Revised Strategy for Monitoring Glacier Length Variation

1. Introduction

Measurements of glacier length variations are the longest continuous observations documenting glacier fluctuations in the Swiss Alps and cover the last 140 years (GLAMOS, 2018). Due to coordinated and systematic monitoring activities since 1880, a large dataset of glacier length variations has been acquired. Fluctuations at the glacier terminus are the result of the dynamic response of the glacier to external climatic forcing. Glacier length variations typically show a filtered and delayed response and often are difficult to be interpreted in relation to individual climatological parameters. Some of the more than 100 long-term series that are presently in the network have a limited value as they are affected by data gaps. Furthermore, systematic errors connected to the applied observational strategy can be present and a careful re-analysis is thus required. In addition, some series of glacier length variation lack geo-localisation, which makes it challenging to relate them to other information and applications in glaciological research. Due to climate change and substantial retreat of glacier termini, several long-term measurements are faced with problems when the glacier snout retreats into inaccessible terrain, and/or the increasing debris coverage hinders the determination of the glacier boundary. New measurement techniques (e.g. remote sensing) and datasets (e.g.data-products of swisstopo), as well as higher requirements for data quality indicate a pressing need for adaptation of the presently applied monitoring strategy for glacier length variation in Glacier Monitoring Switzerland (GLAMOS). This document is a synthesis that resulted from a workshop of the GLAMOS scientific committee on 21 May 2019 and the assessment performed within the GLAMOS Office.

2. Present status

2.1. Observational network

Observations of glacier length variations since 1880 have been documented for about 160 glaciers in Switzerland (GLAMOS, 1986). On a subset of about 120 glaciers systematic, continuous annual measurements have been carried out (Fig. 1). Measurements are presently continued on 100 glaciers, while eight series are interrupted, and seven series have been abandoned, mainly because of the nearly complete disintegration of the glaciers. A few glaciers are observed only sporadically and at irregular intervals. Since the beginning of coordinated and systematic annual monitoring, the surveys are carried out by a collaborative network of people of the cantonal forestry departments, universities and private collaborators. At present, GLAMOS uses annual aerial photographs to determine length variation for 19 glaciers, while for all other glaciers field surveys are carried out. The present network for measuring glacier length variations aims at covering all regions of Switzerland and different glacier types (size, shape, hypsography, etc.).

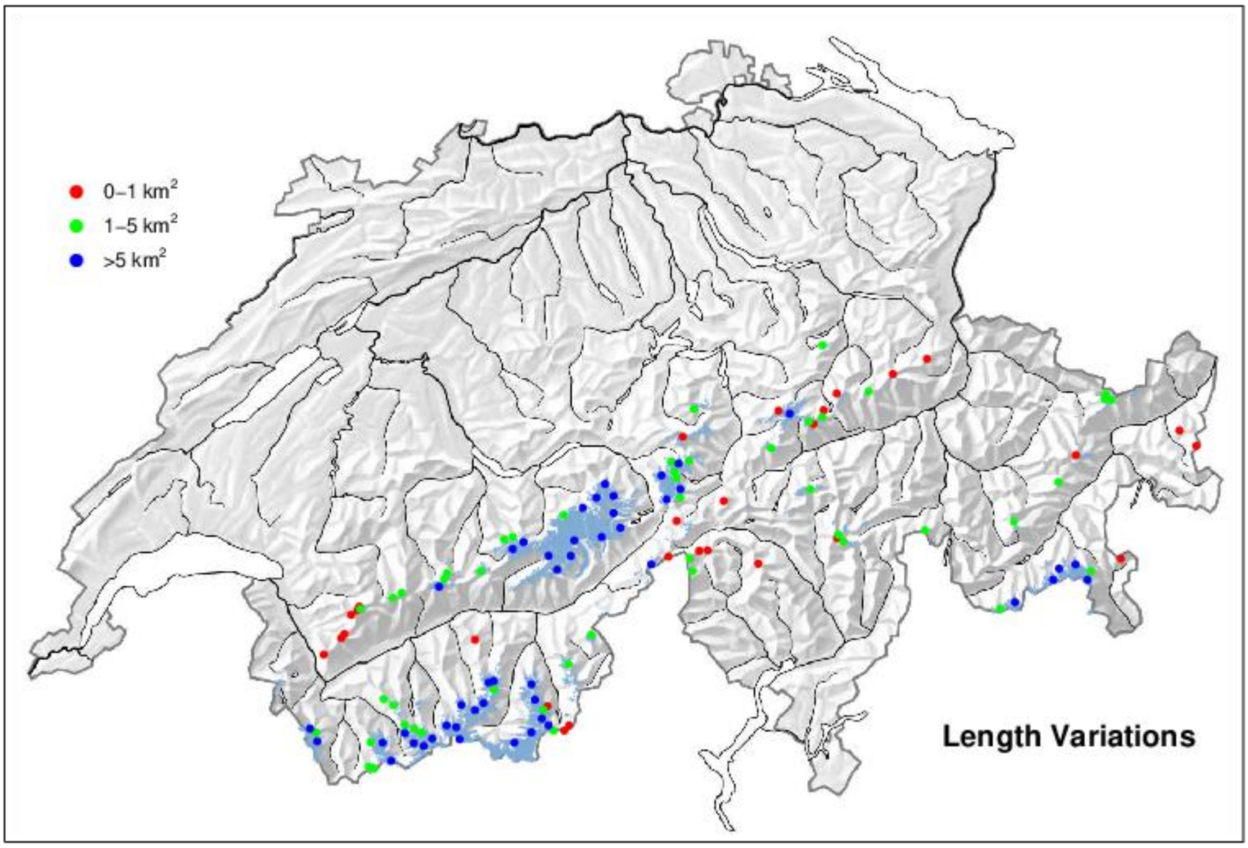

Figure 1: Glaciers presently investigated for length variations by GLAMOS. Glaciers are classified in terms of their surface area.

2.2. Data acquisition methods

First guidelines what and how to monitor glacier evolution were addressed to mountaineers who visited the glaciers in late 19th century (Gletscherkollegium, 1872). Since the beginning of the systematic annual surveys in 1880 a procedure has been established that was based on simple techniques with tape measurement relative to local reference points maintained in the glacier forefield. The advantage was that such measurements could be carried out by collaborators with only limited education and hardware resources available. This was a key factor for the success of the extensive monitoring programme of glacier length variation in Switzerland. The general procedure with field measurements and data evaluation is summarized by Kasser (1976). Already in the early years of the monitoring network, some more advanced techniques based on cartography and surveying were applied on selected glaciers (e.g. Rhonegletscher, see Mercanton, 1915). In more recent years, the traditional tape measurements have mostly been replaced by modern GPS techniques. In cases of difficult access to the glacier terminus, distance meters were used as well. Since the 1960s aerial photographs have been routinely acquired for the production and updates of topographical maps by swisstopo. Special annual surveys of aerial photographs have been started in the 1970s for selected glaciers and were also used to evaluate the change in glacier terminus position. There are some significant disadvantages of the traditional in-situ measuring procedure: Data evaluation is prone to systematic errors. For example, results may depend on the choice of number and location of local reference points. Furthermore, in most cases no correction of true three-dimensional length to the horizontal map plane later used for comparison has been made. Finally, summation of incremental changes may result in the propagation of errors leading to large deviations to the true nature. In addition, often only relative changes have been reported without any reference to geo-location. Only since the 1960s field notes have been collected that contain some information on used reference points.

2.3. Documented length variation

Thanks to the effort of glacier monitoring since the end of the 19th century an extensive data set of glacier length variations has been assembled. Time series for over 100 glaciers in Switzerland exist (Fig. 2).

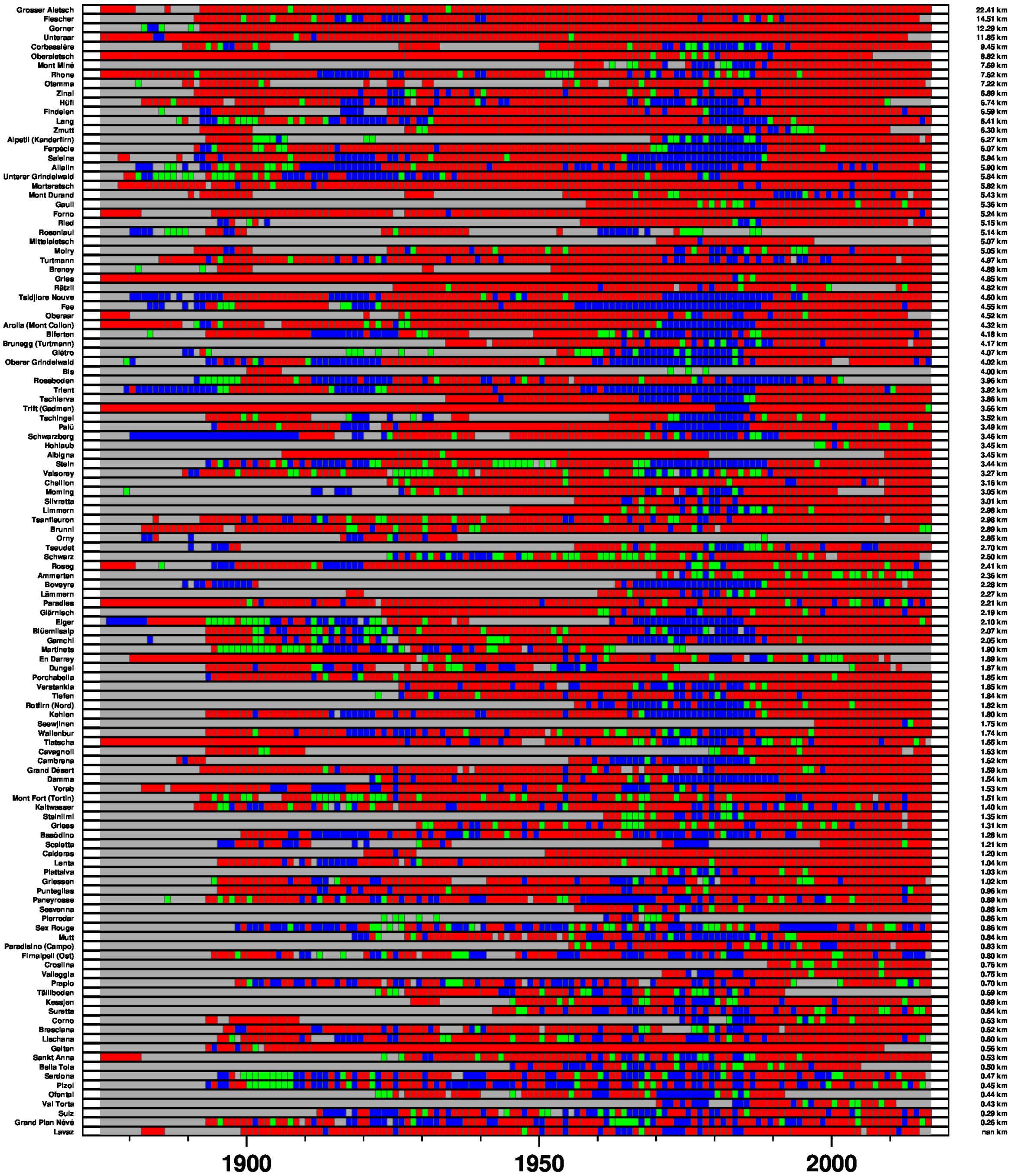

Figure 2: Temporal coverage of the entire length variation data set. Individual glaciers are arranged in descending order regarding their present total length. Red colours indicate retreat, blue advance, and green stationary conditions. Time-transient coverage of annual or multi-annual measurement periods, as well as data gaps are visible.

In a recent study, supported by MeteoSwiss in the frame of GCOS Switzerland, the available time series of length variations have been assessed for systematic biases and data gaps by collecting geo-referenced glacier states (Bauder, 2018). Time series of 118 glaciers with 9’600 individual field measurements were considered and 2’550 georeferenced states have been reconstructed. This assessment revealed 48 uninterrupted series and 25 with only a few short gaps covering a period of more than 100 years. For another about 20 glaciers, uninterrupted time series start before 1950. Based on a systematic procedure the length variation has been re-evaluated and inconsistency and gaps can now be eliminated for more than 100 time series that are still actively surveyed.

All length variation records were rated based on the length of the time series, data gaps and data quality resulting in an attribution of priority for each individual series:

- **Priority 1:** Long and continuous series (start *before* 1925) – presently 73 glaciers
- **Priority 2:** Short but continuous series (start *after* 1925) – 28 glaciers
- **Priority 3:** Series still actively observed (long/short) but discontinuous / data gaps – 14 glaciers
- **Priority 4:** Measurements discontinued (different quality long/short/data gaps) – 6 glaciers

In addition, historic field observations have been reported for another 35 glaciers, but have not been rated because only sporadic measurements or short series before 1950 exist. The rating serves as the basis for further analysis and is used, for example, for GLAMOS publications (GLAMOS, 2018). The rating of the series of glacier length variation also represents an important indicator for deciding on a potential continuation of the observations in the medium to long term. A regular re-assessment of the priority class is required related to the rapid changes due to atmospheric warming.

3. Monitoring strategy

The systematic survey of glacier front variations in the 1880s was originally initiated to document and improve the understanding of glacier fluctuations and their relation to climate. The observation of length variation became one of the major parameters of Swiss glacier monitoring. The general concept of GLAMOS was reviewed in 2002 by the Swiss Academy of Sciences (SCNAT) and the ongoing monitoring programme has been adopted by the Cryospheric Commission (EKK) in March 2007 (see chapter 1.1 in GLAMOS, 2009). The GLAMOS monitoring objectives are in accordance with international principles of environmental monitoring (e.g. GCOS, 2016) and the results contribute to the international efforts coordinated by World Glacier Monitoring Service (WGMS). In order to ensure an optimal data quality and use of available resources, the aims and requirements as well as methods and techniques are periodically re-evaluated.

3.1. Goals of observation

Glacier length variations are key indicators of glacier evolution as they represent the results of the complex and interlinked processes of climate, mass balance, ice-flow dynamics and the response of glacier geometry. Time series of glacier length variation are relevant for both the scientific community, as well as the broader public, as they are a very clear and easily understandable signal of climatic change. A revised monitoring strategy should thus have the following main goals:

- Documentation of glacier length variations as a valuable indicator of climate change.
- Continuation of existing measurement series, because only continuous and long-term series provide relevant information on the response of glaciers to climate change.
- Establish a consistent and reproducible measurement and data evaluation methodology with periodical quality checks.
- Improve data quality by evaluation of new measurement techniques and subsequent integration into the programme.

3.2. Present framework and requirements

The acquisition of length variation observations in the past relied on a network of collaborators having different backgrounds and interests. This concept indicated a large potential and was of great success as is demonstrated by the exceptional continuity of the series that have been acquired. We have evaluated the past observations of glacier length variation regarding different aspects. Based on this assessment the following principles for future observations and continuation of the data series have been defined:

1. The network should rely on a representative sample of various glacier types and should cover all regions of the Swiss Alps.
2. Only geo-localised measurements should be performed.
3. Consideration of a reduction of the number of surveyed glaciers and/or the periodicity of the observations (annual or multi-annual) in order to improve efficiency and reduce costs.
4. Complementing or replacement of field observations by remote sensing (aerial photographs).
5. Periodic re-analysis and homogenisation of field measurements is necessary to avoid any inconsistencies in the data set and biases due to systematic errors.
6. The acquisition of additional meta-information (photographs, natural hazard potential) is highly important and requires periodical in-situ field visits by the observers and is not fully replaceable by remote sensing.

A considerable potential for an enhanced data acquisition is attributed to the operational production of the swissTLM^{3D} by swisstopo that is updated in a 6-year cycle with outlines for each glacier. First tests using the swissTLM^{3D} have shown that the product is very useful to glaciological application and a comprehensive strategy of data exchange with swisstopo has been set up by GLAMOS during the last years. In addition, swisstopo acquires aerial image surveys every three years for all regions of Switzerland. Glacier outlines are not routinely evaluated for every acquired image by swisstopo but the additional imagery permits evaluating additional states of the glacier's terminus position by GLAMOS, hence, allowing shortening the periodicity of the remote observations of glacier length variation, potentially for all relevant glaciers.

Ongoing glacier retreat will have (and in some cases already has) an important impact on future data acquisition. Small glaciers are expected to disappear completely in the near future, which will hamper a balanced selection of glaciers across all regions of Switzerland. Also, the retreat rate is strongly affected by an increase in debris coverage on several glaciers in the network. This makes the identification of the ice margin difficult, both during field surveys and the analysis of aerial photographs. Therefore a combination of approaches (field surveys and remote sensing) is crucial to improve the accuracy of the observations of glacier length variation.

The monitoring of the parameter *glacier length variation* is expected to undergo a significant change with the consistent collection of geo-referenced data. This results in a shift from simple length variations to a full documentation of glacier outlines. Such data is essential for a wide range of scientific analysis as it allows a full re-evaluation of glacier length variation at a later stage, e.g. in the case of a change in the definition of length variation, or if an evaluation for a specific application is needed.

4. Implementation

We have defined **five observation types**, ranging from direct field observations, aerial imagery to the operational swissTLM3D product by swisstopo, for documenting glacier length variation. All considered approaches are have their advantages and disadvantages and strongly differ regarding annual workload and cost. In a comprehensive assessment for each of the 121 glaciers in the present observational network of GLAMOS we have attributed one of the five observation types based on the following criteria:

1. priority of measurement series (defined based on time series length and data quality),
2. availability of annual aerial photographs (“Spezialbefliegungen”) within the current programme,
3. accessibility of the glacier / obstacles for conducting *in-situ* observations.

The present monitoring strategy for glacier length variation as well as potential modifications were discussed at a GLAMOS Scientific Committee Meeting on 21 May 2019. The discussion highlighted the various needs of the different actors in the collaborative network of investigators. Therefore, further bilateral consultation between the collaborators and the GLAMOS Office is necessary during full implementation of the envisaged modified observation strategy in order to achieve full consensus for the selection of observational methods attributed to each individual glacier. With the future changes in earth observation, new options might become available and observation types might be further adapted.

4.1. Data acquisition strategy

The following five observation types for acquiring measurements of glacier length variation were defined. They are outlined below including their pros and cons as well as estimated costs:

FIELD: Annual (or in some cases multi-annual) surveys in the field using surveying techniques that provide geo-referenced data (mainly GNSS and theodolite, or electronic distance meter).

> **Pro:** Traditional method, optimal continuity, high accuracy (no remote interpretation), acquisition of meta-information (e.g. image documentation, natural hazards), only minimal post-processing and timely availability of results
> **Contra:** Relatively expensive, inhomogeneous data acquisition (different observers and instrumentation), and thus partly large effort in data evaluation and training, inaccessibility of glacier tongues due to climate change
> **Cost per glacier:** 350 CHF per year

AIR: Photogrammetrical analysis of aerial photographs acquired on an annual basis within the current programme.

> **Pro:** Annual resolution, complete spatial coverage, high accuracy, homogeneous data evaluation glaciers with difficult field-site access can be covered
> **Contra:** GLAMOS relies on the acquisition and photogrammetrical processing of the images (financed by BAFU or third party), additional effort for data evaluation to be covered by GLAMOS, no field validation, delayed availability of results, relatively high costs, no meta-information (images, observations of potential hazard processes)
> **Cost per glacier:** 350 CHF per year

MIX: Combination of bi-annual field measurements (see above) and glacier outlines provided by swisstopo’s swissTLM^{3D} product. The TLM-product will provide a reference at a time interval of six years, as well as an independent validation of the field observations. The bi-annual in-situ surveys allow a higher temporal resolution. The timing of the field surveys should be coordinated with swisstopo’s aerial surveys.

> **Pro:** Reduced costs per glacier by 40%, ground-truth of FIELD-type complemented with homogeneous photogrammetrical data acquisition.
> **Contra:** Reduced time resolution from one to two years.
> **Cost per glacier:** 205 CHF per year

TLM: Use of glacier outlines provided by the swissTLM^{3D}-product of swisstopo acquired at 6-year intervals.

> **Pro:** Strongly reduced annual costs in comparison to FIELD (90%), AIR (90%) and MIX (85%), homogeneous data evaluation, glaciers with difficult accessibility can be covered, robust as it relies on fully operational data (swisstopo aerial images)
>
> **Contra:** Very low temporal resolution (6 years), photogrammetrical interpretation difficult for debris-covered glacier tongues, no ground-truthing (problematic if the glacier boundary is difficult to identify), no meta-information (images, observations of potential hazard processes), required intensive data processing outside of GLAMOS results in delayed availability of results
>
> **Cost per glacier:** 30 CHF per year

TLM+: Use of glacier outlines provided by the swissTLM^{3D}-product of swisstopo. Here, we intend using the 6-yearly evaluations by swisstopo but complement these by own evaluations based on aerial images acquired by swisstopo at 3-year intervals.

> **Pro:** Strongly reduced annual costs in comparison to FIELD (75%), AIR (75%) and MIX (55%), see TLM for additional advantages
>
> **Contra:** Low temporal resolution (3 years), additional image interpretation by the GLAMOS Office required, see TLM for additional disadvantages
>
> **Cost per glacier:** 90 CHF per year

We note that a balance of the different observation types throughout the network is important to achieve an optimal distribution of the advantages and disadvantages related to each approach. Re-assessing the observation method at regular intervals in the future is crucial, whereas the trend towards less field observations and more measurements based on aerial images shall be preserved.

According to the monitoring strategy proposed here, the observation types MIX, TLM and TLM+ are new, whereas FIELD and AIR have been applied before. The most important conceptual change refers to a shift from mainly annual to 2-year, 3-year or 6-year measurement intervals for about half of the monitored glaciers, resulting in a significant reduction of the overall costs for the length variation programme. Based on a consensus within the GLAMOS Scientific Committee, the annual temporal resolution is not strictly required for length variations, as the changes in the individual year are often not directly related to the weather conditions in the given year, and an immediate reporting (as for glacier mass balances) is thus not necessary. Table 1 summarizes the observation types attributed to each glacier envisaged for implementation and shows statistics on their frequency. A detailed list of all monitored glaciers, their priority within the network, and the observation method is provided in the Appendix.

Table 1: Summary of the methods (observation type) for measurements of glacier length variation and frequency statistics.

Observation type	Description	Number	Percentage
FIELD	Annual field surveys at glacier tongues (traditional approach)	**43**	**36%**
AIR	Annual evaluation of aerial images (“Spezialbefliegungen”) by GLAMOS	**19**	**16%**
MIX	Bi-annual field surveys at glacier tongues, complemented at 6-year intervals with swisstopo data (aerial images, TLM-outlines)	**22**	**18%**
TLM	Evaluation based on swisstopo data (aerial images, TLM-outlines) in 6-year intervals	**9**	**7%**
TLM+	Evaluation based on swisstopo data (aerial images, TLM-outlines) in 6-year intervals, and swisstopo aerial images evaluated by GLAMOS at 3-year intervals	**28**	**23%**
TOTAL		**121**	100%

4.2. Timing of implementation

The implementation of the adopted modifications will be gradual. This ensures continuous data acquisition avoiding data gaps. A reduction in periodicity can be implemented immediately while a change of the measurement technique requires taking into account the acquisition interval of swisstopo for the respective region. The completion of implementing all modifications proposed (see Appendix) is envisaged by the end of the GLAMOS funding period in 2023. The proposed classification will still need to be refined in order to achieve maximal effect and meet individual needs of all local collaborators.

The current modifications after complete Implementation envisaged by 2023 contribute to an overall cost reduction of 17% for the variable *glacier length variation* relative to the last GLAMOS funding period (2016-19). In the coming decade, we expect further shifts in the observation methods towards even less in-situ measurements but a higher share of operational swisstopo data (swiss TLM^{3D}), as well as an overall decrease of the number of glaciers in the network (e.g. due to climate change) likely leading to a further cost reduction.

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Appendix

Detailed list with the period and number of available observations of all glacier in the network, the priority rating and the assigned observational method of individual series to be implemented during the GLAMOS funding period 2020-23:

Glacier	Period	Observations	Priority	Type	Costs (CHF/year)
Allalin	1881-2018	123	1	AIR	350
Arolla	1856-2018	124	1	FIELD	350
Basòdino	1899-2018	92	1	FIELD	350
Biferten	1893-2018	79	1	FIELD	350
Blüemlisalp	1893-2018	110	1	TLM+	90
Bresciana	1896-2018	87	1	FIELD	350
Brunni	1882-2018	97	1	FIELD	350
Cheillon	1924-2018	88	1	FIELD	350
Chelen	1893-2018	116	1	FIELD	350
Damma	1921-2018	87	1	MIX	205
En Darrey	1880-2018	67	1	MIX	205
Fee	1883-2018	108	1	TLM+	90
Ferpècle	1891-2018	120	1	FIELD	350
Fiescher	1891-2015	119	1	TLM+	90
Findelen	1885-2018	90	1	AIR	350
Firnalpeli	1894-2018	78	1	FIELD	350
Forno	1857-2018	108	1	FIELD	350
Gamchi	1883-2018	112	1	FIELD	350
Glärnisch	1923-2018	69	1	FIELD	350
Gorner	1882-2018	121	1	AIR	350
Grand Désert	1892-2018	117	1	FIELD	350
Grand Plan Névé	1893-2018	101	1	FIELD	350
Gries	1847-2018	60	1	AIR	350
Griess	1929-2018	79	1	MIX	205
Griessen	1894-2018	82	1	FIELD	350
Grosser Aletsch	1870-2018	127	1	AIR	350
Hüfi	1882-2010	117	1	TLM+	90
Kaltwasser	1891-2018	111	1	FIELD	350
Lang	1888-2017	117	1	MIX	205
Lavaz	1882-2018	88	1	MIX	205
Lenta	1895-2018	102	1	TLM+	90
Lischana	1895-2016	89	1	MIX	205
Moiry	1891-2018	101	1	FIELD	350
Moming	1911-2017	79	1	TLM+	90
Mont Fort	1892-2018	112	1	FIELD	350
Morteratsch	1878-2018	131	1	FIELD	350
Mutt	1918-2018	74	1	FIELD	350
Oberaar	1926-2013	79	1	AIR	350
Oberaletsch	1870-2007	39	1	TLM+	90
Oberer Grindelwald	1893-2018	103	1	AIR	350
Palü	1894-2018	84	1	FIELD	350
Paneyrosse	1886-2018	95	1	FIELD	350
Paradies	1873-2018	108	1	FIELD	350
Pizol	1893-2018	103	1	FIELD	350
Porchabella	1893-2018	109	1	FIELD	350
Punteglias	1895-2018	108	1	MIX	205
Rätzli (Plaine Morte)	1925-2018	69	1	AIR	350

Rhone	1879-2018	137	1	AIR	350
Roseg	1855-2018	112	1	TLM+	90
Rossboden	1891-2002	109	1	TLM+	90
Saleina	1878-2018	125	1	FIELD	350
Sankt Anna	1926-2018	82	1	FIELD	350
Sardona	1895-2018	102	1	FIELD	350
Schwarz	1924-2015	83	1	TLM+	90
Schwarzberg	1880-2018	86	1	AIR	350
Sex Rouge	1898-2018	93	1	MIX	205
Stein	1893-2018	122	1	FIELD	350
Sulz	1912-2018	83	1	FIELD	350
Tiatscha	1926-2016	78	1	AIR	350
Tiefen	1926-2018	88	1	FIELD	350
Trient	1879-2018	137	1	FIELD	350
Trift	1861-2018	26	1	AIR	350
Tsanfleuron	1892-2018	118	1	FIELD	350
Tsidjiore Nouve	1880-2018	125	1	FIELD	350
Turtmann	1885-2018	120	1	FIELD	350
Unteraar	1876-2013	117	1	AIR	350
Unterer Grindelwald	1879-2018	105	1	AIR	350
Valsorey	1889-2018	119	1	FIELD	350
Verstankla	1926-2018	80	1	AIR	350
Vorab	1882-2018	89	1	MIX	205
Wallenbur	1893-2018	110	1	FIELD	350
Zinal	1891-2018	123	1	MIX	205
Zmutt	1892-2010	62	1	TLM	30
Alpetli (Kander)	1969-2018	48	2	FIELD	350
Ammerten	1970-2018	47	2	FIELD	350
Bella Tola	1945-2005	56	2	TLM	30
Boveyre	1963-2018	46	2	MIX	205
Brunegg	1934-2018	71	2	MIX	205
Calderas	1920-2018	70	2	FIELD	350
Cambrena	1953-2018	54	2	TLM+	90
Cavagnoli	1979-2018	36	2	MIX	205
Chessjen	1945-2018	60	2	AIR	350
Croslina	1989-2018	26	2	MIX	205
Gauli	1958-2018	55	2	MIX	205
Hohlaub	1997-2018	20	2	AIR	350
Lämmern	1960-2018	58	2	MIX	205
Limmern	1945-2018	53	2	MIX	205
Mittelaletsch	1970-1997	19	2	TLM+	90
Mont Miné	1956-2018	53	2	TLM+	90
Paradisino	1955-2018	47	2	TLM+	90
Plattalva	1969-2018	41	2	TLM+	90
Ried	1957-2018	56	2	MIX	205
Rotfirn	1956-2017	58	2	TLM+	90
Seewjinen	1997-2018	19	2	AIR	350
Sesvenna	1956-2018	58	2	FIELD	350
Silvretta	1956-2018	58	2	AIR	350
Steinlimmi	1961-2018	55	2	TLM+	90
Suretta	1942-2018	70	2	TLM+	90
Tschierva	1934-2018	72	2	FIELD	350
Tseudet	1956-2018	56	2	FIELD	350
Valleggia	1971-2018	37	2	TLM+	90
Albigna	1906-2018	20	3	MIX	205
Breney	1895-2018	69	3	TLM+	90

Corbassière	1889-2017	79	3	**TLM+**	**90**
Corno	1893-2018	43	3	**MIX**	**205**
Dungel	1893-2012	51	3	**TLM+**	**90**
Eiger	1876-2018	93	3	**TLM+**	**90**
Gelten	1893-2009	19	3	**TLM+**	**90**
Gietro	1889-2017	66	3	**TLM+**	**90**
Mont Durand	1890-2018	69	3	**TLM+**	**90**
Otemma	1889-2016	73	3	**TLM+**	**90**
Prapio	1898-2018	94	3	**MIX**	**205**
Scaletta	1895-2018	36	3	**TLM+**	**90**
Tschingel	1893-2018	69	3	**MIX**	**205**
Val Torta	1970-2011	30	3	TLM	**30**
Bis	1900-1979	7	4	TLM	**30**
Martinets	1894-1975	59	4	TLM	**30**
Ofental	1922-1992	45	4	TLM	**30**
Orny	1882-1989	21	4	TLM	**30**
Rosenlaui	1880-1988	41	4	TLM	**30**
Tälliboden	1922-1992	55	4	TLM	**30**