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Harmonizing socioeconomic and environmental factors in lake ecosystems: The case of Lake Iseo

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ABSTRACT

The complex interplay between socioeconomic progress and environmental protection poses a major challenge to sustainable development in lake basins. To assess the dynamic relationship between these dimensions, this study applies an integrated framework combining a Coupling Coordination Degree (CCD) model and an Obstacle Diagnosis Model (ODM) to the Iseo Lake sub-basin in Northern Italy from 2008 to 2022. The results show that the system evolved from an initial stage of barely balanced development to a more coordinated configuration, with the CCD increasing to 0.75 in 2022. The long-term improvement reflects both the growth of key socioeconomic indicators and the progressive consolidation of environmental governance frameworks. The ODM reveals a temporal shift in limiting factors: while early-stage coordination was mainly constrained by economic weaknesses, in recent years the environmental subsystem, especially lake water state, has emerged as the primary barrier. These findings suggest that sustaining and enhancing coordination will require continued efforts in nutrient load reduction, infrastructural resilience, and the integration of land-use planning with ecological restoration goals. This study offers a replicable framework for assessing socio-ecological interactions in lake basins and can inform place-based strategies for long-term water resource sustainability.

1. Introduction

Water resources are a critical factor for the sustenance of human societies, impacting economic development, industrial placement, and the overall quality of life in urban and rural areas. Their role extends beyond the provision of basic needs, as they also contribute significantly to maintaining ecological balance and environmental stability (Y. Liu et al., 2020; Marston and Cai, 2016). In addition, water acts as a vital component in the ecosystem, supporting both natural processes and human activities. Beyond being the foundation for economic activities, water resources also play an essential role in mitigating environmental pollutants, as they help absorb and dilute them (Y. Liu et al., 2020; K. Qin et al., 2019). The extent to which water is used efficiently, and the condition of the aquatic environment can serve as direct indicators of a nation's capacity in terms of both technological advancement and economic development.

Lakes are a fundamental natural resource and support a wide range of biodiversity, providing essential and irreplaceable ecosystem services that are crucial for human survival and socio-economic development (Jenny et al., 2020; L. Xu and Chen, 2023). Due to their sensitivity to environmental disturbances, they function as indicators of both regional and global change (Jenny et al., 2020).

The lake basin areas are usually characterized by high population concentrations and substantial socio-economic activities, which are pivotal in driving both social progress and sustainable regional development (H. Liu et al., 2015; L. Xu and Chen, 2023). The integration of economic development and the preservation of ecological functions within lake basins is vital for achieving long-term regional sustainability (Luo and Zuo, 2019; L. Xu and Chen, 2023). This dual objective underscores the importance of promoting and advancing integrated watershed management practices at multiple scales. Responsible utilization and management of lake resources can foster societal development and improve human welfare. Conversely, excessive resource exploitation, along with insufficient environmental protection, can lead to significant ecological and social drawbacks (Ma et al., 2010; L. Xu and Chen, 2023). Furthermore, lakes are increasingly subjected to pressures from both climate change and human activities, which exacerbate existing environmental challenges (Ma et al., 2010; Olsson et al., 2025; O'Reilly et al., 2015; L. Xu and Chen, 2023).

Ongoing population growth, economic expansion, and the

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intensification of human interventions have increasingly placed pressure on lake ecosystems (L. Xu and Chen, 2023; X. Xu et al., 2016) in some cases in parallel with a widespread decline in lakes' capacity to maintain water quality, with phenomena such as pollution and eutrophication becoming increasingly prevalent in freshwater systems worldwide (Huang et al., 2019; L. Xu and Chen, 2023). Focusing exclusively on the water system from a limnological perspective, limnological research has consistently highlighted the progressive deterioration of lake systems, manifested through resource depletion, increasing water temperatures, and rising levels of contamination (Jenny et al., 2020).

Achieving a balance between socioeconomic development and the preservation of aquatic ecosystems has emerged as a major challenge (T. Li et al., 2016; X. Qin et al., 2024; Xing et al., 2019). In many regions, rapid industrial and urban expansion has coincided with a steady decline in water quality, sometimes characterized also by the occurrence of cyanobacterial blooms in lakes, but not always (Dijk et al., 2013; X. Qin et al., 2024; Sun et al., 2018).

Recent research has primarily focused on isolated dimensions or specific phases of lake water governance, such as ecological transformations, hydrological processes, pollutant source tracing, and mitigation strategies, often from highly specialized or disciplinary viewpoints (Y. Cui et al., 2021; Z. Li et al., 2020; L. Xu and Chen, 2023). While these studies contribute valuable insights, they tend to overlook the broader systemic nature of lake environmental management. The governance of lake ecosystems represents a complex, dynamic interplay between ecological processes and socio-institutional factors. The lake ecosystem is shaped by both the structural and functional properties of the lake itself and by governance decisions and socio-economic forces.

Some studies have demonstrated that during the initial phases of economic expansion, water quality can deteriorate but as economic development continues and more resources are allocated to environmental protection and technological innovation, water conditions tend to improve, mutually reinforcing dynamic between the two systems (Y. Liu et al., 2020; Ouyang et al., 2019; Xie et al., 2019). At the same time, environmental degradation, such as water pollution and scarcity, can in turn impose constraints on sustained and healthy economic development, revealing a bidirectional and interdependent relationship (Isik et al., 2019). However, the relationship between these two subsystems does not imply a direct causal or inferential link.

This complexity highlights the need to develop integrated approaches that promote a sustainable and coordinated relationship between socioeconomic development and water environmental quality.

This study aims to investigate the coordinated relationship between socioeconomic development and lake environmental quality in the urban and peri-urban system of Iseo Lake and its hydrographic subbasin, located in Lombardy, northern Italy. To this end, we construct a coupling coordination framework based on the Coupling Coordination Degree Model (CCDM), integrating two sets of indicators that respectively represent the socioeconomic dynamics of the basin and the environmental quality of the lake. Using time series data from 2008 to 2022, the study analyzes the temporal evolution of each subsystem and assesses the degree of coordination between them, providing insights into the sustainability and balance of the system over time.

In addition, the Obstacle Diagnosis Model (ODM) is applied to identify the key limiting factors that hinder the improvement of coordination between the two subsystems. This helps to highlight specific socio-economic or environmental elements that act as barriers to achieving higher levels of coupling, offering practical information for targeted policy intervention.

This research contributes to broadening the application of coordination analysis in freshwater systems, focusing on a mid-sized deep lake with fluctuating oxic-anoxic conditions, an area that has received relatively limited attention in previous CCD studies. In particular, the area selected for this study is the Lake Iseo watershed, focusing on the peri-urban zone of the lake ecosystem. Lake Iseo represents a particularly meaningful case study among deep peri-Alpine lakes because it combines distinctive limnological, sedimentological, and socio-economic characteristics within a relatively compact spatial context. From a physical and environmental perspective, the lake is characterized by a limited surface area (≈60.9 km^2) coupled with a considerable maximum depth (≈256 m). The presence of a large island (Monte Isola) subdivides the basin and influences circulation patterns, contributing to spatial heterogeneity in hydrodynamics and water quality. Limnologically, Lake Iseo is paradigmatic due to its progressive transition from an oligomictic to an intermittently meromictic system. Since the 1980s, complete deep-water mixing events have become increasingly rare, leading to the establishment of a permanently anoxic monimolimnion below approximately 80–100 m depth. This persistent stratification results in a marked vertical decoupling between surface and deep waters, with nutrient accumulation and oxygen depletion confined to the deepest layers. As highlighted by Pilotti and Valerio (2021), this condition produces an ecological paradox in which surface waters may show signs of partial improvement, while the majority of the lake volume continues to experience deterioration. Beyond its physical setting, Lake Iseo is also socio-economically distinctive. Unlike larger and more internationally renowned subalpine lakes such as Lake Como or Lake Garda, Lake Iseo drains a strongly inhabited and historically industrialized watershed that has undergone profound economic transformations over time. For much of the twentieth century, the lake supported intensive industrial activities, particularly in the steel and manufacturing sectors, that relied on its water resources. More recently, the local economy has shifted toward tourism and high-value agricultural production linked to the Franciacorta area. This transition has led to diversified but persistent pressures on the lake ecosystem, associated with urban settlements, infrastructure, tourism intensity, and water use, all concentrated within a relatively small basin.

These characteristics make Lake Iseo particularly suitable for integrated environmental analysis. Its long monitoring history, combined with well-documented limnological processes and sedimentary archives, allows for the investigation of how water quality, sediment dynamics, and lake functioning evolve within a context of long-term socio-economic transformation. For these reasons, Lake Iseo constitutes a paradigmatic case study, offering insights that are transferable to other deep stratified lakes facing comparable environmental challenges under conditions of sustained human use.

Furthermore, this study aims at emphasizing the importance of long-term, integrated analysis for informing regional sustainability strategies and supporting effective decision-making in the governance of complex lake–basin systems.

2. Literature review on CCDM

Only a limited number of studies have approached lake governance through an integrated lens that considers both socioeconomic and environmental subsystems in a unified analytical framework (Y. Liu et al., 2020; X. Qin et al., 2024; L. Xu and Chen, 2023). The concept of "coupling," originally derived from physics to describe interactions between interdependent systems (D. Cui et al., 2019; L. Xu and Chen, 2023), has gained increasing relevance in environmental science. In the context of lake regions, the relationship between socioeconomic development and water environmental conditions reflects a tightly interwoven coupling mechanism, characterized by complex feedback loops, nonlinear interactions, and mutual influence across processes such as urbanization, industrialization, and ecological change (D. Cui et al., 2019; Han et al., 2017; J. Liu et al., 2007; X. Qin et al., 2024; L. Xu and Chen, 2023).

The Environmental Kuznets Curve (EKC) has been widely used to study the relationship between economic growth and environmental degradation (D. Cui et al., 2019; He et al., 2017; Y. Liu et al., 2020; X. Qin et al., 2024; Shen et al., 2018; L. Xu and Chen, 2023). According to this model, environmental pressure tends to increase in the early stages of development, but decreases once a certain income level is reached, forming an inverted U-shaped trend (D. Cui et al., 2019; He et al., 2017; Zhao et al., 2016). Several empirical studies have supported this hypothesis in different contexts (Y. Liu et al., 2020). For example, Orubu and Omotor (2011) found such a relationship between per capita income and water pollution levels in several African countries (Orubu and Omotor, 2011). Similarly, Zhang et al. (2017) identified a comparable trend in China, where water pollutant emissions initially increased with economic growth and then began to decline (C. Zhang et al., 2017). While this approach has provided useful insights, it mainly considers how urban and economic development affects the environment, without accounting for the feedback effects that environmental degradation can have on socioeconomic systems (D. Cui et al., 2019; He et al., 2017; X. Qin et al., 2024). As a result, the two-way interaction between the social economy and water environment is still not well understood (Aljerf, 2018; D. Cui et al., 2019; Okuma, 2017).

The concept of coupling coordination is rooted in the idea that sustainable development depends on a balanced interaction between socioeconomic progress and environmental protection (D. Cui et al., 2019). Within this framework, the Coupling Coordination Degree (CCD) serves as a practical and integrated indicator to assess whether these two systems are evolving in harmony, and to what extent such coordination contributes to regional sustainability (D. Cui et al., 2019; Fang et al., 2016; X. Qin et al., 2024; Sun et al., 2018). By quantifying the degree of alignment between development and environmental quality, the CCD has been widely applied in studies exploring the interactions between urbanization or socioeconomic development and environment, water environment or carbon emissions (Chen et al., 2020; D. Cui et al., 2019; Deng et al., 2021; He et al., 2017; Y. Li et al., 2012; Shen et al., 2018; Song et al., 2018). However, despite its growing use, the application of the CCD model specifically to analyze the relationship between socioeconomic development and lake water quality remains limited. Few studies (Y. Liu et al., 2020; X. Qin et al., 2024; L. Xu and Chen, 2023) have directly examined how the two systems evolve together in lacustrine contexts, leaving a gap in the understanding of their coordinated dynamics. This highlights the need to adopt comprehensive frameworks, such as the CCD, to evaluate the long-term sustainability of lake regions by integrating multiple indicators from both the socioeconomic and environmental subsystems.

Linking results of coupling coordination to policy decisions is crucial to help policymakers evaluate how different development paths and water protection measures may affect system coordination (D. Cui et al., 2019).

3. Materials and method

3.1. Study area

Iseo lake is a deep subalpine lake located in Northern Italy, with a surface area of 61 km^2 and a maximum depth of 256 m. The lake drains a mountainous watershed (Fig. 1) of approximately 1807 km^2, comprising mainly the Valle Camonica (1440 km^2), the Borlezza Valley (131 km^2), and a series of smaller surrounding catchments totalling 176 km^2 (Pilotti et al., 2021). In this study, we focus on the latter group of catchments, corresponding to the portion of the watershed directly drained by the lake (Figs. 1 and 2). This choice was made to specifically investigate coordination dynamics within the area where socio-economic pressures and governance actions are most directly connected to lake conditions. In fact, the CCD does not aim to identify causal or inferential relationships between the two subsystems, but rather to provide evidence of coordination between their respective development trajectories.

The hydrology of Iseo Lake is regulated by a dam located in Sarnico, controlling seasonal water levels and enabling the use of stored water for irrigation in the downstream Po River Plain.

Within the direct drainage area, municipal wastewater is conveyed to the Costa Volpino treatment plant, located upstream of the lake, from which the treated effluent is subsequently discharged directly into the lake. Accordingly, this facility represents the only treatment plant considered in the present analysis, treating almost all of the domestic wastewater from the municipalities it serves. The WWTP in Paratico, which discharges downstream of the lake, was excluded as it does not influence in-lake water quality conditions.

Historically, the Sebino area has been economically driven by the textile industry, particularly silk production based on sericulture, which represented a cornerstone of the local economy for centuries. This sector, however, entered into crisis during the first half of the twentieth century. In the post-war period, the local economic structure progressively shifted toward the development of the steel industry, which for a long time made extensive use of the lake's water resources for production and cooling processes. Earlier phases of industrialization had already taken shape in the second half of the nineteenth century, when industrial activities developed in the area between Lovere and Castro, marking an important stage of early industrial growth in the region. Local production benefited from the exploitation of hydropower from the Tinazzo stream, which had previously supported foundry activities, as well as from the use of peat extracted from the lower part of the lake. The raw materials processed in the area mainly originated from Valle Camonica and Val di Scalve. Industrial development was driven by

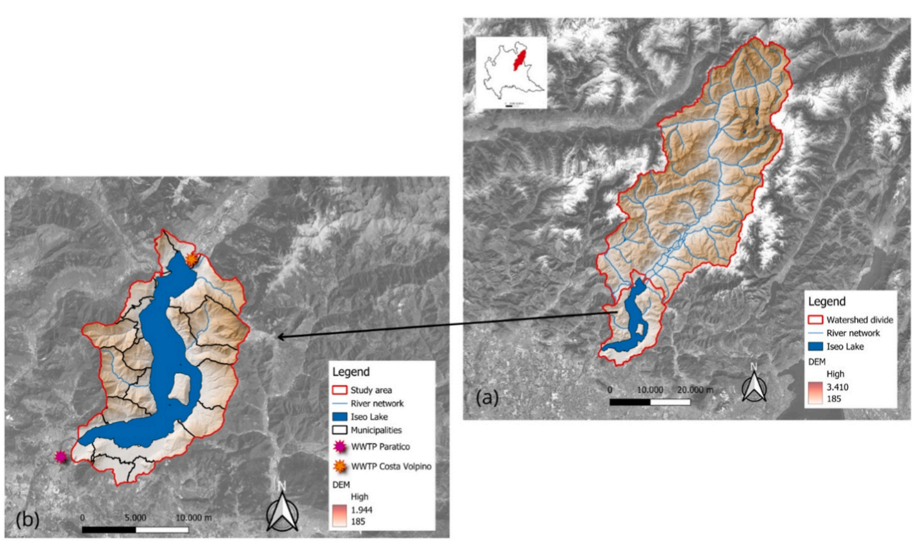

Fig. 1. Study area of Iseo Lake and its basin (a) and sub-basin (b). In Fig. 1b, municipalities are delineated by black outlines corresponding to municipal boundaries.

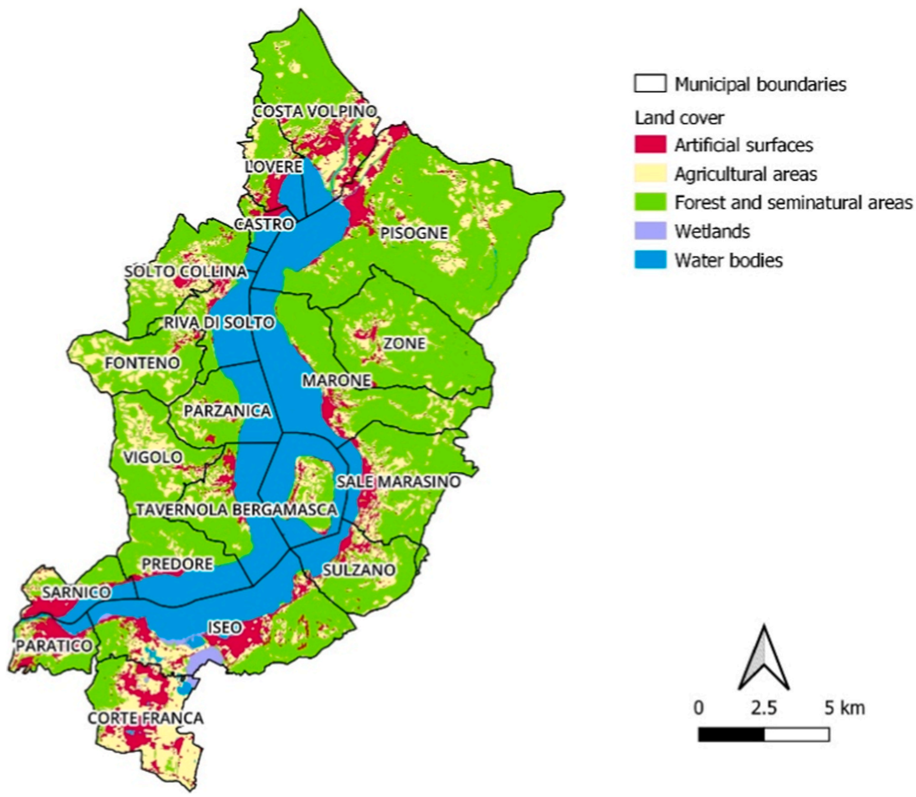

Fig. 2. Study area of Iseo Lake with the land use of the municipalities included in the case study.

continuous attention to technological innovation and by the availability of local energy and mineral resources. Within a few years, industrial activities employed several hundred workers, contributing significantly to local economic growth. At the same time, growing awareness of the strategic role of transportation fostered investments in connectivity with the Po Valley, culminating in the construction of the Sarnico–Palazzolo railway in 1876.

More recently, starting from the late 1990s, the Sebino area experienced a further structural transformation driven by the expansion of viticultural activities and the promotion of the Franciacorta DOCG designation. Tourism developed in parallel and has become the most important economic sector in the area, supported by extensive accommodation capacity and by the high landscape value of Lake Iseo. The local economy is now primarily based on tourism and high-quality wine production, resulting in a significant enrichment of the territory and an intensification of lake-related uses.

Within this long-term socio-economic trajectory, Lake Iseo represents a paradigmatic environmental case among deep subalpine lakes. Despite its relatively limited surface area, the lake is very deep and characterized by steep banks and complex bathymetry, which strongly constrain vertical mixing processes and enhance water column stability (Pilotti and Valerio, 2021). These physical characteristics make the lake particularly sensitive to both anthropogenic pressures accumulated over time and climate-driven changes in thermal stratification.

From an environmental perspective, Lake Iseo is paradigmatic because it has progressively shifted from an oligomictic to an intermittently meromictic system. Long-term observations indicate that complete overturn events have become increasingly rare, leading to the formation of a permanently anoxic deep-water layer below approximately 100 m depth (Pilotti and Valerio, 2021). This persistent stratification prevents effective oxygen renewal of the hypolimnion and promotes the accumulation of nutrients and reduced compounds, creating a marked vertical decoupling between surface and deep waters.

Unlike other large subalpine lakes that have shown clearer recovery following reductions in external nutrient loads, Lake Iseo exhibits a strong internal loading problem. A substantial fraction of the lake's phosphorus pool is stored in deep, permanently isolated waters and sediments, where it remains largely disconnected from short-term management actions targeting surface inputs (Pilotti and Valerio, 2021). As a result, partial improvements in surface water quality may coexist with continued deterioration of deep-water conditions, generating an ecological paradox in which the visible portion of the lake appears to recover while the majority of its volume continues to degrade.

For these reasons, Lake Iseo constitutes an exemplary case study for investigating the interaction between socio-economic development, physical lake dynamics, and water quality evolution. This spatial and hydrological delineation ensures that the coupling analysis accurately reflects interactions between land-based human activities and the lake's environmental status.

3.2. Theoretical framework

The relationship between socioeconomic development and lake water environmental quality can be conceptualized as a coupled system, in which the socioeconomic and environmental subsystems evolve in parallel and exhibit interconnected dynamics. Each subsystem follows its own internal development trajectory, while their interaction is reflected in patterns of coordination and relative constraint over time. From this perspective, socioeconomic development is associated with changes in infrastructure provision, technological capacity, governance arrangements, and patterns of resource use, which together characterize the evolving context within which lake management takes place. At the same time, the lake environmental subsystem is characterized not only by variations in water quality conditions and limnological processes that define the internal state of the aquatic system, but also by the intensity of direct anthropogenic pressures acting upon it, including water withdrawals and wastewater discharges. The co-evolution of these two subsystems may generate phases of alignment or imbalance, observable through changes in their respective development levels. Lake environmental quality represents a fundamental component of the territorial system within which socioeconomic activities are embedded. Water availability, ecosystem conditions, and environmental quality constitute key contextual factors for sectors such as tourism, agriculture, and industry, contributing to the overall configuration of the lake basin system. In this sense, the socioeconomic and environmental subsystems are best understood as interdependent components of a broader coupled system, whose interaction can be assessed in terms of coordination patterns. Degraded water quality, on the other hand, can undermine these sectors, limiting economic opportunities, threatening public health, and reducing the availability of clean water, thus posing a serious constraint on long-term development (Y. Liu et al., 2020; X. Qin et al., 2024).

A conceptual framework is adopted to represent the interactions between the two subsystems, which together are considered as a coupled system (Fig. 3).

To capture the complexity of this bidirectional relationship, we constructed a comprehensive index system based on previous studies and tailored to the specific context of the Iseo Lake basin. The index system includes two distinct but interdependent indicator groups: one representing the socioeconomic subsystem of the lake's catchment area, and the other characterizing the environmental quality of the lake itself. These indicators are selected according to relevance, data availability, and their ability to reflect key processes within each subsystem. Through this structure, the compound system can be quantitatively assessed using the Coupling Coordination Degree Model (CCDM), allowing us to evaluate not only the independent trends of each subsystem, but also the degree of their coordinated evolution over time (He et al., 2017; Y. Liu et al., 2020; X. Qin et al., 2024; L. Xu and Chen, 2023).

The set of evaluation indicators used to characterize the coupling system is presented in Table 1.

The socioeconomic subsystem is represented by a set of 12 indicators covering both economic and social development dimensions, following established approaches in the literature (D. Cui et al., 2019; He et al., 2017; X. Qin et al., 2024). In addition, considering the socio-economic history of Lake Iseo, we adapted the CCD framework by including indicators related to the tertiary sector economy in addition to the secondary sector (X6-X12), which are not considered in some previous studies on other lakes. This allowed us to account for the more recent socio-economic development of the lake area, in which the tertiary sector and the labor force employed therein represent a significant component of the local economy. At the same time, we included per capita income data, which we considered particularly relevant in a local and territorial context such as that of the Iseo municipalities.

Focusing on the environmental subsystem, we include in CCD both turbidity and chlorophyll-a indicators (X13-X14). They are widely used indicators of inland water quality, yet they describe distinct and complementary aspects of lake ecosystems. Turbidity is an optical property of water that quantifies light scattering caused by suspended particles, including inorganic sediments, organic detritus, and planktonic organisms. As such, it primarily reflects physical processes such as sediment input from the catchment, resuspension of bottom sediments, and hydrological disturbances, particularly important in Lake Iseo. However, turbidity alone does not allow discrimination between biologically and non-biologically derived particulate matter. Chlorophyll-a is a photosynthetic pigment ubiquitous in phytoplankton and is commonly used as a proxy for algal biomass and primary productivity. Chlorophyll-a therefore represents a biological indicator closely linked to nutrient availability, trophic status, and eutrophication processes in lake ecosystems. While highly informative of phytoplankton dynamics, chlorophyll-a does not capture the contribution of inorganic suspended matter to water column light attenuation. The combined use of turbidity and chlorophyll-a is thus essential for a comprehensive assessment of lake water quality.

Conceptually, this structure follows a pressure–state logic frequently adopted in integrated watershed assessments. The social subsystem captures structural drivers such as income, industrial composition, demographic dynamics, and urbanization patterns, whereas the environmental subsystem captures both the ecological state of the lake and the intensity of direct hydrological and pollutant pressures acting upon it. This distinction avoids duplication while preserving interpretability of subsystem indices.

3.3. Data sources

The lake water environmental subsystem is structured into two analytically distinct but functionally interrelated components: (i) lake water state, representing the internal ecological and physicochemical conditions of the lake, and (ii) anthropogenic pressures directly exerted on the lake system. Although these pressures originate from socioeconomic activities, they are included within the environmental subsystem because they represent the direct interface through which human activities modify lake functioning. In total, 12 indicators were selected across these two categories, drawing on multiple data sources. Specifically, indicators related to anthropogenic influences were obtained from statistical data provided by local water service operators (Acque Bresciane S.r.l. and UniAcque S.p.A.), the S.I.R.E. (Sistema Informativo Regionale Acque) portal managed by ARPA Lombardia, and ARPA Lombardia itself. Meanwhile, data describing the lake's water state were derived from in-situ water quality measurements and satellite remote sensing. Specifically, the indicators for dissolved oxygen (DO), total phosphorus (TP), ammonium nitrogen (NH_3-N), and late-winter mixing depth were provided by ARPA Lombardia and Lau et al. (2020). Monitoring is currently performed at a single station located at the point of maximum depth of the lake, between the municipalities of Tavernola Bergamasca and Monte Isola, which is considered representative of deep-water processes and long-term limnological dynamics in stratified lakes such as Lake Iseo. Sampling is conducted seasonally, targeting key limnological phases: the stratification period (June–September) for deep hypolimnetic oxygen and ammonium concentrations, and the late-winter circulation period (February–March) for total phosphorus and maximum mixing depth. Chlorophyll-a (Chl-a) and turbidity indicators were derived from both in situ measurements and satellite data provided through the Lakes CCI project[1] and Sentinel-3/OLCI imagery and ARPA Lombardia. Satellite-derived values were averaged across all cloud-free observations available within each calendar year to ensure temporal consistency with field measurements. Chlorophyll-a concentrations are monitored by measurements carried out at the point of maximum depth of the lake (see before for the description) and are about 6 samplings events per year, from spring to autumn.[2] For parameters measured multiple times within a year (e.g., chlorophyll-a, turbidity, dissolved oxygen, and ammonium), annual values used in the CCD calculations were computed as the arithmetic mean of all available observations within the corresponding calendar year. For indicators associated with specific limnological phases (e.g., late-winter mixing depth and winter total phosphorus), the seasonal measurement representative of that hydrological year was used as the annual indicator value. Satellite observations are provided and validated within the Lakes Climate Change Initiative (Lakes CCI) project and by data acquired from the Sentinel-3/OLCI (Ocean and Land Colour Instrument) sensor, processed by the National Research Council-Institute for Electromagnetic Sensing of the Environment (CNR-IREA). Annual socioeconomic development indicators were compiled from statistical datasets obtained from

[1] https://climate.esa.int/en/projects/lakes/about/.

[2] This temporal resolution is designed to capture seasonal variability in phytoplankton biomass, including spring and summer growth phases and potential bloom events, while winter sampling is generally reduced or absent due to low biological activity.

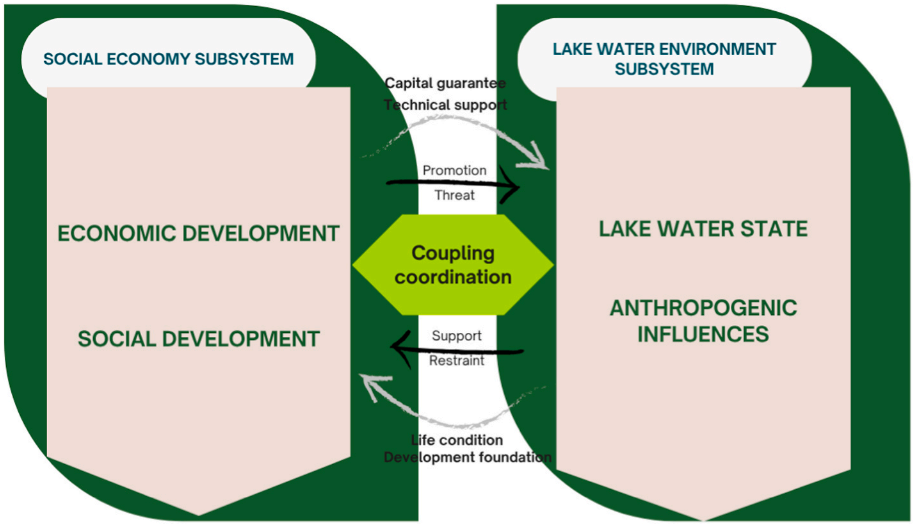

Fig. 3. The effect–feedback framework between socioeconomic development and lake's water state. Figure made by the authors, based on the conceptual mechanism described in Qin et al. (2024).

various institutions, including the Ministry of Economy and Finance (MEF), the Italian National Institute of Statistics (ISTAT), the Statistical Atlas of Municipalities (ASC), the Land Use Map of Lombardy (DUSAF, Destination Use of Agricultural and Forestry Land), and Bureau van Dijk (ORBIS). These indicators capture the direct operational pressures exerted on the lake system by human activities, distinguishing them from broader structural socioeconomic drivers represented in the social subsystem.

3.4. Data pre-processing

To ensure comparability among indicators and eliminate the influence of differing units and scales, all raw data were standardized prior to analysis. Specifically, we applied the range normalization method, which transforms each indicator value into a dimensionless quantity within the [0,1] interval. Indicators were classified as either positive, where higher values represent more favourable conditions for subsystem development, or negative, where higher values indicate adverse conditions. The normalization process followed standard equations for positive and negative indicators, as shown in Equation (1) (D. Cui et al., 2019; He et al., 2017; X. Qin et al., 2024; L. Xu and Chen, 2023; H. Zhang et al., 2011):

$$Z_{ij} = \begin{cases} \dfrac{(r_{ij} - \min\{r_j\})}{(\max\{r_j\} - \min\{r_j\})}, \textit{if } r_{ij} \textit{ is a positive indicator} \\ \dfrac{(\max\{r_j\} - r_{ij})}{(\max\{r_j\} - \min\{r_j\})}, \textit{if } r_{ij} \textit{ is a negative indicator} \end{cases} \tag{1}$$

where r_{ij} and Z_{ij} refer to the primitive and standardized values of the jth indicator in ith year, respectively, and $\min\{r_j\}$ and $\max\{r_j\}$ refer to the minimum and maximum values, respectively.

Following normalization, we calculated the weight of each indicator using the entropy method (EM). It is an objective weighting technique widely used in multi-indicator and multi-criteria evaluation frameworks, including economic analysis, sustainability assessment, composite index construction, and decision analysis. The method is grounded in information entropy theory, originally proposed by Shannon, which measures the degree of uncertainty or disorder in a system. In this context, entropy is used to quantify the amount of information conveyed by each indicator, as reflected by its variability across observational units. This data-driven weighting mechanism ensures that the resulting weights are objective, reproducible, and consistent with the intrinsic structure of the data. This approach reduces the bias associated with subjective weighting schemes and effectively reflect effectively reflect the roles of the indices in the evaluation object (D. Cui et al., 2019; He et al., 2017; Jia et al., 2018; Joshi & Kumar, 2019; X. Qin et al., 2024; L. Xu and Chen, 2023).

The calculation steps used to derive entropy weights are detailed in Equations (2)–(5).

Ratio of the jth indicator in year i, P_{ij}, is given by

$$P_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{m} Z_{ij}} \tag{2}$$

Information entropy of the jth indicator, e_j, is given by

$$e_j = -\ln m^{-1} \sum_{i=1}^{m} P_{ij} \ln P_{ij} \quad (0 \le e_j \le 1) \tag{3}$$

Redundancy in information entropy, d_j, is given by

$$d_j = 1 - e_j \tag{4}$$

Weight of each indicator j, ω_j, is given by

$$\omega_j = d_j \Big/ \sum_{j=1}^{n} d_j \tag{5}$$

where m and n are the statistical year and the number of evaluation indexes in a subsystem, respectively.

3.5. Coupling Coordination Degree Model (CCDM)

The Coupling Coordination Degree Model (CCDM) is commonly applied to assess the interaction and coordination between systems or subsystems, providing a quantitative basis for evaluating the degree to which their development processes are synchronized over time (Feng and Li, 2021; Huang et al., 2020; L. Xu and Chen, 2023).

The calculation method of coupling degree is as follows (D. Cui et al., 2019; He et al., 2017; X. Qin et al., 2024; Shen et al., 2018):

$$P(s) = \sum_{j=1}^{n} \omega_j^s \times Z_{ij}^s \tag{6}$$

$$P(l) = \sum_{j=1}^{n} \omega_j^l \times Z_{ij}^l \tag{7}$$

Table 1
Evaluation indicators of each subsystem.

Subsystem	Element level	Indicators	Direction
Social economy	Economic development	(*X1*) Taxable income (€)	+
		(*X2*) Taxable income growth rate (%)	+
		(*X3*) Per capita income (€/ab)	+
		(*X4*) Gross industrial output value (k€)	+
		(*X5*) Proportion of the secondary industries in total gross production (%)	+
		(*X6*) Proportion of the tertiary industries in total gross production (%)	+
	Social development	(*X7*) Population size (n. of residents)	+
		(*X8*) Population growth rate (%)	+
		(*X9*) Density of population (persons/km^2)	-
		(*X10*) Proportion of employees in the secondary industry (%)	+ +
		(*X11*) Proportion of employees in the tertiary industry (%)	+
		(*X12*) Urbanization (%)	+
	Lake water state	(*X13*) Turbidity (FNU)	-
		(*X14*) Chlorophyll *a* (mg/L)	-
		(*X15*) Deep dissolved oxygen (mg/L)	+
		(*X16*) Total phosphorus (mg/L)	-
		(*X17*) Deep ammonia nitrogen (mg/L)	-
		(*X18*) Maximum mixing depth (m)	+
	Anthropogenic influences	(*X19*) Total water consumption (m^3)	-
		(*X20*) Per-capita water resources (m^3/person)	+
		(*X21*) Domestic wastewater emissions (m^3)	-
		(*X22*) Industrial wastewater emissions (m^3)	-
		(*X23*) Wastewater treatment facilities (n.)	+
Lake water environment		(*X24*) Volume of treated wastewater (m^3)	+

Where *P(s)* and *P(l)* represent the comprehensive development level indexes of the socioeconomic and lake water environmental subsystems, respectively. Higher values indicate better development status of the corresponding subsystem. ω_j^s and ω_j^l denote the weights assigned to each indicator within the socioeconomic subsystems and lake water environmental, respectively. *n* refer to the total number of indicators used in the socioeconomic and lake water environmental subsystems, while Z_{ij}^s and Z_{ij}^l are the normalized values of each indicator within those respective subsystems.

After calculating the comprehensive development level indices of the socioeconomic and lake water environmental subsystems, the CCD model was established between these two subsystems as follows:

$$C = \left\{ P(s) \times P(l) \Big/ [(P(s) + P(l))/2]^2 \right\}^{1/2} \tag{8}$$

$$T = \alpha P(s) + \beta P(l) \tag{9}$$

$$D = \sqrt{C \times T} \tag{10}$$

where *C* refers to the coupling degree ($0 \le C \le 1$): the larger the value, the greater the degree of interaction between systems. *C* indicates the interaction degree of the socioeconomic and lake water environment subsystems, but it does not reflect the coordinated development of the two subsystems (L. Xu and Chen, 2023). *T* represents the coordinated index which reflects the overall coordination level between the subsystems, while α and β therein denote the contribution of the socio-economic factors and water environment to the comprehensive system, respectively. Given the equal importance attributed to socio-economic development and the improvement of lake water environmental quality, both subsystems are assumed to contribute equally to the overall coordination. Therefore, the coefficients are set as $\alpha = \beta = 0.5$ (D. Cui et al., 2019; Y. Liu et al., 2020; X. Qin et al., 2024). *D* is the degree of coupling coordination (CCD) between subsystems. The value of *D* ranges between 0 and 1; the larger it is, the higher the level of coupling coordination development. We divide the CCD of the coupling system into four classes, then further divide into 12 possible types in detail (Table 2).

3.6. Obstacle diagnosis model (ODM)

The Obstacle Diagnosis Model (ODM) is a mathematical model based on an evaluation model, designed to identify the key limiting factors that hinder system development or the achievement of specific objectives (Wu and Hu, 2020; L. Xu and Chen, 2023). In the context of this study, ODM is used to detect the primary barriers affecting the coupling and coordinated evolution between the socioeconomic and lake water environment subsystems over time (L. Xu and Chen, 2023). This approach enables the formulation of more targeted and effective strategies to enhance the overall coordination level. The obstacle degree is calculated as follows:

$$O_j = \frac{F_j \times I_j}{\sum_{j=1}^{m} F_j \times I_j} \tag{11}$$

$$I_j = 1 - Z_{ij} \tag{12}$$

Table 2
Development stages reflecting a coupling coordinated relationship in the coupling system (D. Cui et al., 2019; Y. Liu et al., 2020; X. Qin et al., 2024).

Classes	Types
$0.8 < D \le 1$ Highly balanced development	s(x) < e(y) Highly balanced development with lagging social economy
$0.5 < D \le 0.8$ Barely balanced development	s(x) = e(y) Highly balanced development of social economy and water environment
$0.2 < D \le 0.5$ Slightly unbalanced development	s(x) > e(y) Highly balanced development with lagging water environment
$0 < D \le 0.2$ Seriously unbalanced development	s(x) < e(y) Barely balanced development with lagging social economy
	s(x) = e(y) Barely balanced development of social economy and water environment
	s(x) > e(y) Barely balanced development with lagging water environment
	s(x) < e(y) Slightly unbalanced development with hindered social economy
	s(x) = e(y) Slightly unbalanced development of social economy and water environment
	s(x) > e(y) Slightly unbalanced development with hindered water environment
	s(x) < e(y) Seriously unbalanced development with hindered social economy
	s(x) = e(y) Seriously unbalanced development of social economy and water environment
	s(x) > e(y) Seriously unbalanced development with hindered water environment

Where O_j represents the obstacle degree of the j-th indicator or subsystem in relation to the coordinated development of the overall system. F_j denotes the contribution factor, typically expressed by the indicator's weight (ω_j), reflecting its relative importance. I_j refers to the deviation degree of the indicator, which captures the gap between the actual performance and the ideal state, commonly calculated as the difference between 1 and the normalized value (Z_{ij}) of the corresponding indicator.

4. Results and discussion

4.1. Analysis of the raw indicators

The comprehensive evaluation index system encompasses indicators distributed across four thematic components, as detailed in Table 1. The socioeconomic development of the study area is described through a set of integrated indicators (X1–X12) capturing economic performance, demographic dynamics, labor structure, and land-use changes over time.

Total taxable income (X1) represents the overall economic capacity generated within the sample of municipalities and shows a steady increase from approximately €1.05 billion in 2008 to more than €1.39 billion in 2022. The associated growth rate of taxable income (X2) highlights phases of contraction during the global financial crisis, around 2009-2010, and more recently during the COVID-19 pandemic, followed by a sustained recovery, indicating the resilience of the local economy. In fact, historically, the Sebino area was shaped by industrial activities, first dominated by textile production and later by steel manufacturing, which for a long time relied on the lake's water resources. From the late 1990s onward, the territory underwent a major transition, with tourism and high-quality viticulture, supported by the Franciacorta DOCG designation, becoming important economic drivers. As a result, the quality of the landscape and the ecological condition of Lake Iseo have become central to local sustainable development and long-term sustainability. The increase in per capita taxable income (X3), from about €13,600 to over €18,100, suggests that economic growth was not merely the result of demographic expansion, but rather of improved productivity, income levels, and economic efficiency.

The structure and performance of the productive system are further described by indicators related to the secondary sector. The value of production in the secondary sector (X4) increased, particularly after 2012, reflecting the recovery and consolidation of industrial and manufacturing activities remaining central in the economy of the territory. The proportion of secondary-sector production (X5) and the number of enterprises operating in this sector (X6) indicate that industrial activities remain a key pillar of the local economy, especially in the valley floors and peri-lacustrine areas where infrastructure and accessibility are higher. Nevertheless, when considering the share of employees in the secondary sector (X10), it becomes evident that the increase in productivity mentioned above is not accompanied by a proportional increase in the percentage of workers relative to total employment; on the contrary, a relative decline is observed (Fig. 4).

Over the approximately 20-year period considered, the proportion of workers employed in the secondary sector decreases, while the share of those employed in the tertiary sector increases (X11) (Fig. 5).

Thus, over time, these indicators reflect a gradual rebalancing toward the service sector, in line with broader regional and national trends. Nevertheless, the continued relevance of the secondary sector underscores the hybrid nature of the local economy, combining manufacturing, services, tourism, and specialized activities linked to the lake and surrounding areas. Demographic indicators show a relatively stable population framework. Total population (X7) and population growth rate (X8) reveal only limited fluctuations over the study period, with no evidence of sustained demographic expansion. Similarly, population density (X9) remains broadly constant, indicating that economic development has occurred without significant additional population pressure on settlement patterns. This stability is typical of mature

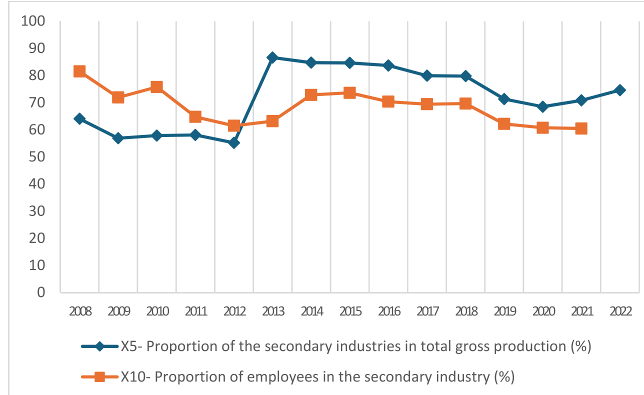

Fig. 4. Temporal trends of indicators X5–X10 over the period 2008–2022.

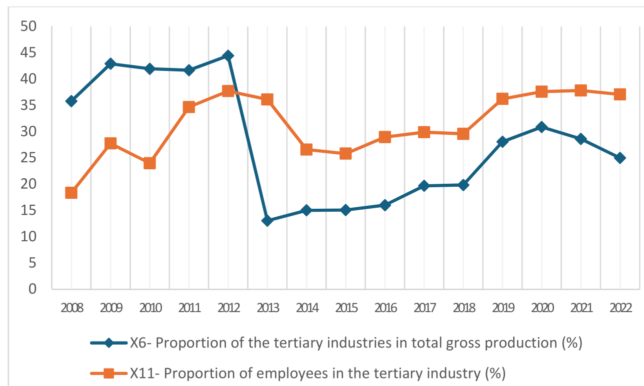

Fig. 5. Temporal trends of indicators X6–X11 over the period 2008–2022.

territorial systems, where economic growth is increasingly decoupled from population growth (Mazzocchi et al., 2013).

Finally, land-use dynamics are summarized by the share of urbanized surface (X12), which increased moderately from approximately 8.7% to 9.3% over the entire period. This growth in urbanized land suggests a regulated pattern of spatial development; the study area, characterized by a sensitive lacustrine environment, agricultural landscapes, and hilly–mountainous zones, is subject to planning constraints aimed at landscape protection and environmental sustainability. These trends are consistent with the strategic goals outlined in the “Territorial Development Framework Agreement” (TDFA) of the Sebino Area and the “Regional Area Territorial Plan of Franciacorta”, both of which promote sustainable growth, landscape protection, and territorial competitiveness. However, a continuous peri-urban expansion in the municipalities involved in the study has occurred during the years, where land take is predominantly associated with the conversion of agricultural land into urbanized areas, following this relatively continuous and incremental pattern, shared by urban and peri-urban municipalities across Lombardy during this period.

The interpretation of lake environmental indicators is consistent with the extensive limnological literature describing Lake Iseo as a paradigmatic case of a deep subalpine lake affected by long-term eutrophication and altered mixing regimes (Pilotti and Valerio, 2021). Turbidity (X13) (Fig. 6) and chlorophyll-a concentration (X14) (Fig. 7) jointly capture the response of the lake's euphotic zone to nutrient availability and physical constraints.

Previous studies have shown that Lake Iseo exhibits marked spatial and temporal heterogeneity, with higher biological activity and suspended biomass typically concentrated in the southern and shallower sectors of the basin, where water residence time is longer and nutrient

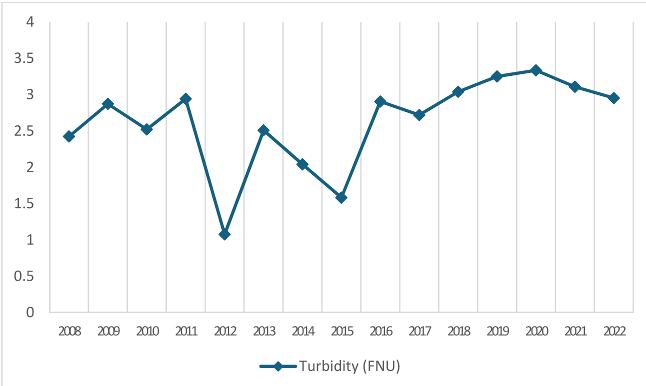

Fig. 6. Temporal trends of indicators X13 over the period 2008–2022.

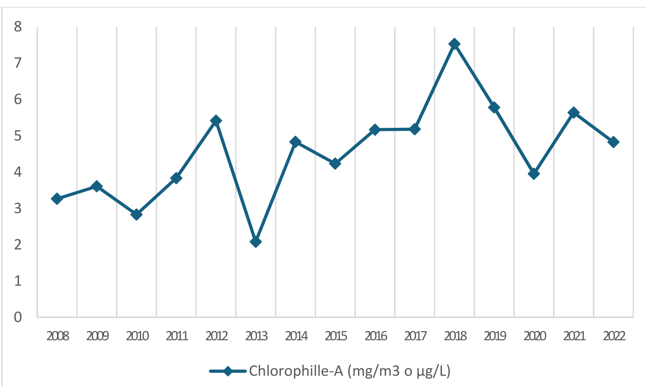

Fig. 7. Temporal trends of indicators X14 over the period 2008–2022.

accumulation is favored (Pepe et al., 2001). Turbidity values (X13) showed variable behavior, with peaks above 3 FNU in recent years and a slight increasing trend after 2018. Chlorophyll-a (X14), widely recognized as a proxy for phytoplankton biomass, represents a core indicator of trophic status under both Italian water legislation and the European Water Framework Directive (Premazzi et al., 2003). Variability in chlorophyll-a concentrations reflects not only external nutrient inputs but also internal lake processes, including sediment nutrient release and stratification-driven isolation of deep waters. In Lake Iseo, reductions in external phosphorus loads have not resulted in proportional declines in phytoplankton biomass, due to the dominant role of internal nutrient loading and lake morphometry. The coherence between turbidity (X13) and chlorophyll-a (X14) trends supports their joint interpretation as indicators of episodic algal blooms and enhanced phytoplankton productivity, particularly during stratified periods. Optical and limnological studies have demonstrated a strong sensitivity of water transparency and reflectance properties to chlorophyll-a concentration and phytoplankton composition, confirming the suitability of this indicator for capturing biological responses to eutrophication in Lake Iseo (Pepe et al., 2001).

Dissolved oxygen concentration in the hypolimnion (X15) provides critical insight into deep-water processes. Long-term observations indicate that Lake Iseo has entered a persistent meromictic condition, with a permanently anoxic monimolimnion below approximately 100 m depth, with frequent near-anoxic conditions (below 1 mg/L), indicating long-term deep-water oxygen depletion, which prevents effective oxygen renewal during winter circulation. The decline in hypolimnetic oxygen observed after 2010 is therefore consistent with a well-documented trajectory of deep-water oxygen depletion driven by enhanced thermal stability, reduced vertical mixing, and high rates of organic matter mineralization (Pilotti and Valerio, 2021). The depth of mixing (X18) represents a key physical control on the ecological functioning of Lake Iseo, as it determines the vertical extent of water column renewal and the potential for oxygen and nutrient redistribution. Variations in mixing depth over time reflect the combined influence of meteorological forcing, lake morphometry, and long-term thermal stability, all of which are critical factors in deep subalpine lakes.

Nutrient indicators further corroborate this interpretation. Total phosphorus concentrations (X16) remain elevated, while ammonium accumulation in the hypolimnion (X17) reflects anaerobic mineralization and sediment release under oxygen-depleted conditions. Previous studies have shown that a large fraction of Lake Iseo's phosphorus pool is stored in deep, permanently isolated waters, where it represents a long-term internal source capable of sustaining eutrophic conditions even when surface inputs are reduced (Premazzi et al., 2003; Pilotti and Valerio, 2021). This mechanism explains the apparent paradox of partial surface water quality improvement coexisting with a deterioration of conditions in the deeper lake volume. Previous studies have demonstrated that Lake Iseo behaves as an oligomictic to intermittently meromictic system, where complete overturn is rare and limited to exceptionally cold and windy winters (Premazzi et al., 2003; Pilotti and Valerio, 2021). In recent decades, the maximum depth reached by seasonal mixing has progressively decreased, often remaining well above the deepest portions of the basin. This limitation in mixing depth prevents effective oxygenation of the hypolimnion and reinforces the persistence of an anoxic monimolimnion. The observed values of X18 are therefore consistent with the documented reduction in deep-water renewal and with the strengthening of thermal stratification. A shallower mixing depth implies that only a fraction of the lake volume participates in seasonal circulation, while deeper waters remain isolated from atmospheric exchange. This physical constraint plays a fundamental role in explaining the long-term decline in hypolimnetic dissolved oxygen (X15) and the accumulation of nutrients, particularly phosphorus and ammonium, in deep layers (X16–X17). Moreover, limited mixing depth has important implications for biological dynamics. By restricting the upward transport of nutrients under normal conditions, reduced mixing may temporarily favor improvements in surface water quality. However, this apparent benefit is counterbalanced by the progressive storage of nutrients in deep waters, which represents a latent risk. Exceptional mixing events, should they occur, may trigger sudden nutrient injection into the euphotic zone, promoting intense phytoplankton growth and elevated chlorophyll-a concentrations (X14), as documented in previous limnological analyses of Lake Iseo (Pilotti and Valerio, 2021). Indicators related to water pressure and use provide additional context on anthropogenic stresses at the basin scale. Total water consumption (X19) within the sub-basin declined after 2012, potentially reflecting both structural changes in water demand and the effects of regulatory interventions. In particular, Lombardy Regional Regulation 9/2015 strengthened withdrawal concessions, promoted efficiency, and improved monitoring of abstractions, contributing to a reduction in overall pressure on water resources. At the same time, per-capita water availability (X20) remained relatively stable and showed a slight improvement after 2016. This trend suggests enhanced system resilience, supported by governance reforms under Regulation 9/2015 and earlier measures introduced by Lombardy Regional Regulation 2/2006, which encouraged water reuse, efficiency, and integrated monitoring. These policies proved particularly relevant during severe drought events, such as those recorded in 2018 and 2022. On the protection and mitigation side, the volume of treated wastewater (X24) increased steadily between 2008 and 2022, reflecting the expansion and upgrading of wastewater treatment infrastructure serving the lake basin. From the side of policy, Lombardy Regional Regulation 6/2019 introduced stricter discharge standards, accelerating technological upgrades and system optimization. Concrete examples include the project approved in 2017 for the adaptation of the Costa Volpino treatment plant, as well as substantial investments by local utilities. UniAcque S.p.A. invested approximately €2.5 million between 2014 and

2019, while Acque Bresciane S.r.l., through its 2021 Industrial and Sustainability Plans (Acque Bresciane, 2021), has outlined further improvements to wastewater treatment and sewer networks, including interventions specifically targeting the Sebino area.

4.2. Dynamic evaluation of the coupling coordination degree model

Fig. 8 illustrates the trends in socioeconomic and environmental development within the Iseo Lake sub-basin from 2008 to 2022.

The socioeconomic development trend for the Iseo Lake sub-basin from 2008 to 2022 highlights distinct phases:

- 2008–2012: The index declined from 0.445 in 2008 to 0.288 in 2012. This early stagnation aligns with the global financial crisis and its prolonged regional effects, compounded by more limited local strategic investment.
- 2013–2018: The index gradually increased, reaching 0.497 by 2018. This upturn could correspond with regional infrastructure initiatives, such as improvements in lake navigation and shore amenities launched by Lombardy Region, with early support sustainable transport on Iseo Lake (Regione Lombardia, 2016b), which stimulated both tourism and local employment. This aligns with the strategic objectives outlined in the Regional Area Territorial Plan of Franciacorta (Tira et al., 2017), which emphasizes the need to promote initiatives, projects, and territorial actions aimed at enhancing local identity and potential within a broader regional network, including Iseo and Garda lakes, the Oglio River park, the Brescia Hills park, and the municipalities of the Brescia plain. The plan seeks to improve residents' quality of life, strengthen the economic system and territorial competitiveness, and reinforce the area's tourism-oriented development.
- 2019–2020: Marked gains had a setback between 2019 and 2020 (index went from 0.461 to 0.424). This reversal reflects the disruption caused by the COVID-19 pandemic and associated travel restrictions, which notably decreased the inflow of tourists and curtailed economic activities.
- 2021–2022: There was a strong recovery, with the index climbing from 0.583 to 0.693. This revival was supported by sustained regional investments in lake mobility, safety, and public access. Regional tourism reports show that in 2022 the Sebino area reached a record of 880478 tourist overnight stays, an increase of 32 % compared to the pandemic year, with tourism focused on cycling and outdoor activities. This may have had a positive impact on economic activities related to tourism. The socio-economic growth observed, especially after 2020, may reflect the progressive implementation of the "Territorial Development Framework Agreement" (TDFA) through DGR 211/2018 and its subsequent integrations. These regional resolutions likely contributed to local revitalization through targeted investments, infrastructure, and coordinated territorial planning, as suggested by the marked index increase between 2020 and 2022.

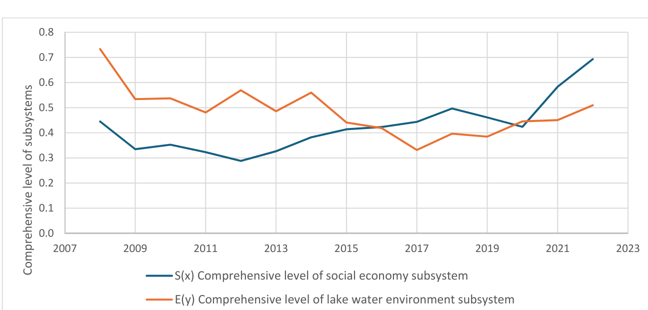

Fig. 8. Trends of socioeconomic and lake water environmental levels.

Overall, the socioeconomic index reveals four key stages: decline (2008–2012), steady recovery (2013–2017), pandemic disruption (2018–2020), and rapid rebound (2021–2022). This pattern mirrors broader regional trends and intervention policies, following the responsiveness of the socioeconomic subsystem to implemented governance measures.

In Fig. 7 we can observe also the temporal evolution of the environmental subsystem index (*Ey*) for Iseo Lake from 2008 to 2022, showing a fluctuating but overall declining pattern until 2012, followed by a sharp deterioration until 2017 and a partial recovery thereafter. This dynamic is consistent with key monitoring data and regional policy milestones.

From 2008 to 2012 the index decreased, indicating the persistence of environmental pressures across the lake catchment. According to ARPA Lombardia (2020), the water quality status of Iseo Lake in the 2009–2011 triennium was rated as "sufficient," while the chemical status remained "not good" due to elevated pollutant levels. Other studies (Legambiente, 2012) from the same period further confirmed the presence of critical bacterial contamination at several sampling points, particularly at the Oglio and Borlezza river mouths, highlighting issues with untreated or insufficiently treated discharges. These critical conditions are consistent with the downward trend of the environmental index in that period.

Between 2013 and 2018, the index declined significantly, reaching a minimum of 0.296 in 2016. Although the chemical status improved to "good" from 2012 onward, the water quality status remained stagnant at "sufficient", according to ARPA monitoring. The environmental subsystem's decline during this phase reflects weaknesses in the lake's purification and drainage infrastructure, which according to Legambiente, remained vulnerable to overflow during heavy rainfall. Historical pollution loads, industrial residues, and tourism-related stress also continued to compromise lake health.

From 2019 to 2022, a moderate rebound in environmental conditions was observed, with the index recovering from 0.292 to 0.461. This recovery phase coincides with multiple regulatory and infrastructural developments. Notably, Reg. Reg. 6/2019 introduced stricter controls on wastewater discharges and alignment with EU standards, likely supporting the improvement in environmental quality. In parallel, Lombardy Regional Regulation April 2006 (Regione Lombardia, 2006) aimed at controlling runoff and washwater, likely supported the increase in lake resilience. Additionally, monitoring by Legambiente (2020) showed that only two out of seven sampled sites exceeded legal limits for bathing waters, and in 2022, the Health Protection Agency (HPA)[3] declared the water quality of Iseo Lake as "excellent" and fully safe for recreational use. These trends confirm progress toward the objectives of the Water Safeguard Plan (WSP)[4] and the Program for the Protection and Use of Water (PPUW)[5] (Regione Lombardia, 2016a), which aim to achieve and maintain "good" ecological and chemical status in accordance with the EU Water Framework Directive.

Overall, the observed evolution of the environmental subsystem reflects the lake's complex response to historical burdens, initial infrastructural limitations, and regulatory interventions. While the recent upward trajectory suggests positive effects from governance efforts and pollution control, the values remain below early-period levels, indicating that continued restoration and adaptive management are still needed to consolidate long-term progress.

We applied the CCD model to examine the co-evolution of the socioeconomic and environmental subsystems in the Iseo Lake sub-basin and assess their level of coordinated development over time. As shown in Fig. 9, the CCD value started at 0.710 in 2008 and decreased slightly in the following years, fluctuating within a narrow range before

[3] Agenzia di Tutela della Salute (ATS)

[4] Piano di Tutela delle Acque (PTA)

[5] Programma di Tutela e Uso delle Acque (PTUA)

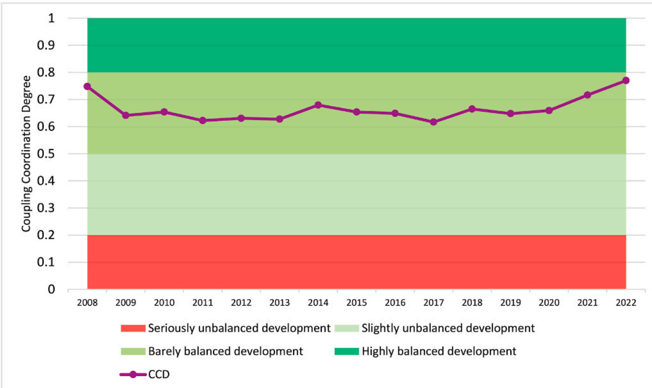

Fig. 9. Evolution trends of CCD in 2008–2022.

gradually increasing to 0.750 in 2022.

According to the classification criteria in Table 2, the system transitioned from a state of development close to being highly balanced (2008) to a long intermediate phase of barely balanced development (2009–2021), before returning to a state close to highly balanced in 2022. The high initial coordination in 2008 reflected a context in which the environmental subsystem ($Ey = 0.585$) was still relatively strong compared to the socioeconomic one ($Sx = 0.445$), suggesting underutilization of available ecological capital.

Between 2009 and 2016, the CCD remained relatively stable, fluctuating between values such as 0.59 (minimum value reached, approaching a slightly unbalanced development) and 0.70. During this period, the socioeconomic subsystem showed modest growth, while environmental conditions gradually deteriorated mainly due to declining oxygen levels and persistent nutrient loading. The lack of immediate improvements in environmental performance limited further coordination gains. The relative imbalance persisted, as the lake's environmental function continued to support socioeconomic use without being adequately protected.

A notable shift occurred after 2016. From 2016 to 2021, the CCD rose from 0.59 to 0.71. This trend coincides with the adoption of regional tools such as the PTA (2016), the acceleration of investments in infrastructure (e.g., UniAcque interventions), stricter regional regulations (Reg. 6/2019 and Reg. 9/2015), and a progressive rebound in socioeconomic indicators, including income and value of industrial output. These measures contributed to strengthening infrastructural capacity and governance frameworks. In this period, the socioeconomic subsystem advanced more rapidly (e.g., rising income and industrial productivity), while the environmental subsystem began to recover from its lowest point, reflecting the initial results of remediation efforts and policy enforcement. An exception to the overall upward trend is observed during the 2019–2020 biennium, where CCD values were comparatively lower than in adjacent years. In 2019, this drop was primarily driven by a deterioration in the environmental subsystem relative to the previous year, whereas in 2020, the decline in CCD appears to be mainly attributable to a contraction in the socioeconomic subsystem, likely linked to the impacts of the COVID-19 pandemic. Nevertheless, by 2021, both subsystems show signs of recovery, as reflected in the rebound of the CCD value.

By 2022, the CCD reached 0.75, approaching a highly balanced state. At this point, the socioeconomic subsystem had overtaken the environmental one ($Sx = 0.693$; $Ey = 0.461$), suggesting an increasing capacity of the local economy to take care of environmental issues. As an example, the implementation of integrated planning tools, such as the Framework Agreement for Territorial Development of the Sebino Area, likely contributed to this outcome by aligning economic revitalization with environmental protection strategies. The evolution of the coupling system reveals a gradual transition from initial ecological dominance to a more synergistic interplay between development and environmental governance, demonstrating the importance of sustained policy efforts and adaptive planning in peri urban lake basins.

The relationship between the socioeconomic and environmental subsystems in the Iseo Lake sub-basin reflects a dynamic broadly consistent with the Environmental Kuznets Curve (EKC) hypothesis (Dinda, 2004), as also found in the study by Xu and Chen (2023). During the phase in which the socioeconomic system was developing, the ecological subsystem exhibited a marked decline—suggesting that economic pressures initially outweighed environmental protection. However, as economic indicators improved steadily after 2015, the environmental subsystem also began to recover gradually, particularly after 2020, indicating a potential inflection point in the coordination trajectory.

4.3. Diagnosis of factors influencing the CCD in the Iseo Lake coupling system

To better understand the constraints that affect the coordinated development between the socioeconomic and environmental subsystems in the Iseo Lake sub-basin, we applied the Obstacle Diagnosis Model (ODM). This approach allowed us to quantify the degree to which specific indicator groups limit the growth of the Coupling Coordination Degree (CCD) over time, focusing both on subsystem-level (Fig. 10) and thematic-level contributions (Fig. 11).

As shown in Fig. 10 the ODM results reveal that, on average, the socioeconomic subsystem presented a greater obstacle to coordination in the first half of the study period, with obstacle values consistently exceeding 50% between 2008 and 2014 and peaking at 67% in 2009–2010. However, a progressive decline occurred thereafter, reaching a minimum of 36% in 2022.

In contrast, the environmental subsystem showed an upward trend, with its obstacle share rising from 33% in 2009 to 64% in 2022. This crossover suggests a progressive transition where the environmental conditions, particularly in the lake water state and pressure domains, became the primary limiting factor in the later years.

Among the four thematic levels examined (Fig. 11), economic development consistently showed the highest obstacle values in the early phase, peaking at 45% in 2009 and remaining the dominant barrier until 2013. This reflected the initially more limited economic performance of the basin relative to environmental goals. High obstacle values were observed in indicators such as per capita income and value of industrial output, which were around 10–11% in the early years and only began to decline after 2015, in line with gradual economic recovery and territorial development strategies. So, over time many of these indicators improved and their barrier effect declined sharply. Social development indicators maintained a moderate but steady influence throughout the study period. Key constraints included population

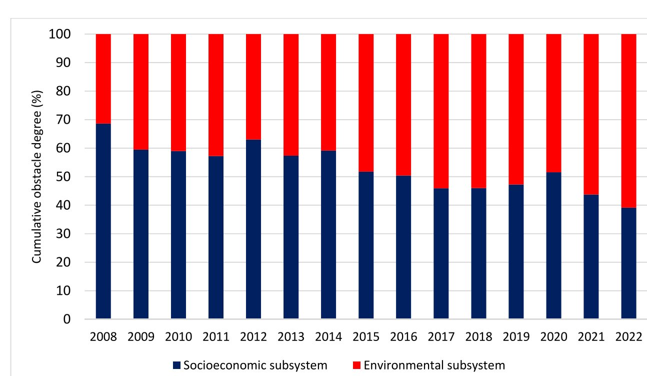

Fig. 10. Obstacle values in Iseo Lake's water environment governance for the two subsystems.

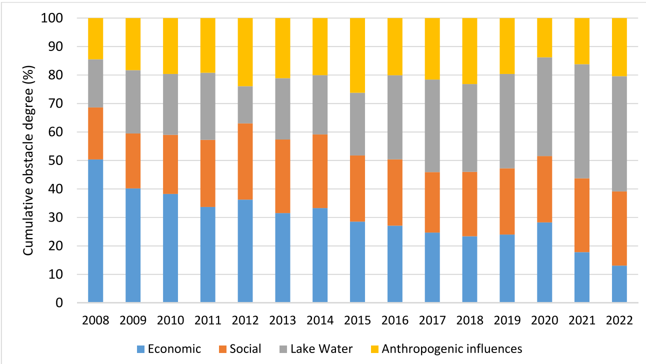

Fig. 11. Obstacle values in Iseo Lake's water environment governance at a thematic-level contributions.

density, with peak values around 11% during mid-period years. This suggests that the demographic stagnation remains a limiting factor despite broader economic progress. Meanwhile, lake water state became an increasingly significant barrier. Obstacle values rose from 14% in 2009 to 47% in 2022, indicating persistent challenges such as hypolimnetic oxygen depletion, high nutrient loads, and turbidity. The hypolimnetic dissolved oxygen indicator remained consistently high after 2012 (up to 8%), confirming critical deep-water anoxia conditions. Similarly, turbidity showed a gradual increase, reaching 14% in 2022, possibly due to episodic algal blooms and aquatic vegetation proliferation, particularly in summer months. The total phosphorus (TP) and ammonium (NH_4^+) concentrations, although fluctuating, contributed to internal nutrient loading and eutrophication.

Anthropogenic influences grew in obstacle particularly between 2010 and 2018 (peaking at 22% in 2012). Key contributing indicators included per capita water resources availability, with obstacle values between 12% and 15% during some years, especially during years of hydrological stress (e.g. 2018). Some protection-oriented indicators, such as treated wastewater volume, displayed non-negligible obstacle contributions in early years, e.g., 10% in 2008-2009, that could indicate an initial deficit in infrastructure. However, their influence diminished after major investments, reflecting system-wide improvements in treatment capacity and management efficiency. Domestic and industrial wastewater emissions had relatively low but persistent obstacle shares, and their late-period increase (up to 4%) may reflect renewed pressure under urban expansion and incomplete separation of wastewater and runoff.

Overall, the ODM results confirm a dynamic transition in limiting factors: initially, underdeveloped economic and social indicators constrained coordination; more recently, it is the environmental subsystem, particularly water quality, that slows further CCD improvement. These findings highlight the need to couple socioeconomic advancement with sustained ecological restoration and nutrient load reduction, as also highlighted in other studies (Pilotti et al., 2021), to maintain and strengthen the path toward coordinated lake basin sustainability.

5. Conclusions

This study examined the long-term interaction between socioeconomic development and lake environmental quality in the Iseo Lake sub-basin by integrating the Coupling Coordination Degree Model (CCDM) with the Obstacle Diagnosis Model (ODM). Using a time series covering the period 2008–2022, the analysis revealed a moderate but progressively improving coupling relationship, with the system evolving from a slightly balanced to a more favorably coordinated state. While early stages of coordination were mainly associated with weaker socioeconomic conditions, recent years are characterized by a shift in the dominant constraints, with environmental pressures, particularly nutrient accumulation and persistent hypolimnetic anoxia, emerging as the primary limiting factors despite improvements in income levels, infrastructure, and governance capacity. From a conceptual standpoint, this study contributes to the existing CCD literature by extending coupling coordination analysis beyond large, highly urbanized lake basins to a mid-sized, peri-urban system, characterized by strong physical constraints and long-term limnological inertia.

Overall, the observed evolution of the coupling system reflects a gradual transition from an initial phase of relative ecological predominance toward a more balanced configuration between socioeconomic development and environmental conditions. However, the persistence of deep-water degradation indicates that further improvements in coordination will require sustained attention to environmental constraints alongside continued socioeconomic advancement.

5.1. Management and governance implications

The results of this study provide relevant insights for lake basin management and territorial governance. As socioeconomic constraints have progressively weakened over time, further improvements in coupling coordination are increasingly associated with the management of environmental limitations, particularly those related to nutrient accumulation and deep-water oxygen depletion. Priority intervention areas include nutrient load containment, enhancement of wastewater treatment efficiency, and increased resilience of sewer and drainage systems, especially in view of climate-driven increases in extreme rainfall events. The findings also highlight the importance of integrating environmental objectives within existing spatial and development planning instruments. Planning tools such as the Water Safeguard Plan and the Territorial Development Framework Agreement can support a more coherent alignment between territorial development strategies and lake protection goals. In this context, nature-based and hybrid approaches, such as runoff control measures and decentralized stormwater management, represent promising options for reducing hydrological stress and improving system robustness.

More broadly, the study suggests that in deep lake basins, maintaining a balanced and low-impact development trajectory requires continuous coordination across governance levels and sectors. Even in contexts where socioeconomic indicators show sustained improvement, environmental constraints may become the dominant limiting factor for coordination, emphasizing the need for adaptive and integrated governance frameworks.

5.2. Limitations and future research

Several limitations of this study should be acknowledged, which also point to directions for future research. First, the analysis focused on the sub-basin directly draining into Lake Iseo, rather than the entire hydrographic basin. While this choice was motivated by the objective of capturing the area most directly connected to lake water quality, future studies could extend the spatial scope to the whole watershed in order to provide a more comprehensive representation of basin-wide dynamics. Second, the CCDM framework is designed to describe patterns of coordination and relative constraints, rather than to establish inferential or causal relationships between socioeconomic and environmental indicators. Future research could explore analytical approaches different from coordination-based frameworks, including econometric or system-oriented models, which may be suitable for investigating potential causal dynamics and temporal dependencies between socioeconomic development and lake environmental conditions. Third, the indicator system did not explicitly include agricultural practices as well as other possible indicators that could potentially be added to the CCD, allowing for a more nuanced characterization of coordination patterns across different socio-environmental dimensions. Finally, while the proposed framework is replicable, the transferability of the results is most direct for deep, stratified lakes with constrained mixing regimes. Applications to shallower or polymictic systems would require careful adaptation of indicators and interpretation, given the different physical and limnological conditions governing their environmental dynamics.

CRediT authorship contribution statement

Simone Manna: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Marco Bartoli:** Supervision, Funding acquisition. **Chiara Mazzocchi:** Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Raw annual socio-economic indicators used in the CCD analysis (2008–2022), prior to normalization and weighting.

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12
Year	Taxable income (€)	Taxable income growth rate (%)	Per capita income (€/ab)	Gross industrial output value (k€)	Proportion of the secondary industries in total gross production (%)	Proportion of the tertiary industries in total gross production (%)	Population size (n. of residents)	Population growth rate (%)	Density of population (persons/km^2)	Proportion of employees in the secondary industry (%)	Proportion of employees in the tertiary industry (%)	Urbanization (%)
2008	1069358240	2678	14045,000	621647,251	64,024	35,788	76138	1588	246,291	81,475	18,320	8731
2009	1050627281	−1752	13602,818	529644,529	56,871	42,891	77236	1442	249,843	71,901	27,722	8776
2010	1069511013	1797	13744,808	517015,978	57,859	41,928	77812	0,746	251,706	75,745	23,964	8821
2011	1099700824	2823	14090,780	428885,000	58,073	41,662	78044	0,298	252,457	64,746	34,646	8866
2012	1107406905	0,701	14121,126	336402,377	55,170	44,429	78422	0,484	254,196	61,479	37,693	8911
2013	1122275743	1343	14256,914	2192698,020	86,592	13,019	78718	0,377	255,156	63,170	36,094	8949
2014	1124537064	0,201	14287,637	3431188,015	84,714	15,000	78707	−0,014	255,120	72,841	26,564	8987
2015	1145872539	1897	14561,117	3489299,652	84,636	15,045	78694	−0,017	255,078	73,592	25,792	9024
2016	1165692349	1730	14862,269	3511115,374	83,669	15,974	78433	−0,332	254,232	70,340	28,937	9073
2017	1188526297	1959	15169,449	3263419,035	79,933	19,657	78350	−0,106	253,963	69,421	29,858	9121
2018	1235456285	3949	15812,019	3347847,886	79,758	19,813	78134	−0,276	253,263	69,636	29,551	9169
2019	1246009513	0,854	15990,061	2931817,562	71,321	28,044	77924	−0,269	252,582	62,142	36,201	9204
2020	1218629618	−2197	15666,640	2524428,399	68,478	30,856	77785	−0,178	252,132	60,739	37,574	9240
2021	1313927667	7820	17074,640	3593100,819	70,816	28,579	76952	−1071	249,432	60,458	37,807	9275
2022	1392414280	5,9734348	18136,062	5008613,967	74,599	24,959	76776	−0,229	247,960	61,425	37,052	9311

Table A2
Raw annual environmental indicators used in the CCD analysis (2008–2022), prior to normalization and weighting.

	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24
Year	Turbidity (FNU)	Chlorophyll *a* (μg/L)	Deep dissolved oxygen (mg/L)	Total phosphorus (μg/L)	Deep ammonia nitrogen (mg/L)	Maximum mixing depth (m)	Total water consumption (m^3)	Per-capita water resources (m^3/inhabitant)	Domestic wastewater emissions (m^3)	Industrial wastewater emissions (m^3)	Wastewater treatment facilities (n.)	Volume of treated wastewater (m^3)
2008	2424	3266	1489	56,330	0,098	50	5960082,640	278,859	7250621,740	397964,250	1	8005652,000
2009	2873	3610	1582	56,330	0,054	100	6046034,080	274,894	7355184,280	407553,750	1	8005652,000
2010	2522	2831	1621	67,407	0,049	100	6091123,360	272,859	7410036,760	414586,050	1	8998710,000
2011	2943	3836	0,515	53,484	0,050	75	6109284,320	272,048	7432130,120	424175,550	1	9197167,000
2012	1077	5416	1045	65,825	0,017	75	6966000,000	270,737	7468127,060	431207,850	1	9668394,000
2013	2510	2083	0,713	75,538	0,018	75	6014055,200	269,719	7496315,140	438559,800	1	9951220,000
2014	2041	4833	0,255	66,392	0,017	50	6013214,800	269,757	7495267,610	449747,550	1	11060309,348
2015	1583	4233	0,012	85,652	0,077	50	6394000,000	269,801	7494029,620	461894,250	1	8969798,958
2016	2906	5170	0,056	81,042	0,087	50	5992281,200	270,699	7469174,590	475319,550	1	9959298,750
2017	2720	5183	0,278	85,922	0,080	90	5985940,000	270,986	7461270,500	481712,550	1	8884571,458
2018	3040	7529	0,834	63,831	0,125	75	6492000,000	271,735	6310956,751	536154,281	1	9101244,583
2019	3251	5781	0,884	100,485	0,189	55	5970536,880	272,467	6662647,704	581809,802	1	9177255,833
2020	3335	3954	0,647	96,447	0,184	62,5	5959886,700	272,954	6657560,724	587243,852	1	10891023,684
2021	3109	5642	0,692	92,408	0,137	70	5896062,240	275,909	11127809,839	834395,241	1	10815086,875
2022	2954	4827	0,601	56,234	0,260	65	5882577,120	276,541	9467862,554	690164,411	1	9454488,542

Table A3
Data source for each indicator.

Indicator Code	Indicator	Primary Data Source
x1	Taxable income (€)	MEF (Dipartimento delle Finanze)
x2	Taxable income growth rate (%)	Based on calculations; MEF (Dipartimento delle Finanze)
x3	Per capita income (€/ab)	MEF; ISTAT; ASC (Atlante Statistico dei Comuni)
x4	Gross industrial output value (k€)	Bureau van Dijk (ORBIS)
x5	Proportion of secondary industries (%)	Bureau van Dijk (ORBIS)
x6	Proportion of tertiary industries (%)	Bureau van Dijk (ORBIS)
x7	Population size (residents)	ISTAT; ASC
x8	Population growth rate (%)	Based on calculations; ISTAT; ASC
x9	Population density (persons/km^2)	ISTAT; ASC; SITUAS (ISTAT)
x10	Proportion of employees in secondary industry (%)	Bureau van Dijk (ORBIS)
x11	Proportion of employees in tertiary industry (%)	Bureau van Dijk (ORBIS)
x12	Urbanization (%)	DUSAF (2007, 2012, 2015, 2018, 2021)
x13	Turbidity (FNU)	Lakes CCI project; Cariplo project; ENVISAT/MERIS; Sentinel-3/OLCI
x14	Chlorophyll-a (mg/L)	Lakes CCI project; Cariplo project; ENVISAT/MERIS; Sentinel-3/OLCI
x15	Deep dissolved oxygen (mg/L)	ARPA Lombardia
x16	Total phosphorus (mg/L)	ARPA Lombardia
x17	Deep ammonia nitrogen (mg/L)	ARPA Lombardia
x18	Maximum mixing depth (m)	ARPA Lombardia; Lau et al. (2020)
x19	Total water consumption (m^3)	Acque Bresciane S.r.l.; ISTAT
x20	Per-capita water resources (m^3/person)	Acque Bresciane S.r.l.; ISTAT; ASC
x21	Domestic wastewater emissions (m^3)	Acque Bresciane S.r.l.
x22	Industrial wastewater emissions (m^3)	Acque Bresciane S.r.l.
x23	Wastewater treatment facilities (n.)	SIRE – Sistema Informativo Regionale Acque; ARPA Lombardia
x24	Volume of treated wastewater (m^3)	UniAcque S.p.A.; SIRE; ARPA Lombardia

Data availability

Data will be made available on request.

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