimento-piani-emergenza-dighe.pdf?MOD=AJPERES&CACHEID=ROOTWORKSPACE-f03628d3-a9ea-4e4f-971c-ab65d1b92442-noJzQ9L> (accessed on 13 April 2025).
90. Luino, F.; De Graff, J.; Roccati, A.; Biddoccu, M.; Cirio, C.G.; Faccini, F.; Turconi, L. Eighty Years of Data Collected for the Determination of Rainfall Threshold Triggering Shallow Landslides and Mud-Debris Flows in the Alps. *Water* **2020**, *12*, 133. [CrossRef]
91. POLARIS CNR Project. Available online: <https://polaris.irpi.cnr.it/> (accessed on 12 May 2024).
92. CNR IRPI Archive Historical Documents. Available online: <https://www.irpi.cnr.it/en/products-services/data/archives/> (accessed on 30 May 2019).
93. AVI Aree Vulnerate Italiane GNDC Italian Project. Available online: <https://avi.gndci.cnr.it/> (accessed on 8 June 2024).
94. Luino, F.; Bassi, M.; Bossuto, P.; Fassi, P.; Belloni, A.; Padovan, N. *Individuazione delle Zone Potenzialmente Inondabili dal Punto di Vista Storico e Morfologico a Fini Urbanistici: Fiume Oglio (Valcamonica)*; PRIR 2000–Cod IReR 2000A21 CNR IRPI Internal report 12/2000; CNR IRPI: Milan, Italy, 2002.
95. RASDA System—Sistema Regionale On-Line per la Raccolta Schede Danni ai Sensi della D.G.R. n. 8/8755 del 22/12/2008. Available online: <https://sicurezza.servizirl.it/web/protezione-civile/rasda> (accessed on 21 June 2025).
96. Money Converter. Available online: <https://inflationhistory.com> (accessed on 3 August 2025).
97. Pedersoli, G.S. *La Lunga Alluvione (1960): Cronaca e Storia Dopo Trent'Anni*; Civitate Camuno Edizioni Toroselle: Artogne, BS, Italy, 1991; p. 287. (In Italian)
98. Italian Ministry of the Interior. Territorial Government Policies. Available online: <https://www.interno.gov.it/it/amministrazione-trasparente/pianificazione-e-governo-territorio> (accessed on 1 June 2025).
99. IFFI ISPRA Geoportal. Available online: <https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corso/suolo-e-territorio-1/iffi-inventario-dei-fenomeni-franosi-in-italia> (accessed on 1 April 2024).
100. PAI ADBPo Geoportal. Available online: <https://pai.adbpo.it/documentazione-pai/> (accessed on 5 March 2024).
101. PGRA ISPRA Geoportal. Available online: https://www.isprambiente.gov.it/pre_meteo/idro/Piani_gest.html (accessed on 9 April 2024).
102. Turconi, L.; Tropeano, D.; Savio, G.; Bono, B.; De, S.K.; Frasca, M.; Luino, F. Torrential Hazard Prevention in Alpine Small Basin through Historical, Empirical and Geomorphological Cross Analysis in NW Italy. *Land* **2022**, *11*, 699. [CrossRef]
103. Paranunzio, R.; Chiarle, M.; Laio, F.; Nigrelli, G.; Turconi, L.; Luino, F. Slope failures in high-mountain areas in the Alpine Region [dataset]. *PANGAEA* **2019**. [CrossRef]
104. Paranunzio, R.; Chiarle, M.; Laio, F.; Nigrelli, G.; Turconi, L.; Luino, F. New insights in the relation between climate and slope failures at high-elevation sites. *Theor. Appl. Climatol.* **2019**, *137*, 1765–1784. [CrossRef]
105. L'Eco di Bergamo Online Journal Archive. Available online: https://www.ecodibergamo.it/stories/valle-di-scalve/diga-del-gleno-95-anni-fa-disastro-ecco-come-leco-racconto-tragedia-o_1295769_11/ (accessed on 21 July 2024).
106. Kuang, D.; Xu, R.; Zhou, W. How do lessons learned from past flood experiences influence household-level flood resilience: A case study of Jiangnan village in Southern China. *Int. J. Disaster Risk Reduct.* **2024**, *114*, 104998. [CrossRef]
107. Mochizuki, J.; Chang, S.E. Disasters as opportunity for change: Tsunami recovery and energy transition in Japan. *Int. J. Disaster Risk Reduct.* **2017**, *21*, 331–339. [CrossRef]
108. Albano, R.; Mancusi, L.; Adamowski, J.; Cantisani, A.; Sole, A. A GIS Tool for Mapping Dam-Break Flood Hazards in Italy. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 250. [CrossRef]
109. Maranzoni, A.; D'Oria, M.; Rizzo, C. Probabilistic mapping of life loss due to dam-break flooding. *Nat. Hazards* **2024**, *120*, 2433–2460. [CrossRef]
110. Seyedashraf, O.; Mehrabi, M.; Akhtari, A.A. Novel approach for dam break flow modelling using computational intelligence. *J. Hydrol.* **2018**, *559*, 1028–1038. [CrossRef]
111. IT-Alert System. Available online: <https://www.it-alert.it/it/> (accessed on 3 October 2024).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.