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IMPLEMENTATION AND EVALUATION OF A TIME-LAPSE CAMERA MONITORING SYSTEM FOR ICE COVER DYNAMICS IN SMALL HIGH MOUNTAIN LAKES OF THE PYRENEES (2021–2024)

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ABSTRACT. Lake ice phenology in small high mountain lakes is a sensitive indicator of climate change, yet its monitoring remains limited due to winter inaccessibility and the spatial and temporal constraints of satellite remote sensing. This study presents the implementation and evaluation of LIMS-TL (*Lake Ice Monitoring System – Time-Lapse*), an automated image acquisition system based on programmed cameras to monitor ice cover in seven natural lakes (6.5–24.5 ha) within the Aigüestortes i Estany de Sant Maurici National Park (Pyrenees), over three winter seasons (2021–2024). LIMS-TL was designed to operate under extreme conditions and was assessed in terms of reliability, energy autonomy, and its ability to capture key freeze-up and break-up events. Through expert visual inspection of over 17,500 images, 90% of key phenological dates (Freeze-Up Start, Freeze-Up End, Break-Up Start, Break-Up End) were identified, and dynamic processes were documented with high temporal resolution. A visual classification method was also developed to assess image quality, applying three categories based on their usefulness for analysis. On average, 80.7% of days yielded at least one valid image per lake during the 2021–2022 season. This work represents the first systematic high-resolution documentation of lake ice phenology in the Pyrenees, successfully identifying the four key dates of the seasonal cycle. The resulting image archive provides valuable visual data for detailed analysis of surface dynamics and associated hydrological processes. Despite some limitations, such as occasional technical failures or snow accumulation on the lens, LIMS-TL proved to be an effective, replicable, and low-cost tool, suitable for standalone deployment or in combination with other observation methods. This methodology offers a solid foundation for expanding the monitoring of lake ice dynamics in mountain regions and enhancing our understanding of its evolution under climate change.

Implementación y evaluación de un sistema de cámaras time-lapse para el seguimiento de la dinámica de la cubierta de hielo en pequeños lagos de alta montaña en los Pirineos (2021–2024)

RESUMEN. La fenología del hielo en lagos pequeños de alta montaña es un indicador sensible del cambio climático, pero su monitoreo sigue siendo limitado debido a la inaccesibilidad invernal y a las restricciones de resolución espacial y temporal de la teledetección satelital. Este estudio presenta la implementación y evaluación de LIMS-TL (*Lake Ice Monitoring System – Time-Lapse*), un sistema de adquisición automatizada de imágenes basado en cámaras programadas para el seguimiento de la cubierta de hielo en siete lagos naturales (6,5–24,5 ha) del Parque Nacional de Aigüestortes i Estany de Sant Maurici (Pirineos), durante tres temporadas invernales (2021–2024). LIMS-TL fue diseñado para operar en condiciones extremas y evaluado en términos de fiabilidad, autonomía energética y capacidad para registrar eventos clave de congelación y deshielo. Mediante la inspección visual experta de más de 17.500 imágenes, se identificó el 90 % de las fechas fenológicas clave (Inicio de la Congelación, Final de la Congelación, Inicio del Deshielo, Final del Deshielo) y se documentaron procesos dinámicos con alta resolución temporal. Además, se desarrolló una metodología de clasificación visual para evaluar la calidad de las imágenes, aplicando tres categorías según su utilidad para el análisis. En promedio, el 80,7 % de los días presentó al menos una imagen válida por lago durante la temporada 2021–2022. Este trabajo constituye la primera documentación sistemática de alta resolución temporal de la fenología del hielo en lagos pirenaicos, al lograr identificar las cuatro fechas clave del ciclo estacional. Las imágenes obtenidas representan un archivo visual valioso para el estudio detallado de la dinámica superficial y de los procesos hidrológicos asociados.

A pesar de algunas limitaciones, como fallos técnicos puntuales o la acumulación de nieve en el objetivo, LIMS-TL demostró ser una herramienta eficaz, replicable y de bajo coste, aplicable tanto de forma autónoma como en combinación con otros métodos de observación. Esta metodología constituye una base sólida para ampliar el monitoreo de la dinámica del hielo lacustre en regiones de montaña y mejorar la comprensión de su evolución en un contexto de cambio climático.

Keywords: lake ice, time-lapse photography, climate change, mountain lakes, Pyrenees.

Palabras clave: hielo lacustre, fotografía time-lapse, cambio climático, lagos de montaña, Pirineos.

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1. Introduction

Lake ice is an excellent indicator of climate change (Magnuson *et al.*, 2000). Both the extent and the thickness of lake ice cover are considered Essential Climate Variables by the World Meteorological Organization (GCOS, 2016, 2022). Under global warming, many lakes exhibit later freeze-up dates and earlier break-up dates, thereby shortening the duration of seasonal ice cover (Benson *et al.*, 2012). These changes in lake ice phenology directly affect hydrological regimes by altering lake evaporation, water levels, heat budgets of the water column, and mixing and stratification regimes, which in turn generate profound ecological impacts on aquatic habitats, primary productivity, and species composition (Prowse and Brown, 2010; Prowse *et al.*, 2011). However, many lake regions lack long-term time series that consistently document ice phenology, limiting our understanding of interactions between lake ice and climate (Zhang and Pavelsky, 2019) and, consequently, broader environmental and ecological interactions.

Lake ice phenology refers specifically to the study of the seasonal processes of freeze-up and break-up, including key milestones such as the start and end of ice formation, as well as the start and end of ice decay (Yang *et al.*, 2019; Zhang *et al.*, 2021). Continuous monitoring of each event enables the assessment of climate variability and its effects on aquatic ecosystems. Nevertheless, obtaining phenological data with high temporal resolution remains challenging in high mountain regions, where extreme conditions and inaccessibility constrain the continuity and accuracy of visual observations.

In the Pyrenees, time series on lake ice phenology are scarce. This is partly because many of the lakes that freeze are located in high mountain areas requiring long approaches on foot or technical ascents to access, which in winter also entails exposure to the hazards inherent to high-mountain environments. This situation has historically limited the systematic collection of in situ data through visual inspection of the state of the ice cover. Despite these constraints, there are some relevant studies which—although not primarily aimed at generating complete phenological series—have provided valuable information on ice dynamics. Notable among these are the works conducted at Lac Redon (Catalan, 1989; Catalan *et al.*, 1992; Ventura *et al.*, 2000), as well as more recent investigations at the mountain-range scale (Jungkeit-Milla *et al.*, 2024; Sabás *et al.*, 2021, 2024).

The formation and disappearance of lake ice are governed by mass and/or energy exchanges among water in liquid and solid states and the atmosphere, which in turn are influenced by climatic factors and lake-specific factors. Among the climatic drivers, air temperature, topography-modulated solar radiation, precipitation, and wind speed are particularly important (O'Reilly *et al.*, 2015; Tom *et al.*, 2022; Zhang *et al.*, 2021). Lake-specific factors include morphometry (depth, surface area, and volume), location (altitude, latitude, and longitude), mineralization, and turbidity (O'Reilly *et al.*, 2015; Schmid *et al.*, 2014; Tom *et al.*, 2022; Zhang *et al.*, 2021). In general, lake-specific factors correlate strongly with freeze-up dates, whereas climatic factors exert a stronger influence on break-up patterns (Zhang *et al.*, 2021).

Currently, ice monitoring relies on direct and indirect methods. Among the direct methods, in situ visual observation (Magnuson *et al.*, 2000), time-lapse photography using automated cameras (Ariano and Brown, 2019; Higgins *et al.*, 2021; Kirchner *et al.*, 2024), and webcam video imagery (Tom *et al.*, 2020; Xiao *et al.*, 2018) stand out. There are also underwater devices that detect the presence of ice without visual interpretation, such as subsurface light sensors—whose signal drops sharply once the surface freezes (Smits *et al.*, 2021)—or near-surface thermistors that, when embedded in ice, record subzero temperatures (Bogdanov *et al.*, 2023). Although these approaches enable precise detection, their application is generally limited to local scales.

Indirect methods are based on remote sensing or on inference from in situ environmental data that require processing, calibration, or validation. These include operational optical sensors (MODIS: 250–1,000 m, 1–2 days; VIIRS: 375–750 m, 1–2 days; Landsat-8/9 OLI: 15 m and 30 m, 16 days [≈8 days combined]; Sentinel-2 MSI: 10–20–60 m, ~5 days) and synthetic aperture radar (SAR) (Sentinel-1: ~10 m, ~6 days, all-weather/day-night), which can capture ice phenology over large spatial extents (Sharma *et al.*, 2020). However, limited temporal resolution (e.g., 16 days; or ~5 days constrained by cloud cover) and the spatial resolution of moderate-resolution products restrict their application to small lakes, although data-fusion strategies across multiple datasets can estimate phenology for lakes as small as 13 ha (Zhang and Pavelsky, 2019).

Another effective strategy is the use of thermistor chains to measure water temperature at different depths, with more accurate ice identification when the upper thermistor is placed closer to the surface (Pierson *et al.*, 2011). Similarly, tracking dissolved oxygen concentration in combination with lake water temperature can be used to infer the presence of ice (Zdorovennova *et al.*, 2021). Furthermore, although freezing depends on multiple factors, in some lakes the timing of freeze-up and break-up can be estimated using empirical models based on freezing and thawing degree-day accumulation derived from air temperature data (Thompson *et al.*, 2005).

Nonetheless, many of the aforementioned methods face limitations when applied to small lakes and/or high mountain environments. Difficult access, the spatial and temporal resolution of satellite imagery, cloud cover, topographic shadows, high instrumentation costs, or the need for frequent maintenance constrain their applicability. In this context, programmed trail cameras operating in time-lapse mode emerge as a promising and effective option for the visual monitoring of surface ice dynamics in small high-mountain lakes. Their use has begun to expand in recent studies, although systematic applications are still scarce.

This study describes and evaluates the design, implementation, and utility of LIMS-TL (Lake Ice Monitoring System – Time-Lapse), a visual monitoring system based on automated cameras, developed to record the surface dynamics of lake ice in seven lakes within the Aigüestortes i Estany de Sant Maurici National Park (Pyrenees) between 2021 and 2024. We detail the technical, operational, and analytical aspects of the workflow, from device installation to image processing and the identification of key freeze-up and break-up events. While a full phenological analysis and an interpretation of the factors controlling the formation, maintenance, and disappearance of ice lie beyond the scope of this article, we include representative examples that illustrate the informational potential of the method. The primary objective is to demonstrate the technical and operational feasibility of this methodology as a robust, replicable, and low-cost tool for lake ice monitoring, thereby contributing to the development of sustainable observation strategies for the study of the cryosphere in high-mountain lacustrine systems.

2. Materials and methods

2.1. Study area and lake selection

The Aigüestortes i Estany de Sant Maurici National Park, located in the central-eastern sector of the Pyrenees, constitutes one of the most representative high-mountain lake districts in southern Europe (Fig. 1). Its landscape is characterized by steep alpine relief and a remarkable density of glacial lakes. Across the Pyrenees, 1,035 lakes larger than 0.5 ha have been identified (Del Castillo Jurado, 2003), including both natural lakes and reservoirs (typically pre-existing lakes enlarged by dams), of which 198 are located within the National Park, representing 19% of the total for the mountain range.

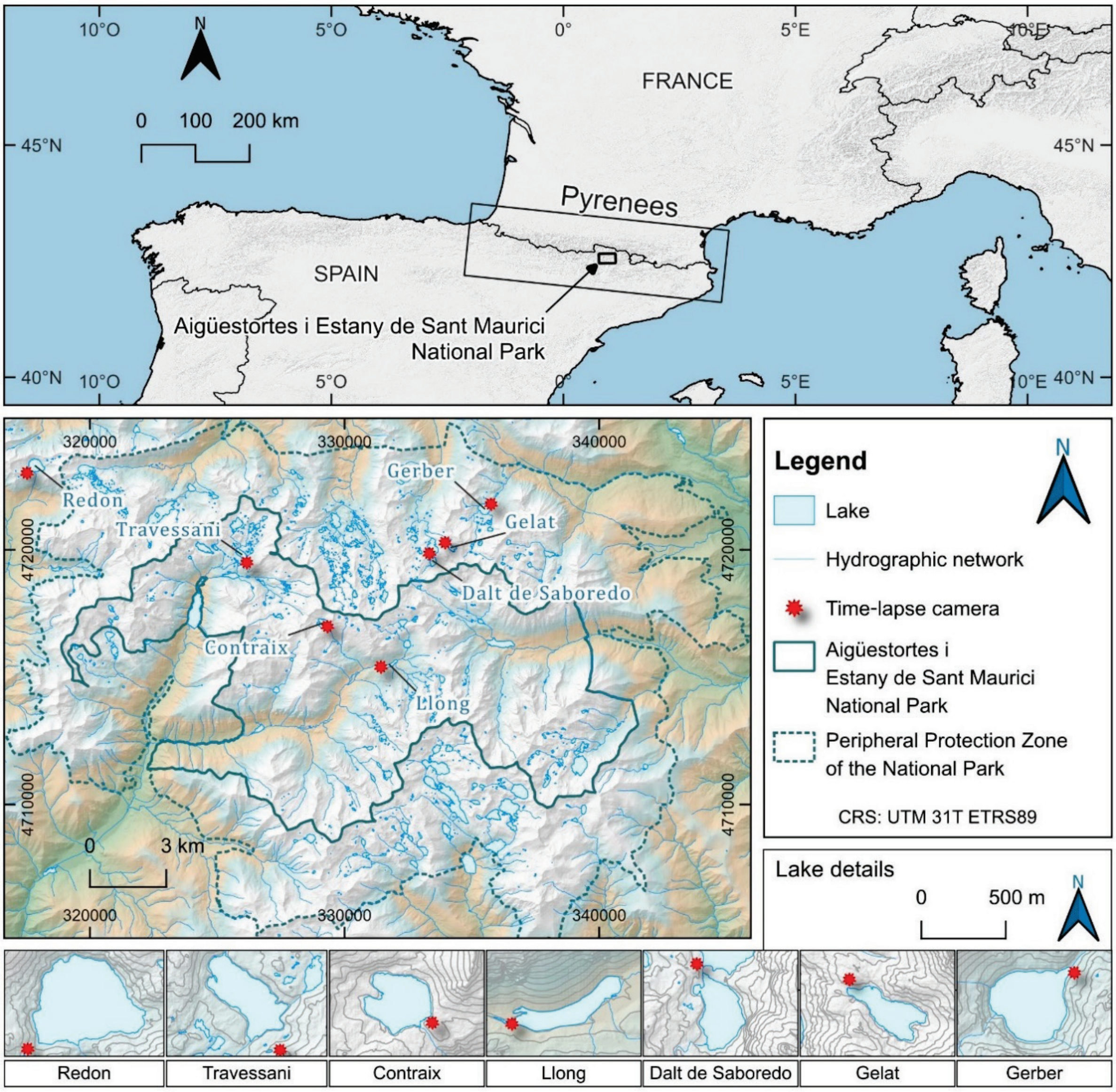

Figure 1. Location. Upper panel: General location of the Aigüestortes i Estany de Sant Maurici National Park. Middle panel: Study area. Lower panel: Lakes equipped with cameras.

This high concentration of lakes results from the action of Pleistocene glaciers on a predominantly granitic and relatively impermeable substrate, combined with a cold and humid mountain climate (Rodríguez-Fernández, 2010). The Pyrenean climate regime is shaped by several geographic gradients: an altitudinal gradient, with summits exceeding 3,000 m a.s.l. (Cuadrat et al., 2024; Delmas *et al.*, 2022); a longitudinal gradient (west-east) reflecting the transition between Atlantic, Continental, and Mediterranean influences (Amblar-Francés *et al.*, 2020; Cuadrat *et al.*, 2024); and a latitudinal gradient (north-south), particularly relevant in the central Pyrenees, where the northern slope exhibits predominantly Atlantic conditions while the southern slope shows a Mediterranean character (Batalla *et al.*, 2018; Cuadrat *et al*., 2024). As a result, snow accumulation differs markedly across the region: the northern slope can reach annual totals of up to 500 cm of snow, roughly double that of the southern slope (Bonsoms *et al.*, 2024, 2025).

For this study, seven natural lakes were selected to represent a broad range of environmental, morphometric, and operational conditions. Lake surface areas range from 6.5 to 24.5 ha, and elevations from 1,999 to 2,570 m, encompassing different orientations, shapes, depths, and microclimates. This diversity responds to the need to capture the widest possible variability in ice formation and decay processes, as well as to ensure the technical feasibility of time-lapse camera monitoring.

Lake selection was based on the 1:5,000 topographic map produced by the Institut Cartogràfic i Geològic de Catalunya (ICGC) (2021) and on a review of specialized literature, following six main criteria:

- *Natural hydrological regime*: lakes affected by hydroelectric infrastructure were excluded, as artificial flow regulation can significantly modify freeze-up and break-up dynamics and is one of the few anthropogenic drivers influencing these processes (Sharma *et al.*, 2020).
- *Altitudinal gradient*: lakes were selected across different elevation ranges to represent the influence of altitude on freeze-up and break-up dynamics, one of the most influential factors in the duration of seasonal ice cover.
- *Topoclimatic representativeness*: lakes were included to reflect the influence of local topography, particularly regarding insolation, wind exposure, and topographic shading.
- Morphometric diversity: heterogeneity in lake shape, surface area, depth, and exposure to wind and solar radiation was prioritized, as these factors strongly influence ice formation and persistence.
- *Feasibility of camera-based observation*: lakes with dendritic morphologies or highly complex shorelines were excluded, as they hinder complete visual coverage from a single fixed viewpoint. Lakes with more compact shapes (circular, subcircular, or subrectangular) (Del Castillo Jurado, 2003) were prioritized, allowing most of the lake surface to be captured with a single camera and thereby optimizing the quality and usefulness of the resulting imagery.
- Minimum surface area (>5 ha): a lower size threshold was set to ensure the feasibility of complementary satellite remote-sensing analyses, whose spatial resolution limits their applicability in very small lakes. Although no explicit upper limit was defined, it was effectively constrained by the hydrological regime criterion, as the largest lakes in the region (>24.5 ha) correspond to artificial reservoirs.

It is noteworthy that only 51% of lakes within the park larger than 5 ha maintain an unaltered hydrological regime (26 lakes), a proportion that decreases to 9.8% among those exceeding 10 ha. This highlights the representativeness of the selected lakes within the regional context. Lac Redon, with 24.5 ha, establishes the upper boundary of the sample as the largest natural lake in the study area. Although it lies just outside the administrative limits of the park, it is managed by the same institution and was included due to its scientific relevance and long-term observational records, which enrich the analysis.

The seven lakes included in the study form a diverse and representative ensemble within the study area (Table 1), commonly referred to as *estanys*, *estanhs*, or *lacs*, depending on the local Catalan or Occitan linguistic influence on toponyms (Alemán-Milán, 2022).

Table 1. Morphometric and location data for the lakes in the study area.

Lake / ***Lat. N, Long. E***	**Elevation (m a.s.l.)**	**Surface area (ha)**	**Max depth (m)***	**Type**	**Basin orientation**	**Morphology***
Lac Redon ***42.640483, 0.778338***	2,235	24.5	73	Cirque	South	Circular
Estany de Gerber ***42.629375, 0.993825***	2,164	15.3	64	Cirque	Northeast	Circular
Estany de Travessani ***42.611138, 0.878078***	2,245	11.3	32	Cirque	Southwest	Subcircular
Estany de Contraix ***42.587531, 0.917561***	2,570	9.9	60	Cirque	Southeast	Subcircular
Estany de Dalt de Saboredo ***42.610515, 0.969681***	2,340	8.1	24	Cirque	Northwest	Subcircular
Estany Llong ***42.573456, 0.950145***	1,999	7.3	12	Valley	West	Subrectangular
Estany Gelat ***42.615386, 0.97833***	2,490	6.5	32	Cirque	North	Subrectangular

**Data from Del Castillo Jurado (2003)*

2.2. Design and implementation of the LIMS-TL monitoring system

The LIMS-TL system was conceived as an automated image acquisition platform designed to operate unattended under the extreme winter conditions typical of high-mountain environments and was tested over three seasons. During autumn 2021, seven cameras (Suntekcam HC-806A trail cameras) were installed at the seven selected lakes, with the objective of documenting the evolution of ice cover from November through June (Fig. 2). In 2023, the camera at Lac Redon was replaced with a Coolife PH700A trail camera, which offers a wider field of view (90°), thereby improving visual coverage of the lake. After one trial winter, in autumn 2024, a progressive replacement of the remaining cameras with this second model was initiated.

Both models were selected for their robustness, low cost, energy efficiency, and ease of programming in time-lapse mode. Although more specialized devices for environmental monitoring exist, general-purpose trail cameras were chosen due to their availability, versatility, and solid field performance, without compromising data quality. These cameras are rated to operate down to -20 °C, are rain-resistant, and are powered by eight AA alkaline batteries. Images—36 or 28 megapixels depending on the model—are stored on SD or microSD cards.

Prior to installation, candidate sites were evaluated according to three main criteria: distance to the lake, stability of the mounting substrate, and quality of visibility. Locations near the lake were prioritized—close enough to enable observation of the ice cover even under adverse weather conditions, yet without excessively compromising the overall field of view. Bedrock outcrops and large erratic blocks were considered the most appropriate supports due to their stability, low visual impact, and landscape integration. An exception was Estany Llong, where a tree was used as the anchoring point. Following preliminary tests, masts and metal structures were ruled out owing to their greater visual impact, installation complexity, and limited harmony with the surroundings. All cameras were installed more than 1.6 m above ground level to prevent burial by snow, except one at Estany Llong (1.35 m).

To ensure adequate visual coverage, a viewshed analysis was performed using a 2 × 2 m resolution digital terrain model from the ICGC. From each proposed location—and assuming an observation height of 1.6 m—the visible lake surface area was computed. Based on these data, the maximum potential visual coverage was estimated, and only sites with visibility greater than 70% were accepted (Fig. 3).

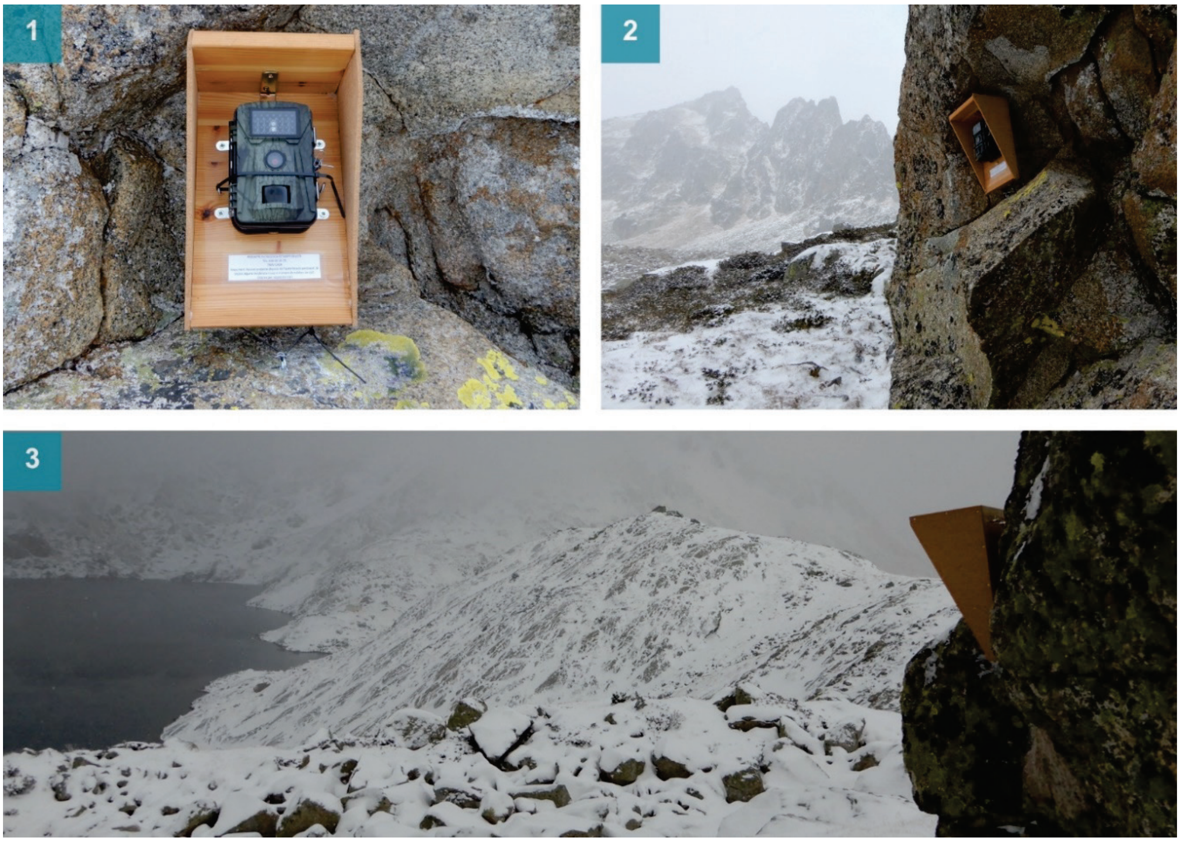

Figure 2. Views of the time-lapse cameras installed for lake-ice monitoring. (1) Detail of the camera and its protective shelter at Estany Travessani, (2) general view of the camera site at Estany Travessani, and (3) general view of the camera site at Lac Redon.

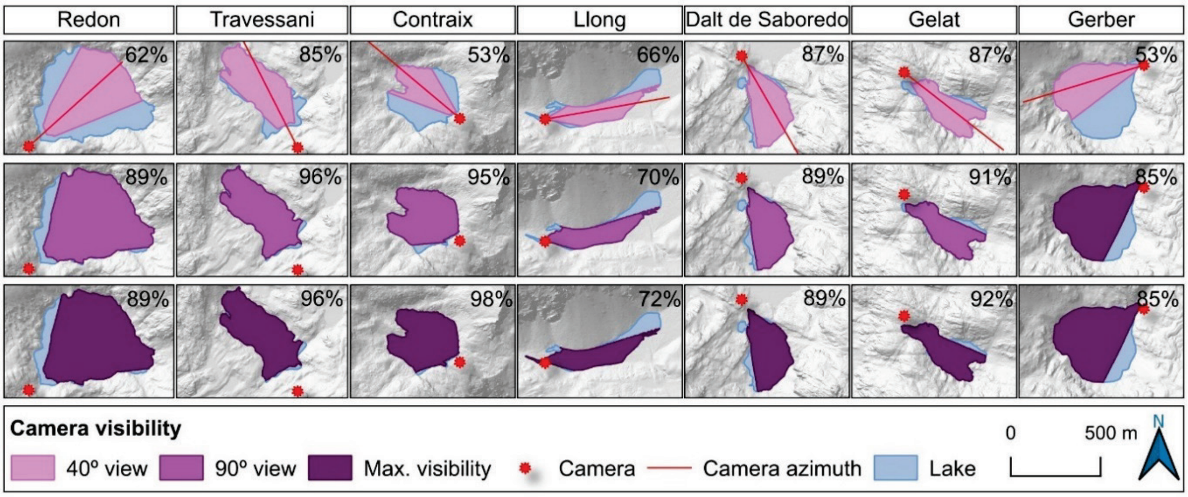

Figure 3. Viewshed analysis from the camera installation points. Comparison of the visible lake surface under three scenarios: (i) 40° field of view corresponding to the HC-806A model, (ii) 90° field of view corresponding to the PH700A model, and (iii) theoretical maximum visibility from the installation point.

Subsequently, given the HC-806A camera's field of view (40°), the fraction of the lake surface captured in the images was determined, yielding coverage between 53% and 87% (Fig. 3). Although these values were initially deemed acceptable, from the third observation season onwards the field of view was expanded to support a broader range of scientific applications and more robust results. Accordingly, the system began transitioning to cameras with a 90° field of view (PH700A), enabling wider coverage (between 70% and 96%) without appreciable image distortion. This improvement also facilitated precise framing during installation.

For protection and mounting, small wooden shelters were designed to shield the cameras from snowfall and prevent internal condensation. In addition, wherever possible, sites without direct solar exposure were chosen to avoid image overexposure and to extend equipment lifespan.

The cameras were configured to capture one image every three hours between 08:00 and 18:00 (UTC+1), producing four images per day. This cadence increases the likelihood of obtaining usable images on days with variable weather conditions (e.g., fog, snowfall, or low light), while preserving the system's energy autonomy.

Fieldwork consisted of installing the cameras at the beginning of each season and removing them at the end of the observation period. Winter maintenance visits were conducted to retrieve images, replace batteries, and clear accumulated snow. During the first season, three inspections per camera were performed; from the second year onward—after confirming that battery performance was maintained for at least six months—the schedule was reduced to a single planned visit per season. To facilitate replicability, Table 2 summarizes the technical criteria for the system's design and implementation together with their rationale.

Table 2. Technical criteria and key aspects of the system design and implementation.

Technical criterion	Recommended configuration	Operational justification
Robustness and autonomy	Cold-resistant, low-power time-lapse cameras capable of operating for long periods without intervention.	Ensure continuity of winter records and minimize failures.
Physical protection	Open, ventilated wooden shelters with an overhanging top.	Prevent snow accumulation and condensation.
Strategic placement	Stable, low-impact mounts (rock or tree), installed >1.6 m above ground and oriented to avoid direct solar radiation.	Reduce risk of obstruction, glare, and exposure.
Optimal visual coverage	Placement that captures the maximum possible lake surface without losing detail.	Balance observable extent with precision in ice detection.
Capture frequency	One image every 2-3 hours during daylight (approx. 08:00-18:00).	Compromise between temporal resolution, energy savings, and data volume.
Minimal maintenance	Limited field visits, adjusted to battery autonomy and winter accessibility.	Reduce logistical load while maintaining system operability.

2.3. Interpretation of time-lapse images for lake-ice phenology characterization

A total of 17,530 photographs were obtained, with resolutions of 8,000 × 4,500 pixels (HC-806A model) and 7,168 × 4,032 pixels (PH700A model), corresponding to the monitoring of the seven lakes over three winter seasons: 2021–2022, 2022–2023, and 2023–2024. The data volume generated across the three seasons exceeded 118 GB.

Image analysis was carried out through visual inspection with the objective of identifying the key dates describing lake-ice phenology. These dates are: Freeze-Up Start (FUS), Freeze-Up End (FUE), Break-Up Start (BUS), and Break-Up End (BUE), following definitions widely used in optical remote sensing (Yang *et al.*, 2019; Zhang and Pavelsky, 2019) and adapted here for terrestrial visual analysis. Owing to the high temporal resolution of the record, FUS was defined as the first day on which ice was observed on the lake surface. BUE was considered as the first day on which the lake appeared completely free of ice. For FUE and BUS, a 10% tolerance threshold was applied. FUE was defined as the first day on which approximately at least 90% of the lake surface was ice-covered. BUS was defined as the first day on which that coverage fell below the same threshold. This methodological decision was based on the observation of occasional retreats after reaching 100% coverage, which in some cases rapidly refroze or remained unchanged for several days. In addition, in the areas farthest from the camera's field of view it was not always possible to determine with certainty whether they were fully frozen. For these reasons, a more conservative threshold was adopted to ensure a more reliable interpretation of the images (Fig. 4 and Table 3).

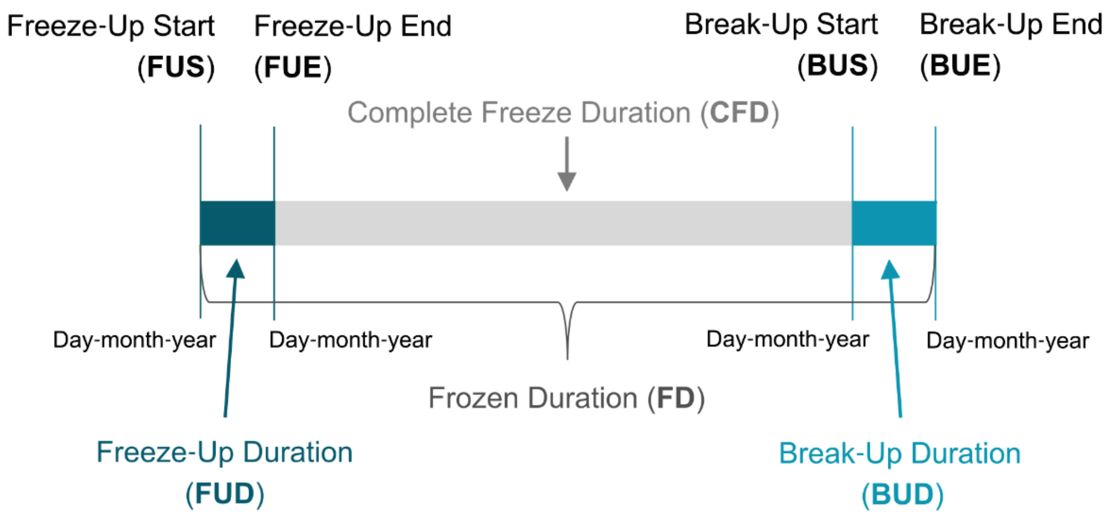

Figure 4. Schematic model of lake-ice phenology in an idealized lake. The timeline shows the key dates (FUS, FUE, BUS and BUE) and the derived temporal metrics (FUD, CFD, BUD and FD) describing the processes of ice formation, maintenance and decay. Source: Author's own work based on Yang et al. *(2019).*

Table 3. Definitions of phenological events and temporal metrics used to characterize lake-ice phenology.

Lake-ice phenology	Abbreviation	Definition
Freeze-Up Start	FUS	First day on which ice is observed on the lake surface.
Freeze-Up End	FUE	First day on which approximately ≈ 90% of the lake surface is ice-covered.
Break-Up Start	BUS	First day on which ice cover drops below ≈ 90%, initiating a sustained reduction.
Break-Up End	BUE	First day on which the lake appears completely ice-free from the start of the day.
Freeze-Up Duration	FUD	Interval between FUS and FUE.
Complete Freeze Duration	CFD	Interval between FUE and BUS.
Break-Up Duration	BUD	Interval between BUS and BUE.
Frozen Duration	FD	Interval between FUS and BUE.

Complete freeze was considered achieved when the frozen surface area of the lake was ≈ 90–100%, visually estimated from representative time-lapse photographs. During the first season, a superimposed grid template was used as a reference; in subsequent seasons, given the sub-maximum threshold (≈ 90%) and the observer's familiarity with lake winter dynamics, the template was no longer necessary. This approach aligns with long-term lake-ice phenology series based on in situ visual observation (Sharma *et al.*, 2022) and with recent applications of direct visual analysis using time-lapse imagery (Kirchner *et al.*, 2024).

From the key dates, four temporal metrics were calculated: the Freeze-Up Duration (FUD), defined as the difference between FUE and FUS; the Complete Freeze Duration (CFD), the interval between FUE and BUS; the Break-Up Duration (BUD), between BUS and BUE; and the Frozen Duration (FD), calculated as the difference between BUE and FUS (Table 3).

Images were classified manually, season by season, without applying any preprocessing or automation. Each image was reviewed individually by a single analyst, following a criterion analogous to that used in daily in situ observations, but with the ability to move backward or forward through the sequence to select the frame that best represented each phenological milestone.

After completing the three seasons, the entire analysis was repeated to assess interpretation consistency. No discrepancies were detected for FUS or BUE. However, differences were observed for FUE and BUS, despite being interpreted by the same observer. In the case of FUE, discrepancies arose from the difficulty of visually assessing complete coverage from a terrestrial perspective, particularly in areas distant from the camera's field of view. For this reason, adopting a ≈ 90% threshold was considered more reliable, as it was more consistently identifiable in the images. In the case of BUS, differences were related to the level of visual detail provided by the images, which allowed the detection of surface-melt signatures or textural changes in the ice that did not necessarily imply a reduction in extent. Ultimately, the adopted criterion was the moment when a clear and sustained reduction of the frozen surface below ≈ 90% was observed, discarding ambiguous or transient signals, or those related to surface melt that did not correspond to actual changes in ice extent.

2.4. Classification and quality assessment of time-lapse images

A basic, manual image quality assessment (IQA) methodology was developed to classify the time-lapse photographs obtained during lake-ice monitoring. This approach draws inspiration from principles widely used in visual image assessment, such as those proposed by Wang *et al.* (2004), and pursues a dual objective: (i) evaluating the usefulness of the implemented observation system and (ii) laying the groundwork for the future development of an automated quality-filtering procedure, given the need to advance toward more objective and reproducible methodologies, particularly in scientific contexts where visual quality influences the interpretation of environmental processes (Chandler, 2013).

The primary purpose is to determine the suitability of each image for extracting relevant information on lake-ice surface dynamics, distinguishing between those that allow detailed analysis of the lake surface and those that only permit partial identification of ice or water—either due to limitations in visible extent or an inability to discern fine-scale features, even when the entire lake surface is visible. To this end, three main quality categories were established: valid, partially valid, and invalid, applied individually to each image captured by the seven cameras during the ice-covered period in each lake corresponding to the 2021–2022 season.

In total, 5,192 photographs were subjected to manual visual inspection by a single analyst, without applying any preprocessing or automated procedures. Classification was based on the ability to discern details of the lake surface, considering various conditions that may affect visual quality:

- *Valid image*: A photograph was classified as valid when it enabled clear and complete observation of all visible lake details and its surface. This implies the absence of significant obstructions or distortions caused by factors such as fog, snow accumulated on the camera lens, overexposure due to direct or reflected solar radiation on snow, or underexposure due to low illumination. The presence of topographic shadows was classified as valid provided that the darkening or contrast relative to illuminated areas was not critical for discerning surface details.

Valid images were considered suitable for detailed analysis of ice dynamics, including the identification of ice types, cracks, openings, and similar features.

- *Partially valid image*: A photograph was classified as partially valid when it allowed identification of the presence of ice or water in the lake, but only in a limited manner—either due to partial visibility of the lake surface or due to insufficient definition to conduct detailed analysis of its characteristics. This limitation was attributed to factors such as fog covering only part of the lake, suboptimal lighting conditions that hindered the distinction of fine-scale features, or any other type of obstruction or reflection which, while not preventing general detection of ice or water, compromised full and precise visibility of the lake surface, including shoreline delineation. Despite these restrictions, these images were considered useful for extracting basic information on lake-ice phenology.
- *Invalid image*: A photograph was classified as invalid when no useful information could be extracted regarding lake-ice dynamics. This included cases of complete obscuration of the lake, such as very dense fog covering the entire surface or snow accumulation fully blocking the camera lens.

Once each image was assigned a quality category, the proportion of each category was determined for each lake, as well as the proportion of days represented by the highest-quality image available each day. In addition, with the objective of evaluating the effectiveness of the monitoring system, temporal patterns in image quality were identified to propose improvements in system design and operation, based on capture frequency and the daily time range.

It is important to note that, in this study, quality classification was applied exclusively to images corresponding to the previously identified ice-covered period. This ensured that the focus remained on detecting ice rather than water, and avoided imposing an arbitrary temporal window, as no common time range existed among all cameras that encompassed the longest ice season. However, in future implementations with automated systems, it may be more efficient to apply the quality filter as a preliminary step to phenological analysis, allowing only images containing useful information to be processed.

2.5. System monitoring and performance evaluation

LIMS-TL was evaluated over three winter seasons to assess its performance under real high-mountain conditions. Three main aspects were examined: system reliability, detection of phenological events, and overall usefulness for lake-ice monitoring.

For each camera and season, the total number of operational days was recorded, as well as the days corresponding to the ice-covered period. Technical issues detected during field visits were also documented, including device failures, memory-card errors, snow accumulation, or problems with the mounting system. Energy autonomy was evaluated as the number of consecutive operating days without battery replacement. This information enabled adjustment of maintenance-visit frequency and confirmed that the system could operate for several months without intervention. Structural robustness was assessed qualitatively by noting whether any unit required repositioning, repair, or replacement.

In addition, the images obtained were examined to verify whether they allowed clear identification of the start and end dates of freeze-up and break-up. This verification was carried out through direct visual inspection of the photographic sequences, without applying automated procedures. Although the detailed analysis of image quality is presented in a separate subsection, the focus here was on determining whether the available material was sufficient to interpret ice dynamics in each lake and season.

This evaluation made it possible to identify both the strengths of LIMS-TL and its main limitations. Based on these observations, progressive improvements were introduced in the system's design and configuration to optimize its performance in subsequent field campaigns.

3. Results

3.1. Operational performance of the time-lapse cameras

Across the three monitoring seasons, the time-lapse cameras operated correctly at four of the seven lakes, capturing the full set of scheduled photographs. At the remaining three lakes, data losses were recorded during the second and third seasons, attributable to memory-card failures or device malfunctions, which were not detected until the scheduled field visits. Only one camera required replacement at the start of the 2023–2024 season.

In no case did data loss occur due to battery depletion. The maximum continuous operating time without battery replacement was 236 days (7.9 months), recorded during the 2022–2023 season, coinciding with the total observation period at that lake (Estany de Contraix). A progressive drift in the cameras' internal clocks was also detected, with delays of up to 23 minutes per season relative to real time. No camera or shelter sustained significant physical damage, although some superficial wear was observed, primarily attributable to prolonged exposure to solar radiation.

In addition to technical aspects, several limitations related to environmental conditions were identified. During the first days of the 2021–2022 season, at three different cameras, snow accumulation on the ground temporarily prevented visibility of the lake. Nevertheless, freeze-up dates could be identified. On other occasions, visibility was affected by fog, heavy snowfall, or low-light conditions. Despite these limitations, the camera locations proved adequate to capture ice dynamics with a single unit per lake.

3.2. Effectiveness in Characterizing Lake-Ice Phenology

The time-lapse camera monitoring system LIMS-TL demonstrated high effectiveness in recording key lake-ice phenological events in high-mountain lakes. Across the three observation seasons (2021–2024), 90% of the key dates—Freeze-Up Start (FUS), Freeze-Up End (FUE), Break-Up Start (BUS), and Break-Up End (BUE)—were successfully identified in the seven monitored lakes.

Based on the available key dates, 83.3% of the temporal metrics associated with ice formation, maintenance, and decay (FUD, CFD, BUD and FD) were obtained. Although this study does not aim to analyze interannual variability or establish generalizable phenological patterns—given its exploratory nature and the limited duration of the time series—the results validate the usefulness of the system as a tool for systematic, high-temporal-resolution observation. It is also worth noting the greater variability observed in break-up timing and duration (BUS and BUD).

In four of the seven lakes (Estany Llong, Estany de Gerber, Estany de Travessani and Estany de Contraix), a 100% success rate in detecting phenological events was achieved across the three seasons. In the remaining three lakes, interruptions were related to technical issues: at Lac Redon, a storage failure prevented calculation of Freeze-Up Duration (FUD) in the second season; at Estany Gelat, freeze-up events in the second year and break-up in the third year were not recorded; and at Estany de Dalt de Saboredo, a malfunction prevented determination of Break-Up Duration (BUD) during the second season. In all these cases, the loss of key events also prevented calculation of derived metrics such as CFD and FD (Fig. 5).

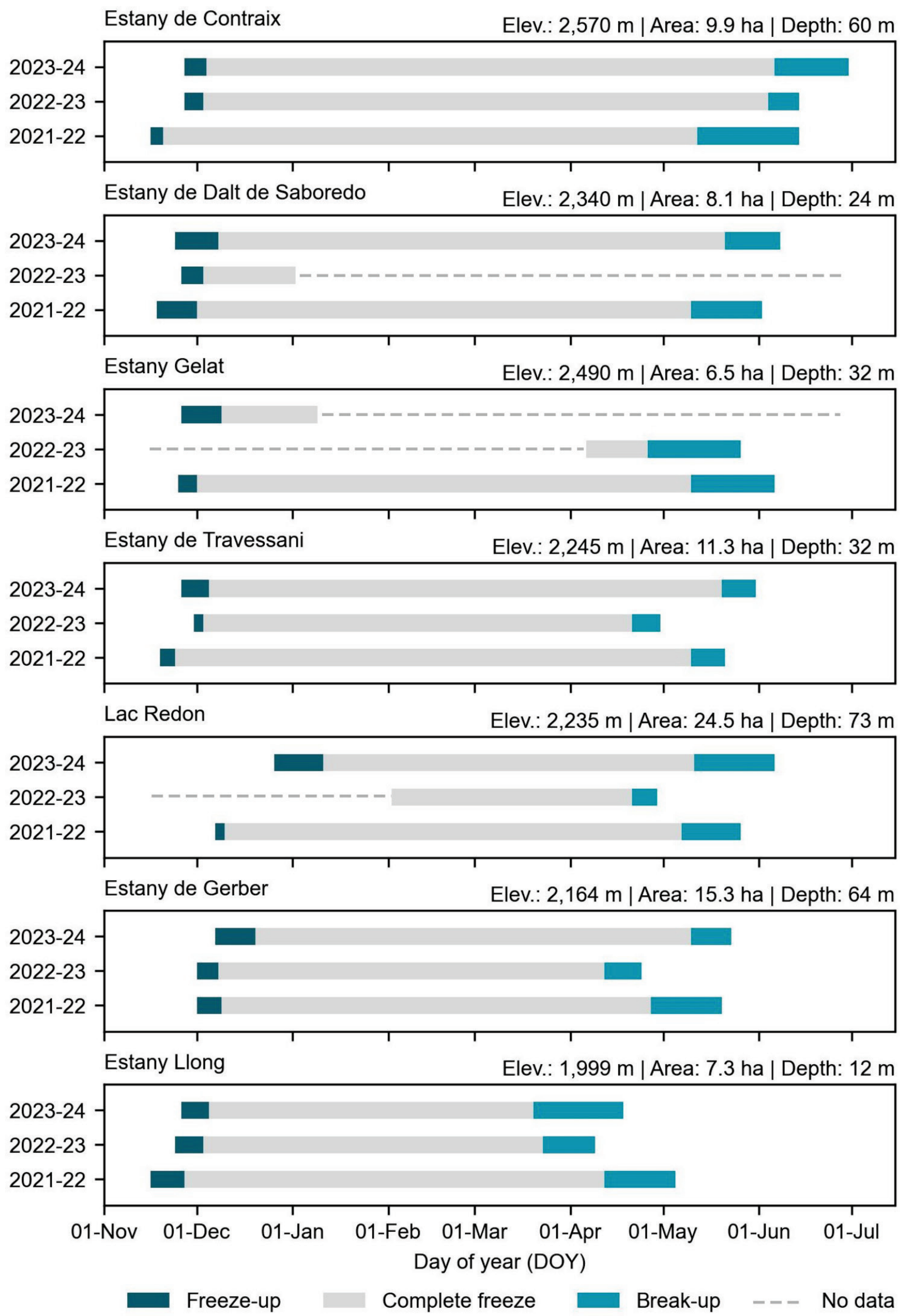

Figure 5. Lake-ice phenology of seven Pyrenean lakes based on visual analysis of time-lapse camera images covering the 2021–22 to 2023–24 ice seasons.

Beyond date identification, LIMS-TL enabled the documentation of differences among lakes with contrasting morphometric and altitudinal characteristics, reinforcing its applicability across diverse contexts. For example, Lac Redon—the largest and deepest lake—exhibited later freeze-up, whereas Estany Llong—located at lower elevation and influenced by tributary inflows—showed earlier break-up and the shortest ice season (150 days on average). At the opposite extreme, Estany de Contraix, located at higher elevation, recorded the longest ice season (208.3 days on average), exceeding the overall mean of 178.4 days (Table 4).

All lakes reached complete freeze only a few days after the onset of the process, with durations ranging from 5.7 to 11.3 days (Table 4). This level of temporal detail—difficult to achieve using other observation methods—highlights the potential of time-lapse cameras to characterize rapid and dynamic processes in high-mountain environments.

Table 4. Average duration of each lake-ice phenology period. Mean durations (in days) of each period of the seasonal ice cycle in seven small high-mountain lakes, calculated from the key dates recorded using time-lapse cameras over three winter seasons. Metrics include: FUD (Freeze-Up Duration), CFD (Complete Freeze Duration), BUD (Break-Up Duration), and FD (Frozen Duration).

Lake	FUD (days)	CFD (days)	BUD (days)	FD (days)
Contraix	5.7	180.3	22.3	208.3
Dalt de Saboredo	11.3	162.5	20.5	196.5
Gelat	9.5	160.0	28.5	193.0
Travessani	5.7	157.7	10.3	173.7
Lac Redon	9.5	134.5	17.7	166.5
Gerber	9.3	135.3	16.0	160.7
Llong	9.7	117.3	23.0	150.0
Overall mean	8.7	149.7	19.8	178.4

In addition to the main phenological events, detailed image analysis revealed a notable ability of the system to capture short-duration phenomena such as intermittent ice formation, crack development, surface-water accumulation, or textural changes in the ice. These processes—difficult to detect through sporadic field visits or satellite imagery—illustrate the added value of this technology for studying fine-scale surface dynamics of lake ice. This capability is especially valuable in small high-mountain lakes, where changes can occur over very short time scales and where other observation techniques are subject to operational or spatial limitations. Figure 6 visually illustrates the ability of LIMS-TL to record both key phenological events and morphological and textural ice features, providing valuable information for interpreting surface-ice dynamics.

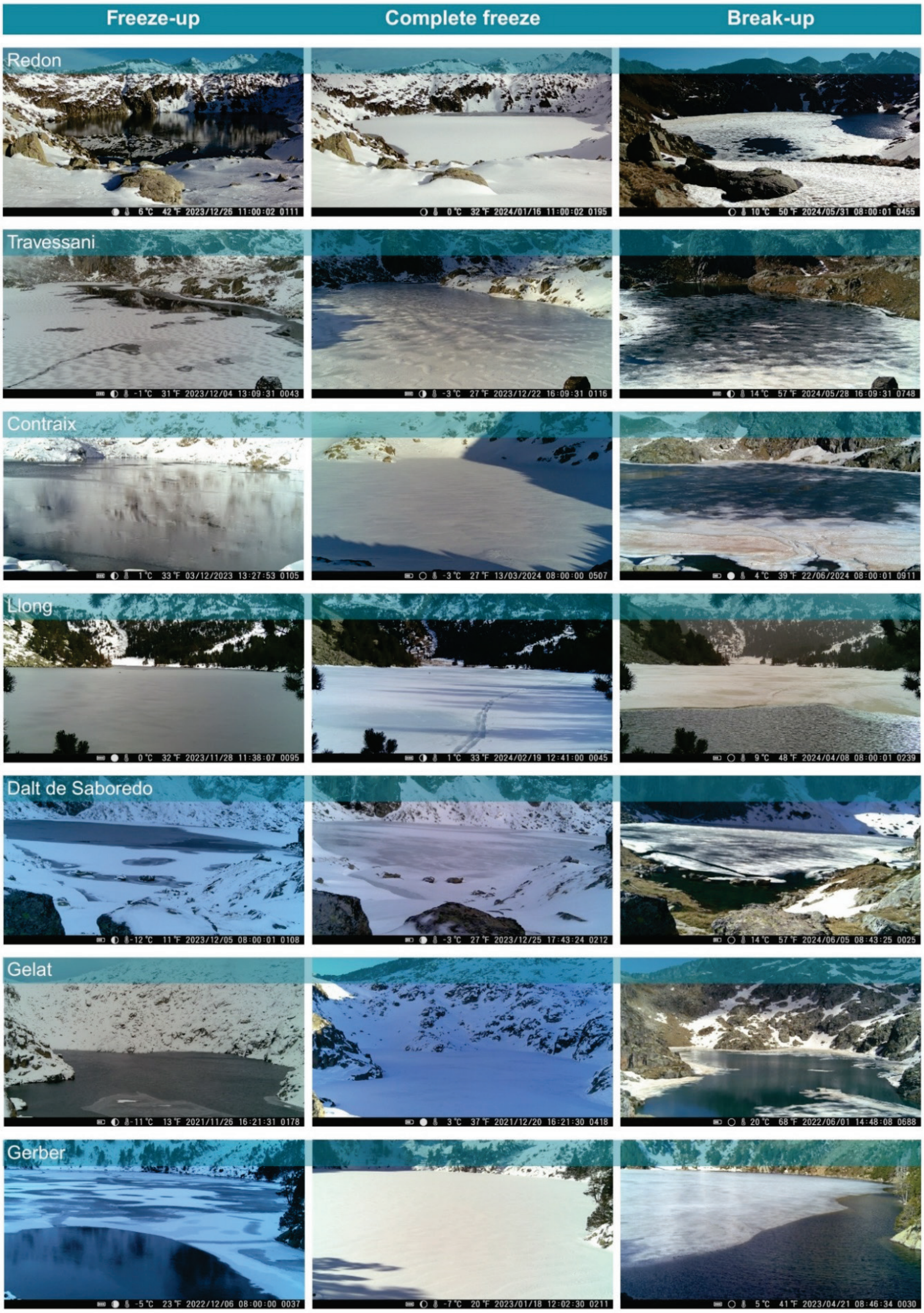

Figure 6. Sample of valid time-lapse camera images from each study lake, showing representative examples of freeze-up (FUS-FUE), complete freeze (FUE-BUS), and break-up (BUS-BUE).

3.3. *Quality of the time-lapse images*

During the 2021–2022 season, an average of 55.2% of images were classified as valid, 33.0% as partially valid, and 11.8% as invalid across the seven lakes (Table 5). According to the classification criteria used, 55.2% of the images were deemed suitable for detailed analyses of lake-ice surface dynamics—including ice types, shapes, and textures—allowing high-resolution spatial interpretation, albeit with the inherent limitations of a terrestrial viewpoint. When partially valid images are also considered, 88.2% of the total set was potentially useful for identifying key lake-ice phenology dates. Only 11.8% of the images provided no relevant information on ice cover.

A comparison among lakes (Table 5 and Fig. 7) highlights Contraix as having the highest proportion of valid images (65.6%) and Redon the lowest (43.0%). Figure 7 enables identification of temporal and spatial patterns related to meteorological conditions and geographic location. For example, periods are observed in which several lakes simultaneously show low-quality images, suggesting shared adverse atmospheric conditions. Conversely, there are days on which most lakes record valid images while some exhibit invalid ones, likely due to lens obstruction caused by snow accumulation—especially during the first third of the season at Redon, Gerber, Llong, and Gelat. At a seasonal scale, an increase in partially valid images is evident during spring, coinciding with higher cloudiness and precipitation frequencies in the Pyrenees.

Table 5. Quality of the time-lapse images.

Lake	**% Valid**	**% Partially valid**	**% Invalid**
Contraix	65.6	25.2	9.1
Travessani	65.1	27.6	7.3
Estany Llong	62.9	26.5	10.7
Gerber	56.2	35.0	8.8
Dalt de Saboredo	49.6	48.0	2.4
Gelat	44.1	37.0	18.9
Lac Redon	43.0	32.0	25.0
Overall mean	55.2	33.0	11.7

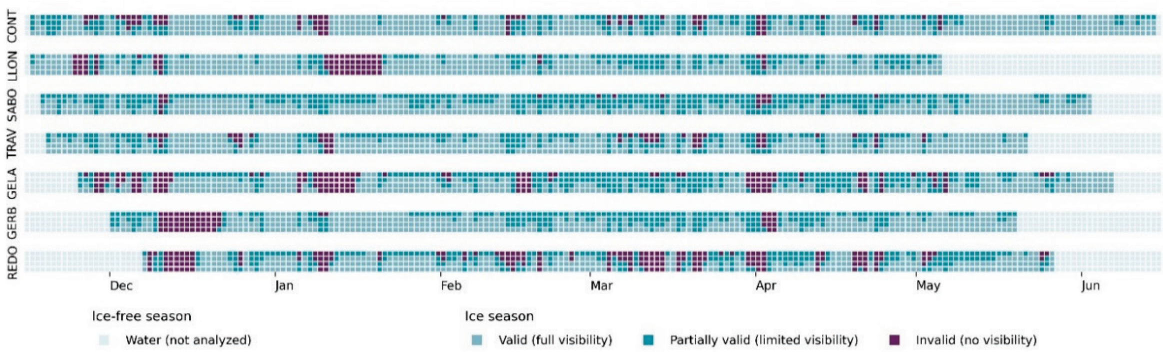

Figure 7. Daily quality of time-lapse images during the 2021–2022 season. Heatmap showing, for each lake and day, the quality of the four images captured. Rows are ordered from bottom to top according to image quality (from highest to lowest), allowing identification of the best and worst daily records for each lake. Temporal and spatial patterns in image quality can also be identified both within and among lakes.

A key indicator of the effectiveness of this methodology is the percentage of days with at least one valid image, which averages 80.7% across all lakes. When partially valid images are included, this value rises to 93.1% (Table 6). These data can be viewed in the first (bottom) row for each lake in Figure 7, which represents the best daily quality recorded. For example, Estany de Contraix shows only five days in which the best available image was invalid.

Table 6. Best daily quality of the images.

Lake	% Days valid	% Days partially valid	% Days invalid
Contraix	86.7	10.9	2.4
Dalt de Saboredo	86.3	13.2	0.5
Estany Llong	85.4	5.8	8.8
Travessani	85.3	13.6	1.1
Gerber	80.6	11.8	7.6
Gelat	72.2	14.9	12.9
Lac Redon	68.4	16.4	15.2
Overall mean	80.7	12.4	6.9

The analysis also reveals that many partially valid cases are due to lighting issues, although these are not the only factors affecting visual quality (Fig. 8). Overexposure occurs through solar reflection on snow, particularly under high solar angles and when snow is present on the ice cover and along shorelines. Underexposure, in contrast, occurs during cloudy days or around sunrise and sunset, when solar angles are low. These patterns suggest the presence of a daily cycle in image quality, as well as a seasonal cycle influenced by the mid-latitude position of the Pyrenees (~42°), enhanced by shadows cast by mountainous terrain. For instance, images taken at 08:00 UTC+1 in December show low illumination, whereas those taken at the same time in March offer optimal conditions. Moreover, the time window with a risk of overexposure progressively expands as the season advances until snow disappears.

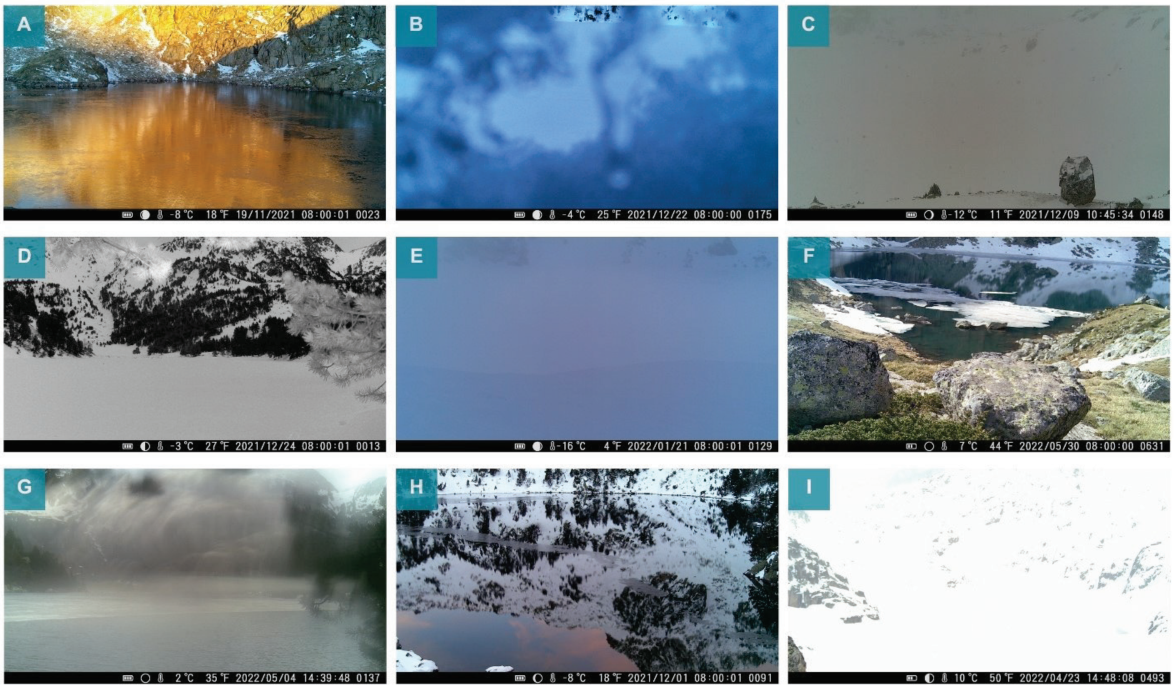

Figure 8. Representative examples of images classified as partially valid. A) Reflections on black ice. B) Partial lens obstruction due to snow accumulation. C) Reduced visibility during heavy snowfall. D) Low illumination in early morning in a valley bottom near the winter solstice. E) Low visibility due to fog. F) Reflections on the lake surface during the break-up phase. G) Distortion caused by raindrops on the lens. H) Intense reflections during the initial freeze-up phase. I) Overexposure caused by sunlight reflected on snow.

4. Discussion

4.1. Key operational challenges and lessons learned

Automatic monitoring cameras have been widely used in scientific studies with different approaches. One is camera trapping, based on motion sensors that trigger image or video capture—a technique extensively used in wildlife research for its ability to document animal behavior without direct interference (López Díaz *et al.*, 2024). The other approach, adopted in this study, is time-lapse photography, which enables image capture at regular intervals and the high-temporal-resolution documentation of dynamic environmental processes.

This type of technology has previously been applied to the study of lake ice (Ariano and Brown, 2019; Higgins *et al.*, 2021; Kirchner *et al.*, 2024), as well as to other components of the cryosphere, including glaciers (Ahn and Box, 2010; Vivero, 2024), snow (Farinotti *et al.*, 2010; Luo *et al.*, 2022), and avalanches (Van Herwijnen *et al.*, 2013). Despite its growing use, time-lapse imagery still offers ample possibilities for new scientific applications—especially for studying rapid, localized processes and for detailed image-based analyses.

From an operational standpoint, the LIMS-TL system exhibited an excellent cost-efficiency ratio. The cameras provided good image quality, high energy autonomy (up to 7.9 months without battery replacement under extreme cold conditions), and low maintenance. Although models integrating small solar panels could further extend autonomy, such solutions were not required in this deployment.

One of the main limitations identified was data loss due to technical failures, particularly involving memory cards or the devices themselves. Even so, the LIMS-TL deployment delivered adequate performance for monitoring ice in small high-mountain lakes. In this context, the relatively simple morphology of the lakes allowed a single camera to consistently capture surface dynamics. Nevertheless, occasional incidents suggest considering a second unit per lake as backup, or implementing telemetry for early failure detection. The latter option, however, presents challenges in areas without mobile coverage, where additional infrastructure (ground repeaters or satellite telemetry) would be required.

Another source of information loss was snow accumulation on the lens, especially during the first season. This problem could be mitigated by increasing the installation height of the cameras or by scheduling more frequent maintenance visits, provided access conditions allow it. In this regard, remote communications would also enable more efficient responses to temporary obstructions.

With respect to capturing frequency, results indicate that the system could benefit from increasing the number of daily images. Since battery performance exceeded expectations, it would be feasible to reduce the interval between captures—for example, to one image every two hours (Kirchner *et al.*, 2024) or every hour—thereby increasing the likelihood of obtaining valid images under adverse weather or low-light conditions. However, this improvement would entail greater complexity in data management and storage.

4.2. System capability to document lake-ice dynamics

This study represents the first systematic, high-temporal-resolution documentation of lake-ice phenology in Pyrenean lakes, encompassing the four key dates of the seasonal cycle and the duration of each ice-cover period. Unlike previous work in the region—such as Sabás *et al.* (2021, 2024), which identified only two dates using subsurface thermistors—this system enabled a more precise characterization of ice formation, maintenance, and decay processes. The results demonstrate the system's ability to generate detailed phenological series, opening new opportunities for the study of winter limnology in high-mountain environments, which are highly sensitive to climate change and characterized by processes occurring at reduced spatial and temporal scales.

The image-capture system implemented through the LIMS-TL method showed robust operational performance and notable scientific potential for accurately characterizing lake-ice dynamics. Thanks to the high temporal resolution of the time-lapse cameras, it was possible to document phenological events that, in small high-mountain lakes, may unfold within just a few days. Although the observation series spans only three winters, the data illustrate marked interannual variability—especially in break-up timing—reflecting its strong dependence on spring conditions. For example, the freeze-up process lasted an average of 5.7 days at Estany de Contraix and 8.7 days across all lakes studied (Table 4), values significantly shorter than those observed in larger lakes in other regions, where durations exceeding 17 days have been reported (Sun *et al.*, 2023; Yao *et al.*, 2016), although methodological differences limit direct comparisons. This ability to capture subtle variations between seasons and between lakes with contrasting characteristics reinforces the usefulness of the system as a tool for systematic observation.

Unlike sporadic in situ observations—which only allow interpretation of ice conditions at the time of the visit—time-lapse images generate a continuous visual archive that can be reviewed retrospectively. This ability to revisit the image sequence not only improves the accuracy of phenological-event identification but also confers documentary value to the imagery, enabling its reuse for other scientific, educational, or heritage purposes.

Furthermore, detailed monitoring of ice dynamics using time-lapse cameras provides valuable information for understanding winter and spring hydrological processes at the water-ice interface, such as differential ice melt, the appearance of cracks with surface water inflow, or the accumulation of Saharan dust that may reduce albedo and influence break-up dynamics. These processes are seldom documented in remote mountain lakes (Fig. 9).

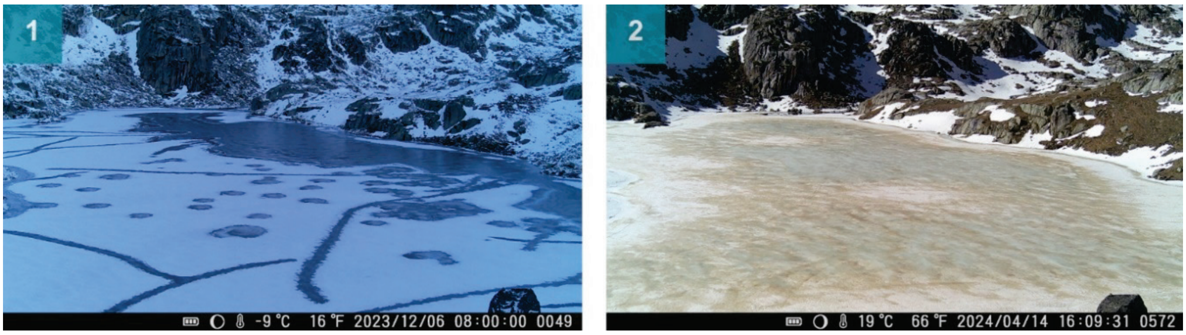

Figure 9. Textural details of the ice cover at Estany Travessani captured by a time-lapse camera during the 2023–2024 season. (1) Water-inflow marks through cracks and holes during freeze-up, and (2) Saharan dust accelerating melt and producing surface slush.

However, the inherent bias of terrestrial visual interpretation must be considered, as the estimation of ice-covered surface area can be affected by the observer's perspective (Zhang and Pavelsky, 2019; Zhang *et al.*, 2021), particularly in larger lakes or those with irregular morphologies. To enhance objectivity in the analysis, it would be advisable to incorporate automated digital-image-processing techniques, such as segmentation algorithms or deep learning models designed for automated classification of ice cover.

As a complement to such automation, a substantial improvement in spatial rigor would involve integrating the georeferencing and radiometric-correction technique of Corripio (2004). This method allows oblique photographs to be projected onto a Digital Elevation Model (DEM), assigning each pixel an exact geographic coordinate and thus eliminating perspective bias in surface calculations. In addition, by comparing image reflectance with known reference points, it is possible to transform the visual archive into quantitative albedo maps. This capability would enable precise quantification of subtle processes identified in this study, such as albedo reduction caused by Saharan dust or the evolution of ice texture, effectively transforming the LIMS-TL system from a visual-inspection tool into a high-resolution ground-based remote-sensing instrument.

On the other hand, the feasibility of these advanced techniques critically depends on the integrity and quality of the visual record. Although the manual quality-classification approach employed in this study proved effective, it presents limitations in consistency over long series and a high operational workload. In this regard, implementing an automated quality filter as a preliminary step—before phenological analysis or geometric correction—would allow processing only those images containing useful information, thereby significantly optimizing the workflow. The use of quantitative metrics such as the Structural Similarity Index (SSIM) of Wang *et al.* (2004), contrast analysis, or machine-learning algorithms for quality control would facilitate the systematic identification of valid captures versus those invalidated by dense fog or snow on the lens. Such automated screening would not only enhance monitoring objectivity but would also be essential for efficiently managing the large volume of data resulting from any future increase in capture frequency. Indeed, experiences in fields such as geotechnics have already validated the usefulness of these filters for environmental monitoring (Kim *et al.*, 2019), reinforcing their potential for scaling lake-ice studies.

5. Conclusions

(1) This study represents the first systematic, high-temporal-resolution documentation of lake-ice phenology in Pyrenean lakes, capturing the four key dates of the seasonal cycle. The LIMS-TL time-lapse camera system proved to be an effective, accurate, and low-cost tool for monitoring small high-mountain lakes, enabling the identification of 90% of these events over three consecutive winters.

(2) In small lakes (6.5–24.5 ha), and provided that shoreline morphology is not excessively complex, a single camera can visually cover most of the lake surface, facilitating implementation in remote environments with minimal infrastructure.

(3) The LIMS-TL system enabled the precise detection of short-duration phenological processes, such as freeze-up, which in some cases occurred in less than one week. This ability to record brief events, combined with the system's robustness and replicability, reinforces its usefulness as a tool for systematic observation in high-mountain environments.

(4) The images obtained constitute a unique visual archive of surface-ice dynamics in high-mountain lakes, with clear long-term scientific and heritage value. The quality assessment showed that the majority of the images were valid for phenological monitoring, reinforcing the reliability of the approach. Overall, this system opens opportunities to extend time series, advance toward automated classification workflows, and improve understanding of how high-mountain lake ecosystems respond to climate change.

(5) Finally, this study identified both the strengths and several operational limitations associated with using time-lapse cameras in high-mountain environments. Their deployment requires careful planning that accounts for technical, logistical, and interpretive considerations. Although the system is robust, using two cameras per lake or integrating telemetry could reduce data loss and increase monitoring reliability.

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Author Contribution

Òscar Alemán-Milán conducted this work in its entirety as the sole author. His contributions cover all stages of the research process, including conceptualization, methodological development, data collection and analysis, manuscript writing, visualization of results, project management, and part of the project funding. Academic supervision was provided by his PhD supervisors, who have been acknowledged accordingly.

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