Alpine Water Extent and Lake Level Monitoring in Switzerland (AlpineWELLS)

Final Report

Image: Bathymetry survey using the Hydrone catamaran on Lake Rhone (VS), 18 August 2021. Photo by T. Ryser.

D. Odermatt

Eawag, Department Surface Waters – Research and Management

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Content

1 Summary

The extensive deglaciation of the Swiss Alps due to climate change represents a major change of alpine geomorphology and leads to the formation of several hundred new lakes in previously glaciated depressions. Appropriate documentation and profound understanding of this environmental change are needed. The Swiss hydrometric network under the coordination of FOEN is currently in revision to better meet such novel requirements, concerning the impacts of climate warming on small lakes in general, and those at high elevation in particular. The GCOS 2016 Implementation Plan specified five Essential Climate Variables for lakes: Lake Water Extent, Lake Water Level, Lake Surface Water Temperature, Lake Ice Cover and Lake Water-Leaving Reflectance. The goal of the AlpineWELLS project is to evaluate a monitoring program that relates to the global requirements for these Essential Climate Variables, yet takes into account specific observational challenges and information resources for alpine lakes in Switzerland.

We compiled the first glacier lake inventory for Switzerland, with an analysis of glacier lake evolution stages since the Little Ice Age using historical glacier boundaries. In total, we identified 1192 lakes that formed in the entire period. Of these, 987 still existed in 2016. The lakes are well distributed over the whole glaciated area of Switzerland. We also added an assessment of lake dam materials and other hazard related variables. We furthermore reviewed remote sensing techniques that can potentially support the monitoring of glacier lakes at large scale, using lake Essential Climate Variables as baseline parameters. Current requirements allow compliant monitoring only for a few hundred of the World's largest lakes. We hypothesize that adjusted requirements could enable critical Earth observations, from remote sensing and model simulations, for a far larger number of smaller lakes, and specifically for new glacier lakes in Switzerland. We will assess this hypothesis in the scope of ongoing AlpineWELLS project activities funded by FOEN, which allows us to perform experimental in situ measurements, both automated and manual, and collect reference data for the assessment of promising remote sensing techniques.

2 Scientific report

2.1 Introduction

With a total area of about 900 km^2 and an estimated ice volume of 53 km^3 in 2017, glaciers represent a large water reservoir in Switzerland. Results from a regional glacier model accounting for ice flow dynamics (Zekollari et al., 2019) project that, between the years 2017 and 2100, the total ice volume of all Swiss glaciers will decrease by 59%, 75%, and 94% under low (RCP2.6), moderate (RCP4.5) and severe (RCP8.5) emission scenarios, respectively (Ayala et al., 2020). This extensive deglaciation represents a major change of alpine geomorphology and leads to the formation of several hundred new lakes in previously glaciated depressions. Socio-economic impacts concern water availability, hydroelectric power production, tourism and natural hazards. Appropriate documentation and profound understanding of this environmental change are needed. The Swiss hydrometric network under the coordination of FOEN is currently in revision to better meet this requirement, concerning the impacts of climate warming on small lakes in general, and those at high elevation in particular.

The GCOS 2016 Implementation Plan specified five Essential Climate Variables (ECVs) for lakes: Lake Water Extent (LWE), Lake Water Level (LWL), Lake Surface Water Temperature (LSWT), Lake Ice Cover (LIC) and Lake Water-Leaving Reflectance (LWLR). The feasibility of these ECVs at global scale and using satellite Earth observation (EO) data is currently being demonstrated in the scope of the ESA Climate Change Initiative (CCI). The current version 1.1 of CCI Lakes products was published in 2021 and resolves 253 of the largest lakes worldwide in 1/120° (ca. 1 km at mid latitudes) spatial resolution. The only Swiss lakes included are Lakes Constance, Geneva and Maggiore. The abovementioned requirements for the Swiss hydrometric network demonstrate that we need baseline monitoring products from EO data at smaller spatial scales. Our overarching goal is thus to evaluate a monitoring program that relates to global ECV requirements yet takes into account specific observational challenges and information resources for alpine lakes in Switzerland. LIC was in the focus of two previous projects in the framework of GCOS Switzerland, our initial focus was thus on the other four ECVs.

The AlpineWELLS project funded in the framework of GCOS Switzerland comprises of two work packages. First to compile a glacier lake inventory for Switzerland, and second to review and evaluate ECV monitoring methods for these lakes. A complementary project funded by the Federal Office of the Environment (AlpineWELLS-FOEN, 2020-2024, PI D. Odermatt) provides for the practical exploration and cost-benefit analysis of such methods. In doing so, it contributed strongly to the second work package of the present project, which is why we report some of these methods and preliminary results below. An outlook on other, ongoing research projects that are focused on glacier lake monitoring is given in Section 2.6.

The main accomplishment of AlpineWELLS is the publication of the Swiss glacier lake inventory (Mölg et al., 2021) and the huge media echo it triggered (see Section 2.5). The study also raised awareness among aquatic researchers and in the remote sensing community. In consequence, we established collaborations with hydrodynamic modelers who will adopt high-alpine test sites and integrate remotely sensed water quality parameters in the models (Gaudard et al., 2019). Furthermore, we successfully proposed three Swiss glacier lakes as calibration and validation sites for the French-Indian satellite mission TRISHNA, which is planned for launch in 2024 and will be the first to allow high spatial resolution (50 m) estimates of Lake Surface Water Temperature (LSWT) in the entire Alpine region (Lagouarde et al., 2018).

2.2 Methods and activities

2.2.1 Swiss glacier lake inventory (summarized from Mölg et al., 2021)

The scope of the Swiss glacier lake inventory deviates slightly from the project proposal in that we did less methodological, and more applied work. Because the development of a method to extract glacier lake outlines from orthophotos was obsolete after such outlines became available with Swisstopo's topographic landscape model (*swissTLM3D*) in 2020. Instead, we incorporated an analysis of glacier lake evolution stages since the Little Ice Age (LIA) using historical glacier boundaries. We also added an assessment of lake dam materials and other hazard related variables.

Our analyses are based on lake and glacier boundaries from previous studies and national cartographic records by Swisstopo, which we complemented with lake and glacier boundaries derived from Swisstopo's national orthophoto mosaics, *SWISSIMAGE* (Table 1). These datasets were combined to generate a time series of lake boundaries from 1900 to 2016 within the deglaciated area, similar to the study by Viani et al. (2017) for North-Western Italy. Lake boundaries were either manually mapped or inferred by combining glacier and lake boundaries of present and subsequent points in time, respectively. To establish a basis for future hazard assessment, several additional lake variables were retrieved using the *SWISSIMAGE* mosaic from 2014-2016 (hereafter referred to as '2016'; spatial resolution 0.25 m) and the corresponding national Digital Elevation Model (DEM) *swissALTI3D*, with a spatial resolution and vertical accuracy of 2 m.

Table 1: Overview of datasets used and produced for the Swiss glacier lake inventory (from Mölg et al., 2021).

Datasets previously available:	**Source**
Lake boundaries 2006	*swissTLM3D*
Lake boundaries 2016	*swissTLM3D*
Glacier boundaries 1850	Paul (2003), Maisch et al. (2000)
Glacier boundaries 1900	Freudiger et al. (2018)
Glacier boundaries 1973	Müller et al. (1976), Maisch et al. (2000)
Glacier boundaries 2016	*swissTLM3D*

Datasets produced by Mölg et al. (2021):	**Method**
Lake boundaries 1946	Mapped, inferred from *SWISSIMAGE*
Lake boundaries 1980s	Mapped, inferred from *SWISSIMAGE*
Lake boundaries 1900	Inferred from *SWISSIMAGE*
Lake boundaries 1973	Inferred from *SWISSIMAGE*
Glacier boundaries 1946	Mapped from *SWISSIMAGE*
Glacier boundaries 1980s	Mapped from *SWISSIMAGE*

Mapped as referred to in **Error! Reference source not found.** means that we manually defined complementary lake and glacier boundaries using *SWISSIMAGE* mosaics for 1946 and 1979–1985. These orthophotos have a spatial resolution of 1 m (1946) and 0.5 m (1980s) and were generated using the same DEM and set of ground control points in order to achieve a high geolocation agreement. We *inferred* lake extents for dates or regions where direct lake mapping was not possible (1900, 1973, snow-covered lakes in 1946 and 1980s), by using glacier boundaries and the lake boundary of the next available date. This means that lake boundaries for a specific date t1 were either (1) taken from existing datasets, (2) mapped directly from orthophotos, or (3) inferred from the subsequent date t2 based on whether they were located completely or partly inside or outside the glacier polygon of date t1 (Figure 1). Please refer to Mölg et al. (2021) for further details.

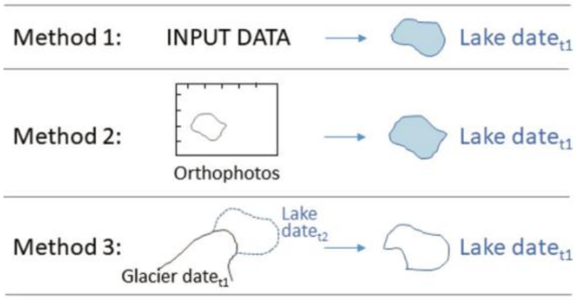

Figure 1: Methods of lake outline definition (from Mölg et al., 2021). INPUT DATA is from swissTLM3D, orthophotos are from SWISSIMAGE.

2.2.2 ECV monitoring in high-alpine lakes

The AlpineWELLS-FOEN project provided for pressure, temperature and turbidity sensor systems in two glacier lakes, and for unmated pressure measurements in three other glacier lakes. The two main monitoring sites were chosen according to a good accessibility, a similar and relatively large size, and to represent both, a lake that is still in the process of formation and in contact with the glacier, and one whose formation was recently completed. We selected Lake Rhone (VS) and Steisee (BE) near Sustenpass as respective sites. We furthermore installed a pressure sensor in Lake Vadret (GR), the largest natural glacier lake in Switzerland (Figure 2). While deploying these sensors, we acquire ground reference measurements of LWLR using a WISP-3 spectroradiometer (Hommersom et al., 2012), and we perform bathymetry surveys using a single-beam sonar on a Hydrone catamaran by Seafloor Systems Inc., Shingle Springs CA, United States (see front page).

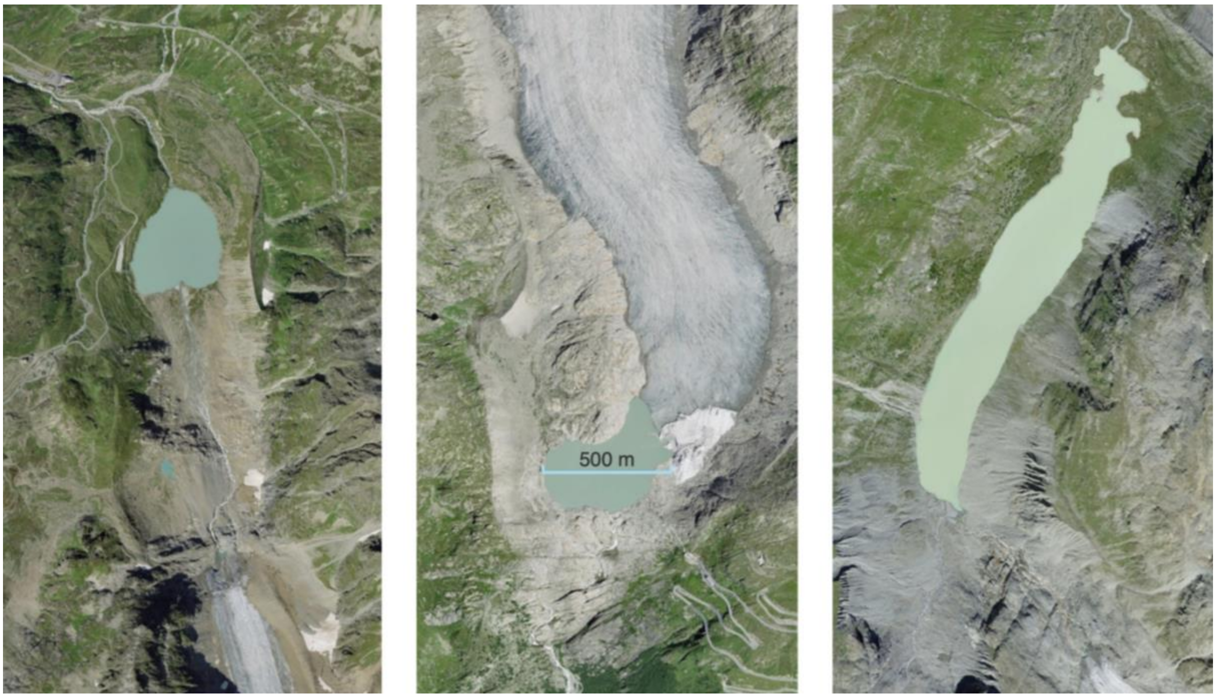

Figure 2: SWISSIMAGE true-colour images of the three AlpineWELLS test sites Steisee (BE, right), Lake Rhone (VS, center) and Lake Vadret (GR, right). All images are to scale.

The monitoring sensor systems for use in the AlpineWELLS-FOEN project was designed in close collaboration with the FOEN project *Temperaturmonitoring in Schweizer Seen* (PI Martin Schmid, Eawag), which aims to establish a monitoring framework for small lakes in Switzerland using in situ measurements and 1D simulations (www.simstrat.eawag.ch). Main requirements were that the sensor systems should allow, physically and functionally, year-round deployment, and long-term use with minimal degradation (e.g. sensor drift). We chose a simple and inexpensive setup with expensive, high-quality sensors by RBR Ltd. (Ottawa, Canada), namely RBR duo and solo sensors. The sensors are mounted on two types of buoyant moorings. The thermistor chains are deployed in the lakes' centres, while single turbidity and pressure sensors are deployed near the outflows and in easily accessible near-shore locations, respectively. The thermistor chains are installed with a weight and an acoustic releaser at the lower end, and a buoy at the upper end (Figure 3). The length of the chains is such that the buoy floats at around 2 m below the water surface in order to avoid damage from freezing.

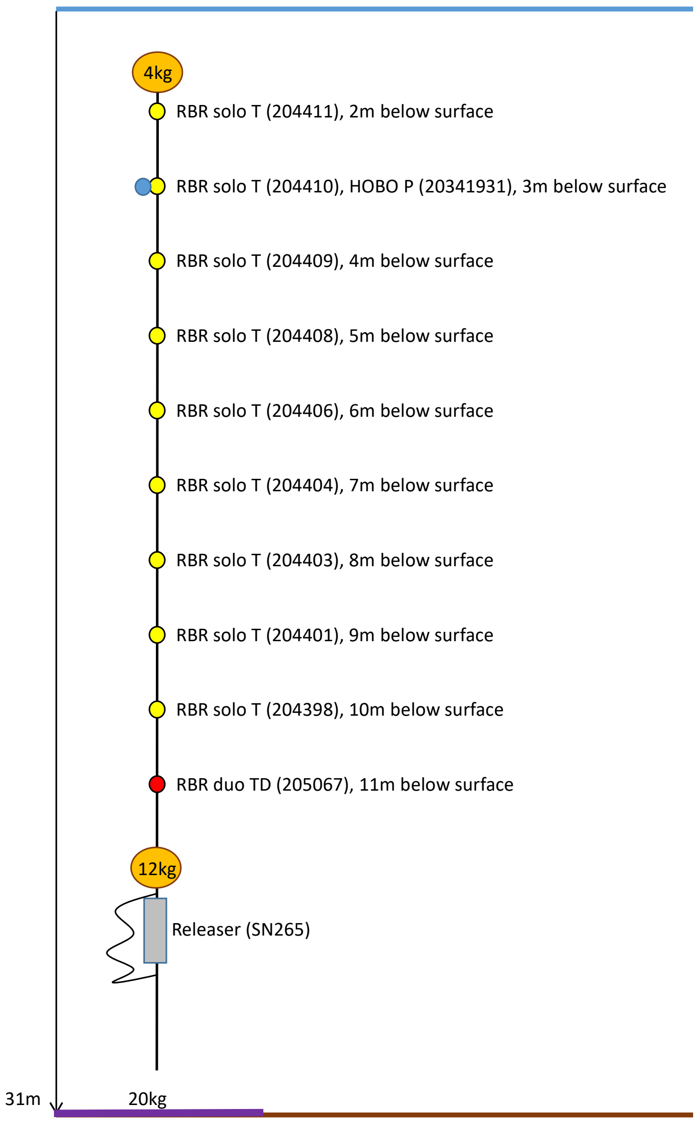

Figure 3: Thermistor chain schematic for Lake Rhone (VS). An analogous chain is deployed in Steisee (BE), but with RBR duo sensors at 2 and 4 m depth, which measure temperature and turbidity.

We reviewed different methods to retrieve ECVs from Sentinel-2 Earth observation data (Drusch et al., 2012). For LWLR retrieval we use Acolite (Vanhellemont and Ruddick, 2014) and C2RCC (Brockmann et al., 2016). We also use an arithmetic algorithm and LWLR from Acolite at 842 nm (Dogliotti et al., 2015) to retrieve turbidity. LSWT is also available from Acolite (Vanhellemont, 2020). Methods for LWE, LWL and LIC retrieval are currently in development.

2.3 Results

2.3.1 Swiss glacier lake inventory (summarized from Mölg et al., 2021)

In total, we identified 1192 lakes that formed in the area that has become deglaciated since the LIA (Figure 4). Of these, 987 still existed in 2016. Three of these lakes (Lake Theodulglacier VS, Bortelseewji VS, Griessee VS) formed naturally but were artificially dammed and enlarged for hydropower production. Twenty-four of these lakes are reservoirs without a naturally formed processor. They cover an area of around 8.5 km^2 and we disregarded them for further analysis apart from the generation of hazard parameters.

The lakes are well distributed over the whole glaciated area of Switzerland. Most lake area formed in the geographic regions with the most extensive LIA glaciation, namely the southwest (1.92 +/- 0.08 km^2), followed by the central northern Alps (1.33 +/- 0.04 km^2) and south-eastern Switzerland (1.18 +/- 0.05 km^2). In the northwest, almost 1.2% of the deglaciated area became lake surface, while the central Northern Alps showed with about 0.5% the lowest value.

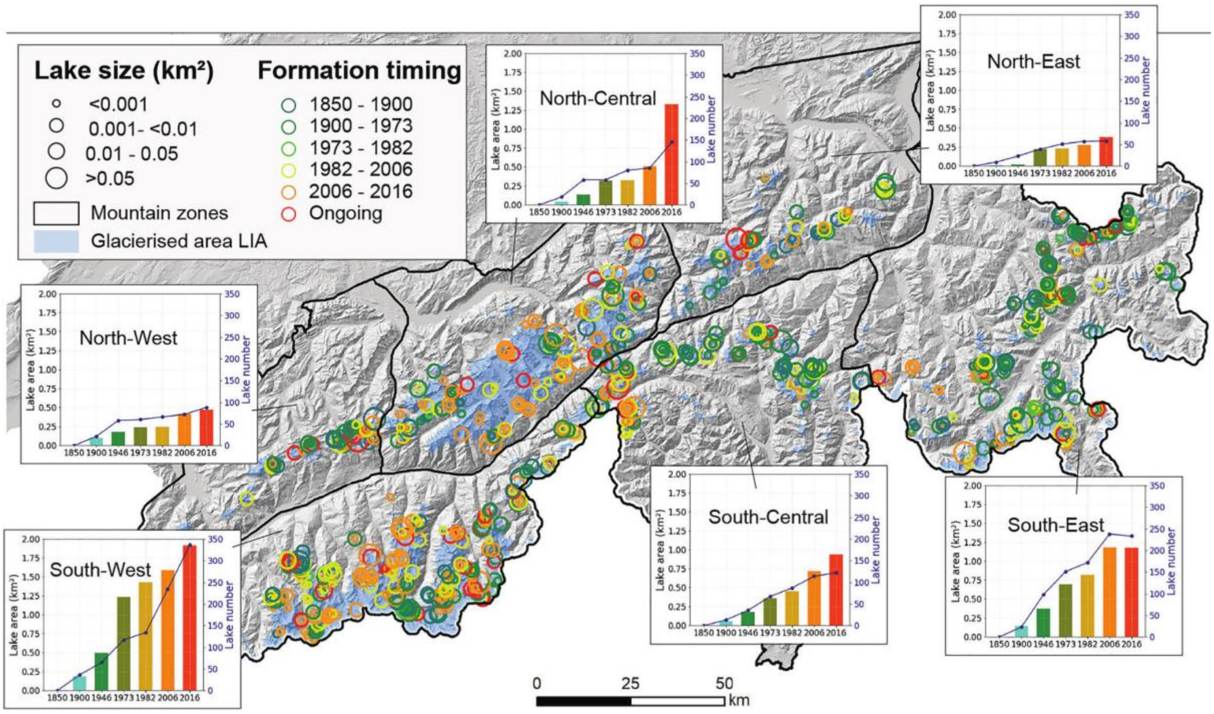

Figure 4: Lake size and formation timing (first appearance) for all lakes in the Swiss glacier lake inventory (from Mölg et al., 2021). Note that the time intervals are uneven, e.g. the 2016 period represents 10 years of lake formation, the 1900 period represents 50 years.

The total lake area in 2016, combining natural and artificially enlarged lakes, adds up to 6.22 +/- 0.25 km2. More than 90% of the lakes are smaller than 1 ha (Figure 5a-c). The medium elevation of lake formation is roughly 2600 m above sea level (a. s. l.), ranging from 1215 m to 3427 m in 2016 (Figure 5d). In 2016, 169 lakes were larger than 0.005 km2 (0.5 ha), 26 of these were ice-contact lakes. Ice-contact lakes are well distributed over the whole Swiss Alps, with a similar spatial distribution as the total lake area, showing that lakes form even in areas where only small glaciers are left.

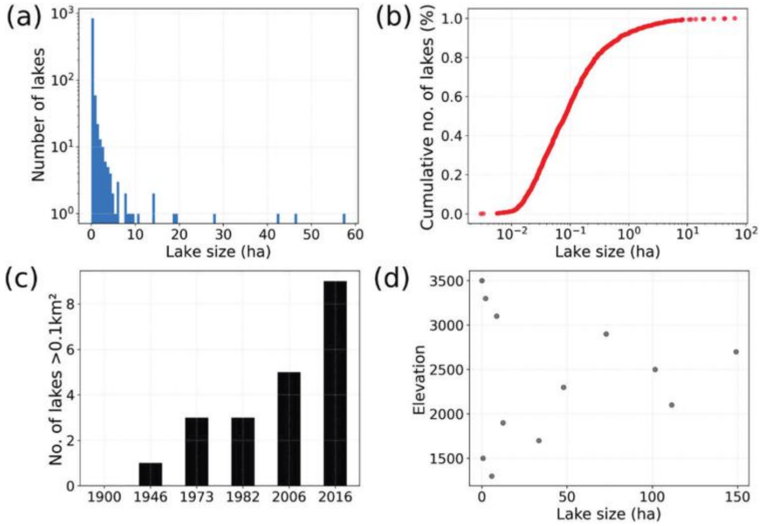

Figure 5 a): Lake size histogram (logarithmic scale on y-axis). b) Cumulative lake size distribution. c) Evolution of number of natural lakes larger than 10 ha. d) Cumulated lake area (ha; 2016) per 200 m elevation bin, starting at 1200– 1400 m (from Mölg et al., 2021).

2.3.2 ECV monitoring in high-alpine lakes

The 2021 GCOS Status Report (WMO, 2021) specifies a low (2), medium (3) and good (4) adequacy for small, medium and large lakes, respectively. It does not give a definition of these size classes. But the success stories, networks and databases that it mentions are limited to 100 (LWL and LWE in HYDROWEB), 250 (LIT, LSWT, LWL in HYDROLARE) or 253 lakes (LIC, LSWT, LWE, LWL, LWLR in ESA CCI), which can hence be considered as the large ones. It can be argued that these are the lakes that critically contribute to the Earth's climate.

However, there are roughly 182'000 and 24 million lakes in the world with an area larger than 1 km^2 and 1 ha, respectively (Verpoorter et al., 2014). Many of these lakes could be critically affected by the Earth's climate, e.g. if stratification cancels vertical mixing and causes anoxia (Woolway and Merchant, 2019). FOEN's interest to extend Switzerland's hydrometric network reflects the need for monitoring of smaller and elevated lakes. However, GCOS' lake ECV requirements are largely driven by the needs for large lakes and the system specifications of primarily oceanographic satellite sensors, such as medium resolution spectro- and thermal radiometers, or radar altimeters (Table 2). We here discuss alternative spatio-temporal resolution requirements for small glacier lakes. Corresponding uncertainty and stability requirements can be estimated in the future, based on in situ measurements that are currently being acquired in the AlpineWELLS-FOEN project.

Table 2: General lake ECV requirements (according to WMO, 2016), without those given specifically for large lakes. Spatio-temporal sampling requirements shaded in grey are not applicable for glacier lakes in Switzerland. Alternative approaches based on data with a higher spatial resolution are discussed below.

ECV	Frequency	Resolution	Uncertainty	Stability (per decade)
Lake Ice Cover (LIC)	daily	300 m	10%	1%
Lake Ice Thickness (LIT)	monthly	100 m	1-2 cm	n.a.
Lake Surface Water Temp. (LSWT)	weekly	300 m	1 K	0.1 K
Lake Water Extent (LWE)	daily	20 m	10%	5%
Lake Water Level (LWL)	daily	100 m	10 cm	1 cm
Lake Water-Leaving Reflectance (LWLR)	weekly	300 m	30%	1%

LIC has not been in the focus of AlpineWELLS, because two other projects on the subject were funded in the framework of GCOS Switzerland (e.g. Tom et al., 2020). However, by supervising the development of a high-resolution lake ice mapping application by an MSc student, we have obtained results that indicate that the combined use of Landsat satellites, Sentinel-1 and Sentinel-2 enables two to three day revisit times and 10 to 30 m resolution. Concerning uncertainty and stability, it seems worth reconsidering that ice-on and ice-off phenology metrics are more suited for small lakes than percent ice covered area.

LIT has also not been in the focus of AlpineWELLS, and it is hard to imagine it as a remotely sensed observable in the case of small glacier lakes. However, lake 1D hydrodynamic models such as Simstrat are capable to estimate black and white ice cover (Gaudard et al., 2019, Appendix B). Satellite-observed lake-ice phenology (LIC) could help to improve the accuracy of these estimates.

LSWT monitoring in small lakes requires a much better spatial resolution than used in current LSWT services for CCI or Copernicus. Currently, the best option is 100 m resolution by different Landsat sensors, whose use was previously demonstrated for small lakes (Schaeffer et al., 2018; Tavares et al., 2019; Vanhellemont, 2020). None of these studies are focused on high-alpine lakes, which we will make using the reference data described in Section 2.2.2 and the LSWT retrieval method by Vanhellemont (2020). It is worth noting that more 100 m thermal data from the newly launched Landsat-9 is about to become available, and 50 m resolution LSWT will be enabled by the TRISHNA mission (Lagouarde et al., 2018; see also Section 2.6). Other future thermal satellite missions that strongly improve high-resolution data availability include NASA’s Surface Biology and Geology (SBG) mission (60 m thermal bands, launch 2027; Cawse-Nicholson et al., 2021) and the Copernicus Land Surface Temperature Monitoring (LSTM) mission (50 m thermal bands, launch 2029; Koetz et al., 2018).

LWE monitoring in previously glaciated areas using machine learning-based classification algorithms was recently demonstrated for high-elevation (Wangchuk and Bolch, 2020) and high-latitude areas (Dirscherl et al., 2020; How et al., 2021). The temporal resolution of such applications is improved by the combined use of spectral features in high-resolution optical data (Zhang et al., 2020) and surface roughness signals in Synthetic Aperture Radar (SAR) data (Santoro et al., 2015). Currently the best satellite-based LWE for the Swiss Alps is available in the Global Surface Water Explorer (https://global-surface-water.appspot.com), which provides monthly water extent updates with a latency of more than one year and a spatial resolution of 30 m (Pekel et al., 2016). The same data is used for monitoring the Sustainable Development Goals’ target 6.6.1 (https://www.sdg661.app/), but it is not meant to meet specific requirements for high-alpine areas. We are therefore currently developing an algorithm to estimate the dynamics of high-alpine lake extent (https://alpglacier.geo.uzh.ch/, see Section 2.6).

LWL can be retrieved accurately from spaceborne radar altimeter data. The latest generation of these altimeters use a SAR sampling technique, and they are available e.g. on CryoSat-2 (Villadsen et al., 2016) or on Sentinel-3A/B (Kittel et al., 2021). However, with footprint diameters of roughly 300 m and a scattered sampling pattern, these altimeters are, likely with a few exceptions, not applicable for Swiss glacier lakes. Alternatively, LWL can be estimated using LWE and Digital Elevation Models (Penton and Overton, 2007). However, we expect that LWE in most glacier lakes are smaller than single Sentinel-1 or Sentinel-2 pixels, which strongly limits the potential of this approach in comparison to case studies for larger lakes (Zheng et al., 2016; Zhu et al., 2014).

LWLR, in other words the spectral aquatic reflectance obtained after atmospheric correction, is available from virtually all optical remote sensors and using a wide range of methods. A comprehensive overview of method performance for Sentinel-2 and Landsat-8 data is available from Pahlevan et al. (2021), and Landsat-8 LWLR was also validated for small reference datasets acquired in high-alpine lakes (Matta et al., 2017). The results suggest that LWLR retrieval in turbid glacier lakes can achieve a comparable accuracy like in large, clear lakes, where adjacency effects from surrounding land surfaces are smaller, but most at-sensor radiance origins from atmospheric backscattering while aquatic backscattering is a rather faint background signal. First results acquired in the AlpineWELLS-FOEN project on Lake Rhone (e.g. Figure 6) confirm this potential.

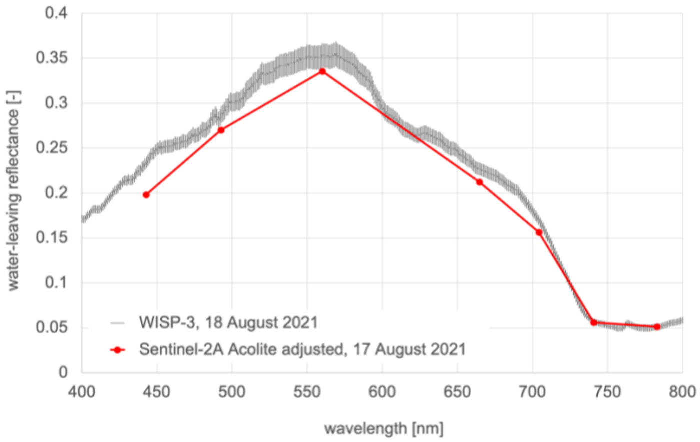

Figure 6: Hyperspectral LWLR measured in Lake Rhone, 18 August 2021, as mean and variance in grey. The red line indicates Acolite-corrected Sentinel-2A LWLR for an image acquired on 17 August 2021.

Over all, there seems to be a large potential to retrieve ECVs in Swiss glacier lakes at an accuracy and adequacy that allows monitoring these lakes' evolution in combination with simple 1D model simulations, but adjusted requirements are needed to specify this use case.

2.4 Conclusions and limitations

The Swiss glacier lake inventory is the first to feature consolidated glacier lake formation observations for the Swiss Alps, and it demonstrated our limitations in predicting lake formation. Linsbauer et al. (2012) predicted the formation of up to 166 lakes larger than 1 ha in the period between 1973-2016. Only 90 of them (56%) actually formed, most of which remained smaller than 1 ha. On the other hand, we mapped a total 216 new lakes in the same period, whereof 74% are smaller than 1 ha.

Our review of ECV monitoring techniques for glacier lakes in Switzerland and globally revealed that the gap between current ECV monitoring requirements and state-of-the art monitoring techniques is large. But for most parameters, promising Earth observation applications for glacier lakes could be built when either target-specific requirements are defined (LIC, LWLR), improved algorithms and future satellite missions become operational (LWE, LSWT) or integrated use with models was realized (LIT).

The project implementation was mostly according to plan. Minor deviations occurred due to changes in data availability (see Section 2.2.1), staff composition (see Section 2.7) and the emergence of two other, closely related projects (see Section 2.6). The main consequence is that we will continue to investigate ECV monitoring in glacier lakes, and we will continue to benefit from accomplishments made in the AlpineWELLS project funded in the framework of GCOS Switzerland.

2.5 Outreach work, publication of data and results

2.5.1 General public

The project was on display on the EAWAG and MeteoSwiss websites.

A press release related to the Swiss glacial lake inventory was forwarded by several press agencies and published by hundreds of communication channels, mostly online news sites but also Swiss newspapers and radio channels.

RSI produced an interview and news report (https://www.rsi.ch/play/tv/redirect/detail/14279853).

France24 produced a portrait video during our 2021 field work on Steisee BE (https://f24.my/85j0).

2.5.2 Conference contributions

Mölg, N., Huggel, C., Herold, T., Storck, F., and Odermatt, D.: Swiss-wide post-Little Ice Age glacial lake evolution. Poster presentation at the Swiss Geoscience Meeting 2020, online, 6-7 November 2020.

Mölg, N., Huggel, C., Herold, T., Storck, F., Allen, S., Haeberli, W., Schaub, Y., and Odermatt, D.: Inventory and genesis of glacial lakes in Switzerland since the Little Ice Age. Oral presentation at the EGU General Assembly 2021, online, 19-30 April 2021, https://doi.org/10.5194/egusphere-egu21-12144.

Naegeli, K., D. Odermatt: Thermal remote sensing in rugged terrain – monitoring the high-alpine cryo- and hydrosphere. Abstract submitted to the TRISHNA Days Workshop, Toulouse (France), 22-24 March 2022.

Tom, M., M. Santoro, D. Odermatt, H. Frey: Glacial lake water extent mapping from space. Abstract submitted to the ESA Living Planet Symposium, Bonn (Germany), 23-27 May 2022.

Tom, M., H. Frey, D. Odermatt: A deep learning approach for mapping and monitoring glacial lakes from space. Abstract submitted to EGU, Vienna (Austria), 23-27 May 2022.

2.5.3 Scientific publications

Mölg, N., Huggel, C., Herold, T., Storck, F., Allen, S., Haeberli, W., Schaub, Y., and Odermatt, D. (2021a). Inventory and evolution of glacial lakes since the Little Ice Age: Lessons from the case of Switzerland. Earth Surf. Process. Landf. 1–14, https://doi.org/10.1002/esp.5193.

Mölg, N., Allen, S., and Odermatt, D. (2021b): Inventory and evolution of glacial lakes in Switzerland since the Little Ice Age. PANGAEA, https://doi.org/10.1594/PANGAEA.934190.

Odermatt, D., Tom, M., Frey, H., Brechbühler, M., Wulf, H., Irani Rahaghi, A. F., Rünzi, P., and Mölg, N. (in preparation). Monitoring essential climate variables for glacier lakes.

2.6 Outlook

The abovementioned AlpineWELLS-FOEN project will continue until 2024. In the end, we will have measured of up to three parameters (pressure, temperature, turbidity) in three lakes (Lake Rhone VS, Steisee BE, Lake Vadret GR) during two to three years. This dataset will be key for the design of continued ECV monitoring activities in glacier lakes, by FOEN on one hand, and the Eawag Remote Sensing Research group on the other hand. We will furthermore perform a cost-benefit analysis to inform FOEN's long-term strategy concerning glacier lakes.

In the case of LWE (and eventually LWL) retrieval, we are currently developing a dedicated glacier lake mapping algorithm for Sentinel-1 and Sentinel-2 in the scope of an ESA project lead by the University of Zurich (AlpGlacier, 2021-2022, PI F. Paul), and with reference to the Swiss glacier lake inventory. Using the results from this project, we aim to provide regularly updated (e.g. 10 day) glacier lake extent information for Switzerland. We also consider integrating LIC phenology as a side product, based on results from the corresponding projects by ETHZ in the framework of GCOS Switzerland on one hand, and on an ongoing MSc thesis at the University of Zurich (supervision: Hendrik Wulf, Daniel Odermatt) on the other hand.

The potential for LSWT retrieval in small lakes will strongly improve with the launch of the French-Indian TRISHNA satellite mission, which is planned in 2024 with an unparalleled spatial resolution of 50 m. Together with the University of Zurich, Eawag is involved in a six-year ESA Prodex project named TRISHNA Science and Electronics Contribution (T-SEC). This project supports a new group which is specializing in thermal remote sensing under the lead of Kathrin Nägeli. Specifically for glacier lakes, it provides for a 2-year postdoc position in 2023-2024.

Further objectives should evaluate different use cases for glacier lake ECVs, e.g. the evolution of particle input, light availability and biological activity with reference to stages of deglaciation, or the estimation of future lake aggradation based on volume and particle input.

2.7 Acknowledgements

I would like to express my sincere thanks to Nico Mölg, who played a key role in planning the project and enriched it with an exceptional study. I was pleased that he was able to celebrate a wonderful new addition to his family at the same time and very much regretted his departure from the project. I would like to thank Manu Tom and Holger Frey for their successful, ongoing collaboration. I would also like to thank all the co-authors for their scientific contribution, and MeteoSwiss and FOEN for their financial support and funding for the two AlpineWELLS projects.

2.8 References

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