Interreg
Alpine Space

Co-funded by the European Union

DiMark

D 2.1.2 Pilot action report

Description of key lakes, connected into pilot action, and new phenomena in alpine lakes

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Date of the document	04/24/2026
Version	1
Project	DiMark

Part A- description of key lakes

In DiMark, lakes in the alpine region are represented by 6 key lakes (Bled, Garda, Geneva, Greifensee, Mondsee, and Upper Lake Constance). These lakes are perialpine lakes, located both north and south of the alpine massive (Fig. 1), thereby extending across most of the east-western Alpine range from Lake Geneva towards Lake Bled. In the following, a short summary of the key lakes is presented, emphasising the characteristics of each lake.

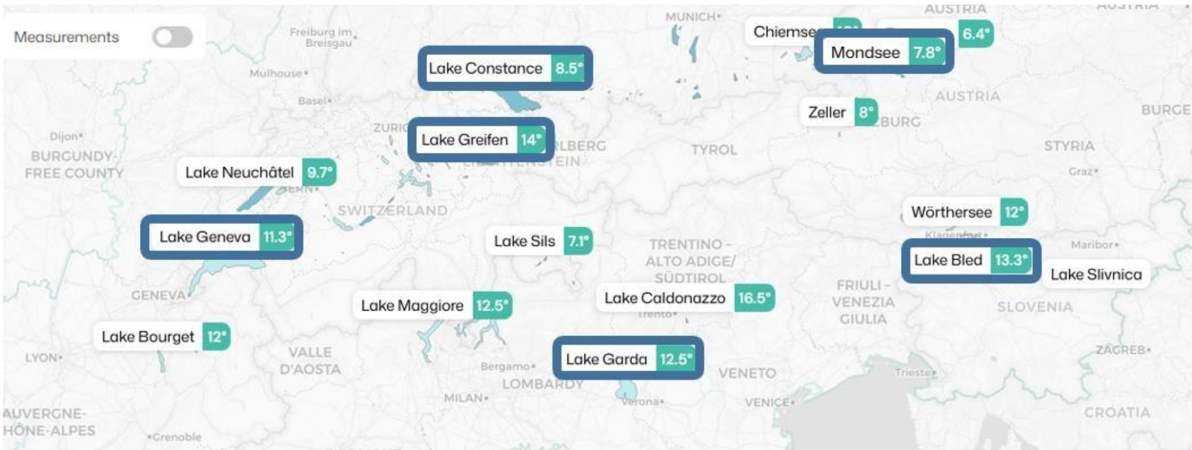

Fig. 1 Location of the 6 DiMark key lakes (names highlighted with a blue border) as presented in the Alplakes homepage (https://www.alplakes.eawag.ch/).

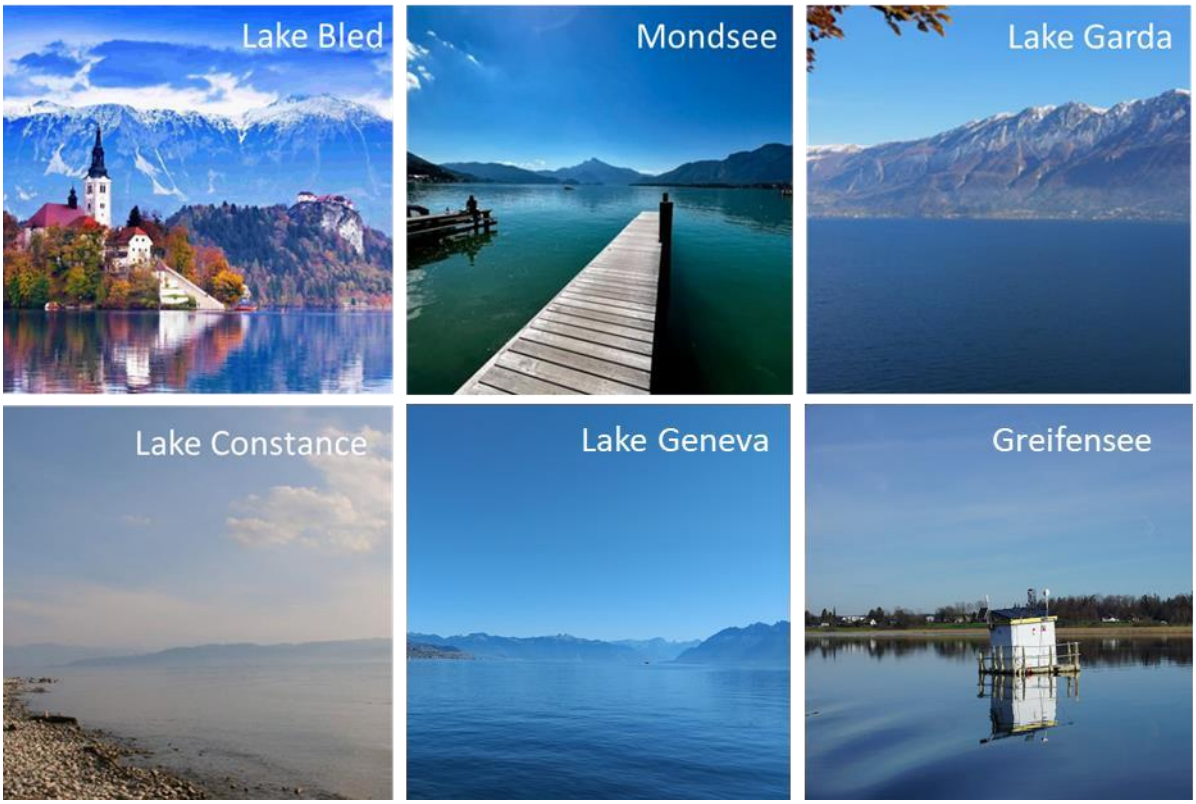

Fig. 2 Pictures of the 6 Dimark key lakes. Pictures by Orlange Anneville (Lake Geneva), Daniel Odermatt (Greifensee), and from https://www.alpine-space.eu/project/dimark/.

Lake Bled (SI)

Lake Bled is the smallest of **DiMark** key lakes (1.5 km^2). It is a national Slovenian icon (Fig. 2) and the most important Slovenian lake for tourism. Celebrated for its stunning island, Lake Bled has seen rising environmental pressures from tourism and shoreline development. These activities, in combination with fish feeding, add to nutrient pollution, fueling potentially harmful cyanobacterial bloom. These blooms can disrupt the lake's delicate ecosystem, turning the seemingly pristine lake water putrid brown or red. Lake Bled is the only lake in Slovenia which occasionally turns into scarlet colour due to blooms of the potentially toxic cyanobacteria *Planktothrix rubescens*, whereas all other Slovenian lakes or acumulations with cyanobacterial bloom are more greenish in colour (www.ciano.si).

Lake Mondsee (AT)

Mondsee is a mid-sized Alpine lake in Austria (around 14 km^2), located in the Salzkammergut Lakes area (Fig. 2), known for its warm summer temperatures and popularity among locals and tourists. It's surrounded by villages and settlements and agriculturally used landscape. This lake allows plenty of recreational activities like swimming, diving, sailing, and paddleboarding (SUP) as well as camping or fishing. Its shoreline is home to cultural events and festivals throughout the year, making it one of the more active lakes in the

Salzkammergut region. The lake supports a variety of aquatic species, including two native fish species, leading to its Natura 2000 status. The lake ecosystem provides habitat for red-listed waterbirds, amphibians and mammals. Its wetlands and littoral zones are ecologically most valuable, though increasingly pressured by human activity. The relatively large catchment of 250 km^2 results in a higher sensitivity of the lake ecosystem to global change, including eutrophication through run-off events but also by tourism and in general, land use. These nutrients can feed algal and cyanobacterial blooms, especially after extreme precipitation events and stratified conditions in the water column. Such blooms may reduce water quality, endanger aquatic life, and can disrupt recreational use - posing risks both to the environment and public health. This is why DiMark offers an excellent opportunity for this particular lake to co-develop, together with local stakeholders and other experts, both a visualisation tool and a cyano-risk prevention model, enabling better and more efficient water management.

Lake Garda (IT)

Lake Garda, the largest lake in Italy (covering over 370 km^2), is one of the most iconic and visited lakes in the Alpine region (Fig. 2). With its mild climate and easy access from cities like Milan and Verona, Garda attracts millions of visitors every year for swimming, sailing, windsurfing, and sightseeing. Despite its beauty, Lake Garda faces increasing pressure from tourism, especially during peak summer months, leading to overloaded wastewater systems and increasing pressure on the lake's natural habitats, high recreational use - from boats and marinas to lakeside resorts - contributes to nutrient inflows, which over time can lead to eutrophication and the appearance of harmful algal blooms.

As part of the DiMark project, Lake Garda will serve as an important pilot for testing scalable monitoring systems and the model for cyano-risk. The goal is to give local authorities and lake managers a clearer picture of when and where water quality issues may arise - helping them respond more effectively and plan long-term measures to protect the lake's ecosystem. For a lake that provides drinking water, supports agriculture, fisheries, and tourism, such a tool is essential for improved water management and protecting environmental health.

Upper Lake Constance (DE/CH/AT)

Upper Lake Constance - known as Bodensee - Obersee - is one of the largest lakes in Central Europe, lying between Germany, Austria, and Switzerland (Fig. 2). Covering more than 470 km^2 and reaching depths of over 250 m, it plays an important role in drinking water supply, fisheries, recreation, and cross-border cooperation. With alpine rivers like the Rhine flowing into it, and an extensive catchment that includes agricultural, industrial, and urban areas, Lake Constance is an important and complex freshwater system.

Although Lake Constance has benefited from decades of international cooperation on water protection, new problems are emerging. Warmer summers and changing rainfall patterns can promote algal and cyanobacterial blooms, especially in shallow bays and areas near river inflows. These blooms may reduce water quality, threaten biodiversity, and pose a risk to bathing areas. Likewise invasive species such as the Quagga mussel disrupt the food web and energy flows of the lake. The large size of the lake and the fact that it is shared by three countries make coordinated monitoring and rapid response particularly important. As a key pilot site within the DiMark project, Upper Lake Constance offers a unique opportunity to test cross-border approaches to early-warning systems and data visualisation tools. DiMark will link traditional water quality monitoring with satellite-based Earth observation, helping authorities detect and track bloom risks in near real time. This is especially valuable in border zones, where lake conditions can change quickly, and responsibilities are shared.

Lake Geneva (CH/FR)

Lake Geneva - or Lac Léman, as it's known in French - is one of Europe's largest lakes (Fig. 2), stretching across Switzerland and France with a surface area of over 580 km^2.

Surrounded by vineyards, the nearby Alps, and cities like Geneva, Lausanne, and Évian, the lake is both a natural wonder and an active, multi-use lake supporting transport, tourism, and water supply. It provides drinking water, supports recreational and commercial fisheries, provides thermal lake energy for cooling/heating systems, and draws millions of people to its shores each year for swimming, sailing, and tourism.

In the past, Lake Geneva suffered from eutrophication, especially during the 1970s and 1980s. Agriculture, industrial waste, and untreated sewage led to nutrient overload, algal blooms, and oxygen depletion in deep water. A long-term international effort involving both countries helped reduce phosphorus levels and improve wastewater treatment, setting a good example for cross-border water protection.

Today, the picture is changing again. Climate change can make the lake more vulnerable to algal and cyanobacterial blooms because of rising surface temperature, longer stratification periods and intense rainstorms that can increase the risk of runoff and re-suspension of nutrients from sediments - especially near the Rhône inflow and urban shorelines. For DiMark, Lake Geneva offers a chance to apply modern tools to an old but evolving challenge. The lake is large, deep, and internationally governed - making it an ideal testing ground for the satellite-based visualisation platform and the cyano-risk model. These tools will help lake managers, public health authorities, and municipalities respond more quickly to signs of bloom development and shifts in water quality.

Lake Greifensee (CH)

Greifensee is a small but ecologically significant lake located just northeast of Zurich, Switzerland, covering about 8.5 km^2. Despite its modest size, it plays an important role in the region: serving as a drinking water source, recreation area, and biodiversity hotspot. Its proximity to urban centers makes it a popular destination for walking, birdwatching, kayaking and swimming (Fig. 2).

Greifensee is experiencing elevated nutrient levels from agriculture and wastewater, which cause oxygen depletion and cyanobacterial blooms. Thanks to improvements such as improved sewage treatment and stricter agricultural practices, phosphorus inputs have decreased, but they remain noticeable and nutrient recycling from sediments prevents the lake's recovery from eutrophication, too. Its manageable size makes detailed monitoring possible, but internal nutrient cycling, variable bloom conditions, and diverse human uses continue to present challenges. Warmer water temperatures and stronger thermal stratification can extend the bloom season and reduce oxygenation in deeper layers, which may occasionally release phosphorus stored in sediments, supporting new blooms even if external nutrient inputs have been reduced.

Within the DiMark project, Greifensee is a key pilot site for understanding how small, and more shallow lakes - especially those at the interface of agglomerations and rural areas – may respond to warming and changing nutrient dynamics. This will help local authorities anticipate harmful conditions and deal with water management more efficiently.

Part B- New phenomena in alpine lakes

Whitening events in key lakes - Pilot action for Lake Constance

Whitening events represent a transient event in many peri-Alpine hardwater lakes. Despite being a transient phenomenon, it is of importance for lake functioning and even the role of lakes in the global carbon budget. Furthermore, there is an indication that the length of these transient phenomena has increased during the last decades. During a whitening event, the lake will establish a striking turquoise colour, and thus, whitening events can be detected using satellite observations. Massive calcium carbonate precipitation and subsequent sedimentation of calcite will reduce phosphorus concentrations due to co-precipitation, as well as reduce light availability in the water column, and thus may interfere with the development of algal and cyanobacterial blooms. Furthermore, sedimentation of calcite crystals during such events will enhance the role of lakes as a carbon sink. Improving our ability to detect whitening events and infer using remote sensing tool to predict particulate inorganic carbon concentrations and carbon sedimentation would improve our understanding of lake functioning and their role in the global carbon cycle (Many et al. 2024).

Several approaches (e.g, AreaBGR index, Band reflectance at 560nm (Heine et al. 2017; Escoffier et al. 2022) in combination with different atmospheric correction tools (Steinmetz et al. 2011; Brockmann et al. 2016) exist to detect whitening events. Escoffier et al. (2022) showed that in Lake Geneva whitening events can be detected using band reflectance at a single wavelength (560 nm). However, previous approaches did not statistically link remote sensing products to measured calcium carbonate or particulate inorganic carbon (PIC) concentrations.

Within DiMark, measurements of particulate inorganic carbon concentrations (PIC) were done in Lake Constance approximately biweekly based on samples of the upper 20 m of the water column. In addition to direct measurements of PIC with the carbon analyser, PIC was estimated using the turbidity sensor of a YSI EXO II multiparameter probe. The latter allowed us to estimate average PIC values both for the 0-20 m and the 0.5 m water column.

Both directly measured PIC and probe-estimated PIC were linked to the above mentioned approches in order to test whether these approaches could predict seasonal variability of PIC concentrations and thereby whitening events in Lake Constance.

Best results were achieved using Case 2 Regional CoastColour (C2RCC) atmospheric correction with vicarious calibration at 620 nm, reaching an R^2 of 0.611 (Table 1, Fig. 3). However, also other bandwidths exceeding 560 nm yielded comparable results. Hence, the bandwidth used in Lake Geneva (560 nm) to predict whitening events can also be used to predict PIC concentrations in Lake Constance. With respect to different estimates of PIC (carbon analyser (0-20 m), EXO probe (0-20 m) and probe (0-5 m)), the various approaches and atmospheric correction methods did not show large differences in predictability.

Table 1: Performance comparison of different retrieval approaches for PIC estimation.

Approach			N	Range	R^2	RMSE (µg/L)
Polymer		Band 560	31	0.064 - 45.613	0.368	7.933
		AreaBGR	31	0.064 - 45.613	0.452	7.392
		Rw620	31	0.064 - 45.613	0.393	7.776
C2RCC	With Vicarious Calibration	Band 560	33	0.064 - 86.724	0.436	13.792
		AreaBGR	33	0.064 - 86.724	0.590	11.752
		IOP_bpart	33	0.064 - 86.724	0.551	12.298
		IOP_btot	33	0.064 - 86.724	0.518	12.745
		Rhow620	33	0.064 - 86.724	0.611	11.450
	Without Vicarious Calibration	Band 560	36	0.064 - 86.724	0.518	12.694
		AreaBGR	36	0.064 - 86.724	0.521	12.652
		IOP_bpart	36	0.064 - 86.724	0.497	12.956
		IOP_btot	36	0.064 - 86.724	0.126	17.082
		Rhow681	36	0.064 - 86.724	0.584	11.791

Table 2: Performance of individual spectral bands (RW) for PIC estimation across Polymer and C2RCC approaches.

	C2RCC with Calibration			C2RCC without Calibration			Polymer			
Rw	N	R2	RMSE(µg/L)	N	R2	RMSE (µg/L)		N	R2	RMSE (µg/L)
400	33	0.196	16.460	36	0.087	17.466	400	31	0.263	8.567
412.5	33	0.224	16.173	36	0.113	17.215	412	31	0.267	8.547
442.5	33	0.331	15.017	36	0.219	16.151	443	31	0.269	8.535
490	33	0.468	13.389	36	0.366	14.547	490	31	0.283	8.456
510	33	0.537	12.487	36	0.438	13.706	510	31	0.311	8.288
560	33	0.590	11.752	36	0.518	12.694	560	31	0.368	7.933
620	33	0.611	11.450	36	0.575	11.910	620	31	0.393	7.776
665	33	0.611	11.450	36	0.583	11.807	665	31	0.363	7.965
673.75	33	0.610	11.460	36	0.583	11.797	681	31	0.358	7.996
681.25	33	0.609	11.475	36	0.584	11.791	709	31	0.222	8.807
708.75	33	0.608	11.493	36	0.585	11.768	754	31	0.244	8.678
753.75	33	0.602	11.578	36	0.581	11.826				

Using the established relationships between PIC concentration and band reflectance, it is possible to predict PIC concentrations in various parts of Upper Lake Constance, but also Lower Lake Constance, using Sentinel-3 data to extend our time series to the period 2016-2025. First results suggest that the particulate inorganic carbon pattern observed with ground truth data can be reliably predicted using Sentinel-3 at the measurement site (Fig. 2, site d), but also at other sites in Upper Lake Constance (e.g., site b). Deviation in peak PIC concentrations occurred mainly during the PIC peak in 2024. The alleged deviation in 2024 was presumably not real, as during peak PIC concentrations, satellite observations were largely unavailable due to persistent cloud cover. The seasonal whitening signals (enhanced PIC concentrations) are less clear, however, in the eastern part of Lake Constance (site c), which is characterised by enhanced turbidity due to River Rhine inflow, and the more shallow Lower Lake Constance (site a).

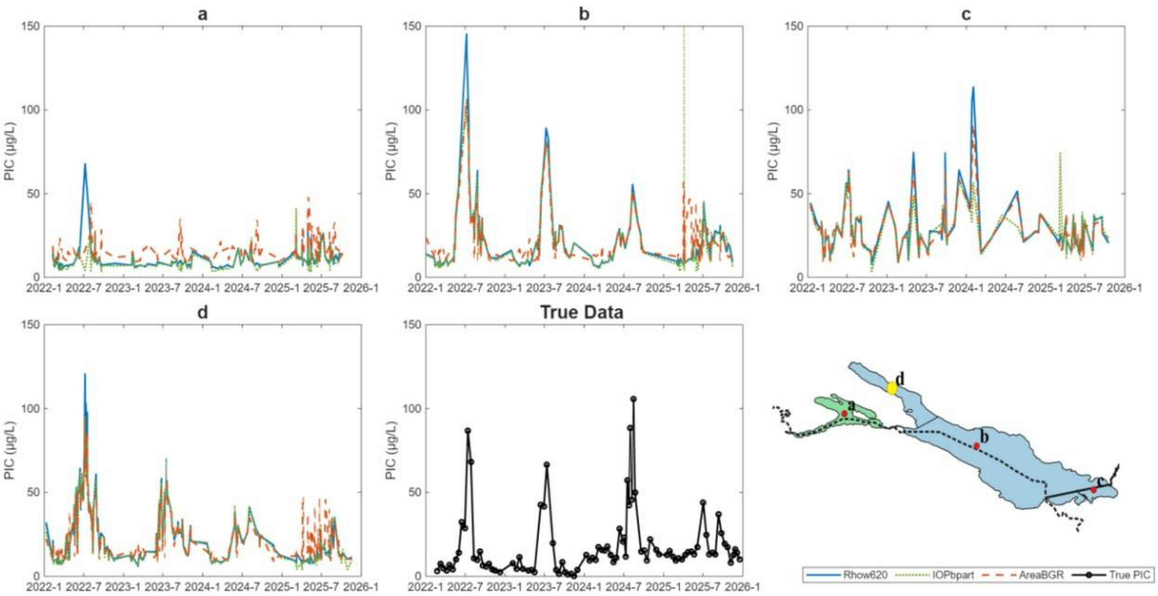

Fig. 2 Estimation of PIC concentration at various sites of Lake Constance from Sentinel-3 using C2RCC with different vicarious approaches.

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