Quantifying the overall effect of artificial glacier melt reduction in Switzerland, 2005–2019

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1. Introduction

Due to the effect of more frequent summer heat waves (Fischer and Schär, 2010), glacier mass loss has seen a fast acceleration in the Alps over the last decades (Beniston et al., 2018; Zemp et al., 2015; Zemp et al., 2019). Besides the significance of glaciers both as a symbol for climate change and a healthy mountain environment, they are an economic factor as they are highly attractive to tourists, and as their retreat hampers the operability and profitability of glacier ski resorts across the European Alps (Diolaiuti et al., 2006; Fischer et al., 2011, 2016). For this reason, considerable efforts have been undertaken since the early 2000s to develop approaches to artificially slow down the melting of snow and ice in order to maintain glacier surface elevation where needed (e.g., Olefs and Fischer, 2008; Senese et al., 2020). In a few glacier ski resorts, artificial snow production, also in combination with snow farming is applied to facilitate operability into the summer and to reduce glacier melt rates (Pelto, 2009; Grünwald et al., 2018). Covering the glacier surface with white geotextiles has become increasingly widespread in recent years as an efficient technique to locally reduce ice melt, and the approach has been scientifically studied in detail (e.g., Olefs and Obleitner, 2007; Olefs and Lehning, 2010; Fischer et al., 2016). These assessments mostly focused on the local scale and emphasized on the physical processes of artificial glacier melt reduction, and less on the cost-effectiveness and the scalability of the approaches. The public discussion of glacier wastage is now also directed towards the saving of whole glaciers by technological solutions (Oerlemans et al., 2017) but integrative studies of the related costs are lacking.

Technical management of glacier melt, hence influencing their mass balance, has been of interest since several decades. Various materials and techniques were investigated with regard to their capabilities to preserve snow and ice. Materials tested included foams (Grove et al., 1963), sawdust (Herrmann and Stehle, 1967), wood chips (Skogsberg and Lundberg, 2005) and different tarps and textiles (Olefs and Obleitner, 2007) deployed on top of the glacier surface. Experiments were also conducted by injecting water into the snow pack and by snow compaction (Olefs and Fischer, 2008). Of these approaches, only the use of geotextiles laid out on top of the spring snow surface has been shown to both have a significant effect on melt and to be practical in the
operation of high-alpine ski resorts (Olefs and Fischer, 2008; Senese et al., 2020). Geotextiles typically consist of polyester und polypropylene fibres and are fabricated in rolls of 50 m length and 4–5 m in width. They have a weight of about 0.5 kg m\(^{-2}\) and a thickness of 3–4 mm. The high efficiency of geotextiles is related to their effect on the surface energy balance and was studied both at a theoretical level using different modelling approaches and experimentally in the Austrian Alps (Olefs and Obleitner, 2007; Olefs and Fischer, 2008; Olefs and Lehning, 2010). Geotextiles have a high albedo and exert a radiation effect by reflecting more incoming shortwave radiation than melting snow and ice surfaces. They thus significantly reduce the overall energy available for melt. Furthermore, geotextiles have favourable thermal properties and reduce melt due to smaller turbulent heat fluxes. The semi-permeable characteristics of geotextiles also inhibit the formation of puddles that would warm up and affect the snow by seeping water (Olefs and Fischer, 2008).

Already in the hot summer of 1947 efforts to reduce glacier melt were employed with sawdust being placed on the roof of a touristic ice cave at Jungfraujoch, Switzerland, for reducing melt. Glacier ski resorts have been covering spring snow for several decades (e.g. since 1993 at Zugspitze, Germany). Various studies have shown that geotextiles can reduce the melting of snow and ice by between 50 and 70\% compared to unprotected surfaces, thus demonstrating the efficiency of the approach (Olefs and Obleitner, 2007; Olefs and Fischer, 2008; Olefs and Lehning, 2010; Nestler et al., 2014; Senese et al., 2020). After the early 2000s, geotextile coverage of glaciers has been increasingly utilized by more than a dozen ski resorts in Austria, France, Germany, Italy and Switzerland. The aim is either to maintain the operability of ski runs (e.g. counteracting ice surface lowering), or to construct snow depots permitting a timely preparation of the slopes in the coming winter (snow farming). On Rhonegletscher, Switzerland, a considerable area (0.05 km\(^2\) in 2019) is covered by geotextiles at the glacier snout since more than a decade to ensure access to an artificial ice cave, a touristic attraction during summer.

Fig. 1 visualizes the basic concept and functionality of managing glacier melt based on geotextiles for three common cases: the geotextile is either placed in the accumulation area or at the equilibrium line of glaciers, and is typically removed in autumn to permit snow accumulation and skiing. The coverage is then re-installed again before the onset of the melting season; the geotextiles can be re-used for several years (Fischer et al., 2016; Senese et al., 2020). These approaches are related to a higher effort in maintenance but allow incorporating natural (or artificially enhanced) snow mass and, thus, potentially even building up ice height. It is used by glacier ski resorts. Permanent coverage of the glacier surface in the ablation area (Fig. 1) is only known to us for one site in the Swiss Alps. Maintenance costs are lower but the geotextile only becomes active after the depletion of winter snow. Furthermore, the permanent installation leads to problems related to glacier flow, crevassing and uneven melt rates, resulting in a degradation and possible rupture of the geotextiles, hence impacting on their efficiency over time.

A spectacular idea to artificially slow glacier retreat was recently proposed by Oerlemans et al. (2017). Based on large-scale technical snow production on Vadret da Morteratsch, Switzerland, the authors aim at reducing the mass loss of an entire valley glacier. The concept is thus different than for the local small-scale interventions described above, which result in a direct economic benefit rather than the saving of an entire glacier. The project has not yet been implemented, however, during a pilot phase snow making is tested off-glacier over a small area.

Whereas the functioning and the efficiency of presently applied techniques to artificially reduce snow and ice melt are well understood and investigated, no regional-scale study on the temporal changes in geotextile-covered areas is available. Related impacts on overall glacier mass balance have been assessed by Fischer et al. (2016) based on ice surface elevation changes but have not yet been quantified at an annual scale. Furthermore, the financial cost of saving glacier ice, i.e. avoiding melt, by direct measures has not been assessed so far, although this is a relevant factor for determining the profitability of such approaches. Moreover, any discussions on the scalability of the presently conducted local efforts to larger scales (e.g. an entire glacier, Oerlemans et al., 2017, or a mountain range) strongly depend on an estimation of related costs, as well as concurrent impacts on the environment (e.g., Anesio et al., 2009; Obwegeser, 2015).

In this study, we provide the first assessment of long-term changes in glacier areas affected by artificial melt reduction measures at the scale of the Swiss Alps. By combining remote-sensing observations with an extensive dataset of direct mass balance measurements, we quantify the effective glacier volume saved by artificial melt reduction in Switzerland over the period 2005–2019 and discuss the contribution to overall, ongoing glacier mass loss. Relying on information gained during interviews with operators responsible for the glacier coverage, we estimate the annual costs of technically reducing glacier melt, spanning a wide range of management strategies and cases. This allows defining the financial cost of preventing the melt of 1 m\(^3\) of glacier ice in Switzerland. By hypothetically upscaling our results to all Swiss glaciers, we provide a first-order assessment of the general feasibility and the requirements for saving glaciers at the mountain-range scale, and put these numbers into the broader context of climate change. These considerations allow assessing and pondering the feasibility of glacier protection measures at the large scale.

2. Study sites

We detected nine sites across Switzerland with currently active measures to artificially reduce glacier melt (Fig. 2). They are found in different regions of the Swiss Alps, with varying regional climate and at elevations of between 2250 and 3250 m a.s.l. At all sites, geotextiles of a similar type are in use. The first installation was between 2004 and 2009.
for all sites except for one (started in 2017), and efforts are continued until today. At present, the area with artificial melt reduction ranges between about 4000 m$^2$ and 50,000 m$^2$ per site. Two other sites are known that applied geotextiles at a small scale (Glacier du Tortin, Verbier; Milibachgletscher, Lötschen) but they are not included in the present study since the coverage only lasted between about 2006 and 2010 and was then abandoned for unknown reasons. Geotextile coverage is related to glacier ski resorts in all but one site, and the share of the artificially protected area presently ranges from 0.1% (Feegletscher) to 100% (Diavolezza) of the total area of the respective glacier. Fig. 3 presents images of selected sites shedding light on different aspects of geotextile coverage.

3. Data and Methods

3.1. Remote imagery

For mapping the past extent of areas covered with geotextiles for all sites, we rely on high-resolution aerial imagery acquired by the Swiss Federal Office of Topography (swisstopo). The orthophotos have a ground resolution of 0.25–0.5 m (0.1 m in some cases), are cloud-free, and have been typically acquired in three-year intervals in late summer (swisstopo, 2020). Sometimes also shorter time intervals are available. Artificially covered areas were very clearly detectable at all sites due to a pronounced albedo contrast, cast shadows and a surface pattern different from surrounding snow and ice, and were manually digitized. Based on repeated digitization by different glaciologists, we estimate an uncertainty in measured area of ±3%. The number of available aerial images per site is given in Table 1.

For three of the nine sites, no high-resolution images were available for the most recent year of the study (2019). For gaining up-to-date information on geotextile coverage, satellite imagery from Sentinel-2A/B scenes was used (e.g., Gascon et al., 2017). Although the covered areas are relatively small in comparison to the images’ ground-resolution (10 m), it was possible to clearly distinguish geotextile coverage in most cases. Estimated uncertainties in measured areas are ±15%. For years without a direct observation of the covered area, we apply linear interpolation with uncertainties arbitrarily increased by a factor of three relative to the direct observations.
For all sites, the median elevation of the area protected by geotextiles was determined based on a recent digital elevation model (DEM, swisstopo, 2018). In some cases, this involved averaging for several covered patches in different parts of the same glacier (e.g. Vorab, Titlis). The area and the elevation range of all glaciers with artificial melt reduction was extracted from the Swiss glacier inventory referring to the period 2008–2011 (Fischer et al., 2014). The timing of the inventory refers to about the center of our study period.

For Rhonegletscher, the site with the largest covered area, additional DEMs with a spatial resolution of 0.5–1.0 m are available for each year between 2012 and 2019, except for 2018 (GLAMOS, 2017, 2020). Surface elevation of these DEMs has been evaluated based on aerial photogrammetry and is co-registered to tie points outside the glacier. Uncertainty in local-scale elevation information is estimated as ±0.5 m based on comparison over stable terrain next to the region of interest. This dataset permits a detailed assessment of annual ice surface elevation changes and, thus, the effect of geotextiles on local mass loss. By subtracting observed elevation change in nearby areas experiencing natural melt only, and by integration over the covered area, the ice volume gained at the annual scale can be inferred.

### 3.2. Glacier mass balance

Information on snow and ice melt rates in the area unaffected by artificial melt reduction is required for assessing the effect of geotextiles. Previous studies focusing on individual sites and years have measured melting in situ (Olefs and Fischer, 2008; Olefs and Lehning, 2010; Nestler et al., 2014; Senese et al., 2020), whereas our emphasis on a longer period (2005–2019) and many sites necessitates an estimation of the local melt rates based on alternative datasets.

For a third of the sites, data from an in situ mass balance monitoring programme is available, providing the spatial distribution of melt rates based on seasonal measurements at between 4 and 11 locations distributed over the glacier. These point measurements have been extrapolated to the entire glacier surface (GLAMOS, 1881–2018). For the other sites, the closest glacier with seasonal mass balance observations was attributed (Table 1). Distances to the respective study sites are between 1 and 20 km, and we thus assume those measurements to be representative for the sites with geotextile coverage. For each site and each year, we extract the summer mass balance \( b_b \) at the elevation of the covered area from the observed mass balance distribution. \( b_b \) spans the period between April/May and September (the exact dates are defined by the respective field surveys, see GLAMOS, 1881–2018, for details), and is a good indicator for annual ablation rate. Where mass balance observations were attributed from a neighbouring glacier (Table 1), observed mass balance gradients were referenced to the median elevation of the investigated glacier. This is to account for a potential difference in the glaciers’ average elevation due to different local climate forcing (e.g. snow accumulation, solar radiation).

In areas unaffected by technical measures next to the investigated sites, mean annual natural snow and ice melt rates (average of 2010–2019) are between −6 m water equivalent (w.e.) per year and −2 m w.e. yr\(^{-1}\) (Fig. 4). Seven of the covered sites show average melt rates in a narrow range between about −2.5 and −2 m w.e. yr\(^{-1}\) despite of elevations varying between 2800 and 3250 m a.s.l.. Similar melt rates at different elevations can be explained by variations in local climatic characteristics (mainly snow accumulation) that are responsible for substantial differences in equilibrium line altitudes across the Alps (e.g., Ohmura et al., 1992).

#### 3.3. Observed melt reduction by geotextiles

Estimating the effect of artificial glacier melt reduction by geotextiles requires knowledge on their ability to locally reduce the melt rates when compared to uncovered areas. We term the ratio between these two melt rates the efficiency \( \epsilon \), with \( \epsilon = 0\% \) indicating no effect, and \( \epsilon = 100\% \) indicating the complete suppression of snow and ice melt.

No additional field data was acquired in the present study. We base our assessment on published in situ measurements, in which the efficiency of geotextiles was derived by comparing the melt over unprotected areas to the one below the geotextile. The measurements span over time intervals between a week and the entire summer period. Table 2 provides a compilation of studies. On average, an efficiency of \( \epsilon_0 = 59\% \) has been reported for geotextiles in the first year after installation. Fig. 5 illustrates direct observations of the effect of geotextiles in the case of one of our study sites (Bauder, 2006). We note that, besides the material properties (Olefs and Fischer, 2008; Senese et al., 2020), \( \epsilon_0 \) is likely to depend on topographical parameters such as the slope angle, the aspect and the elevation of the site. These factors will influence the relative importance of energy-balance components modified by the geotextile coverage. For example, this theoretically implies a higher efficiency for sites with maximal solar radiation input, as geotextiles are most efficient in reducing short-wave radiation (Olefs and Lehning, 2010). However, the number of available studies (see Table 2) for investigating or including these dependencies is too small, and we base

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**Table 1**

| Site          | Start | \( n_{SEC} \) | Mass balance | Dist. |
|---------------|-------|--------------|--------------|-------|
| Rhonegletscher| 2008  | 9(0)        | Rhone        | 0 km  |
| Diavolezza    | 2009  | 4(0)        | Murtrial     | 11 km |
| Vorab         | 2006  | 4(0)        | Findelen     | 19 km |
| Titlis        | 2005  | 5(1)        | Rhone        | 20 km |
| Feelegletscher| 2005  | 7(0)        | Findelen     | 9 km  |
| Corvatsch     | 2006  | 5(0)        | Corvatsch    | 0 km  |
| Gemsstock     | 2004  | 6(1)        | St. Anna     | 1 km  |
| Theodulgletscher | 2006 | 6(1)        | Findelen     | 11 km |
| St. Annafirn  | 2017  | 1(0)        | St. Anna     | 0 km  |

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For Rhonegletscher, the largest site with the most geotextile coverage, we extract the sum of summer mass balance measurements used for each site, along with its horizontal distance (Dist.) to the covered area.
our considerations on the average value of $\epsilon_0$. 

### 3.4. Structured interviews

For acquiring direct information on the practical management of geotextiles and the respective costs, questionnaires with seven questions were sent to operators responsible for artificial glacier melt reduction. From the seven contacted organisations, six responded and shared experiences gained over the past decade. The replies included qualitative and quantitative information about the organisations’ investments and returns from the applied technique. This permits determining the costs of purchasing, placing and maintaining the geotextiles for each site. As anonymity was granted to the participants, we are unable to list detailed financial costs specified for the individual sites.

### 3.5. Computing saved ice volume and costs

Combining data on (i) the area covered by geotextiles, (ii) local melt rates affected by the coverage, and (iii) the efficiency of melt reduction, the ice volume annually saved by the technical intervention can be computed. For each site and each year $t$, we calculate the saved ice volume $V_{\text{saved}, t}$ with

$$V_{\text{saved}, t} = a_t \cdot \epsilon_0 \cdot \left( S_{\text{cov}, t} - \tau \right),$$

where $a_t$ is the local natural snow and ice melt (m w.e.) cumulated over one year next to the geotextile coverage. Not knowing the exact dates of placement and removal of the coverage, we here use $a_t$ referring to the period with observations of the summer balance for the respective glacier. $\rho_{\text{water}} = 1000$ kg m$^{-3}$ and $\rho_{\text{ice}} = 900$ kg m$^{-3}$ are the densities of water and ice, respectively, and are used to covert locally saved glacier mass into an ice volume. $S_{\text{cov}, t}$ is the area covered in year $t$, and $\tau$ is the efficiency of the melt reduction as an average over the lifetime of the geotextile. Qualitative observations and experience of the ski resorts indicate that the efficiency of geotextiles decreases with time, most likely due to a lowering of the geotextile’s albedo as well as mechanical abrasion reducing the thickness of the fabric. Thus, geotextiles are typically replaced at intervals of between three and eight years according to the operators. However, no long-term data on the magnitude of the efficiency loss was available to us, and we roughly estimated a progressive annual reduction of $\epsilon$ by 5% of its current value for seasonally replaced geotextiles, and 10% in case of a permanent installation. Verifying the rate of efficiency decrease is difficult as it will be influenced by various factors that are hard to quantify and vary spatially. An assessment of our estimates is performed using long-term elevation change observations at Rhonegletscher (see Results). Based on the spread in reported numbers (Table 2) and the poorly constrained annual reduction in $\epsilon$, we set the overall uncertainty in $\tau$ as ±20% of its value. We use this estimate for quantifying the uncertainty in $V_{\text{saved}, t}$ (Eq. 1).

For estimating the annual price of saving 1 m$^3$ of glacier ice, we set up a simple equation taking into account three individual factors related to the financial costs of artificial glacier melt reduction. The information on these factors is based on the interviews with the operators responsible for the geotextile coverage. The price $P_t$ of saving 1 m$^3$ of ice in year $t$ is computed as

$$P_t = S_{\text{cov}, t} \left( (C_{\text{material}} + C_{\text{placem}}) / \tau + C_{\text{maint}} \right) / V_{\text{saved}, t},$$

where $S_{\text{cov}, t}$ is that year’s covered area and $V_{\text{saved}, t}$ is the saved ice volume (Eq. 1). $C_{\text{material}}$ is the material cost in Swiss Francs (CHF) m$^{-2}$, involving the purchase and delivery of the geotextiles, as well as sandbags as sinkers. $C_{\text{placem}}$ is the cost (CHF m$^{-2}$) related to deploying the geotextiles, which includes (i) transportation to the site (by helicopter or snowcat), (ii) placement of the geotextile on the glacier, and (iii) further amendments such as the seaming of individual rolls or the anchoring to the surface with sandbags. $C_{\text{material}}$ and $C_{\text{placem}}$ refer to the cumulative costs over the years of operability, and their sum is thus divided by the average lifetime $\tau$ (yr) of the geotextile. $C_{\text{maint}}$ is the annual cost (CHF m$^{-2}$ yr$^{-1}$) of maintaining the geotextiles, e.g. related to the seasonal removal and re-installation, or to reparation. Note that $P_t$ (Eq. 2) also depends on the saved ice height ($V_{\text{saved}, t} / S_{\text{cov}, t}$) in each year, which is determined by the efficiency of the geotextile and the local melt rate. The higher the melt rate, the more ice can be saved. This leads to the somewhat paradoxical situation that the price of 1 m$^3$ of ice is lower in years with strong glacier melt, than in average years.

### 4. Results

#### 4.1. Area covered by geotextiles

The glacier area covered by geotextiles throughout the Swiss Alps has strongly increased over the last 15 years and reached 0.18±0.01 km$^2$ by 2019 (Fig. 6). Whereas before 2010, mostly small areas were covered (sometimes only for testing the feasibility), geotextile coverage at many sites was continuously extended afterwards. The last seven years have seen a doubling of the total area covered by geotextiles. This is partly due to considerable investments into this technique at Rhonegletscher with a covered area of 0.05 km$^2$. Despite the recent boost in active glacier melt reduction in Switzerland, the covered surface corresponds only to about 0.02% of the current total glacier area in Switzerland.

| Reference                  | $\epsilon_0$ | Location          |
|----------------------------|--------------|-------------------|
| Bauder (2006)              | 60%          | Gemmstock, Switzerland |
| Olefs and Fischer (2008)   | 60%          | Schaufelferner, Austria |
| Nestler et al. (2014)      | 57%          | Mount Aragatz, Armenia |
| Senese et al. (2020)       | 69%          | Doode Est, Italy |
| Senese et al. (2020)       | 49%          | Presena Ovest, Italy |
| **Average**                | **59%**      |                    |

Table 2: Studies documenting the local melt reduction by geotextiles based on in situ observations of snow and ice melt. $\epsilon_0$ refers to the percentage reduction in melting compared to an uncovered location in the first year after installation. The site and country of the respective observation is given.

| May 2005 | September 2005 |
|----------|----------------|
| Spring 2005 | uncovered (P3) | covered (P4) |
| Autumn 2004 | +1.60 m w.e. | -2.05 m w.e. | -0.70 m w.e. |
| Autumn 2005 | -0.45 m w.e. | +0.90 m w.e. |

Fig. 5. Observed melt reduction due to the placement of geotextiles at the end of winter in the case of Gemmstock in 2005 (Bauder, 2006). Measured summer ablation rates at uncovered (P3) and covered (P4, see Fig. 2b) locations are given in metres water equivalent (m w.e.).
4.2. Observations of saved ice volume

The differencing of high-resolution DEMs at the snout of Rhonegletscher demonstrates the considerable effect of the geotextile coverage (effective since June 2008) on ice loss. Between 2012 and 2016, elevation change next to the geotextile-covered area was between –20 and –25 m, whereas the covered region only experienced elevation losses of 5 to 15 m (Fig. 7). Between 2012 and 2019, an ice height of up to 35 m was saved by the technical intervention (Fig. 7b). This is substantial and has permitted the continued operability of the ice cave. Note that interpretation of the cumulative ice height saved between 2012 and 2019 is complicated by the fact that the covered area increased over time and that geotextiles were partly replaced or re-enforced at the most critical locations (e.g., entrance to the cave). Furthermore, ablation rates are higher than surface elevation changes because of (limited) ice emergence due to glacier flow. The effect of the newly formed proglacial lake is considered to be minor, as the contact area between the water and the zone covered by geotextiles only developed in late 2018.

Fig. 7 also illustrates the considerable spatial variability in the effect of geotextiles on melt reduction. On the one hand, this is driven by differing periods of coverage, on the other hand by small-scale effects. At the seams of two rolls, the efficiency is substantially higher due to a double geotextile layer (see e.g., Nestler et al., 2014). This causes an undulation aligned in the direction of the seams (Fig. 7a, see also Fig. 3). Due to ice flow, crevasses form in the covered area, and result in tension and rupture of the geotextiles, leading to locally strongly enhanced melt rates. This process amplifies over time, and eventually leads to an inefficient melt reduction and the need of replacing the geotextiles. These observations relate to a permanent installation in the ablation area, and are much less critical for seasonal removal and replacement on top of the spring snow (Fig. 1).

We validate the time-evolution of the computed, saved ice volumes, against the observations based on the differencing of DEMs for Rhonegletscher (Fig. 8). The general trend is within the uncertainties of the computations (according to Eq. 1, uncertainty determined by the efficiency of the melt reduction) and the observations. This generally confirms our estimates of \( \epsilon \) and the degradation of the efficiency over time.

Between 2014 and 2016, however, notably smaller ice volumes were saved according to the comparison of DEMs than estimated from Eq. 1. This could be explained by a stronger degradation of the geotextiles than assumed, or by unknown changes in the management of the geotextiles. However, also the saved ice volume determined by DEM comparison might be subject to considerable uncertainties (Fig. 8). We assume an uncertainty of about ±20% as the observational dataset does not provide direct information on the dynamics of the coverage during the considered time interval.

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Fig. 6. Evolution of total glacier area covered by geotextiles for artificial melt reduction in Switzerland, including uncertainties (grey band). The number of active sites is stated in the lower part of the figure. The covered area of Rhonegletscher with a permanent installation is shown separately. Percentages refer to the share of the overall glacier area in Switzerland covered at each point in time.

Fig. 7. (a) Observed surface elevation change at the snout of Rhonegletscher between 2012 and 2016, demonstrating the effect of artificial glacier melt reduction using geotextiles. The extent of geotextile coverage in 2016 is shown with the dash-dotted line and has varied little over the here-considered four years. Elevation changes are only shown within the glacier surface of 2016. A cross-profile is indicated, and the location of the close-up in the context of the entire glacier is shown in the inset. (b) Observed cumulated effect of artificial glacier melt reduction on ice surface elevation on a South-North profile between 2012 and 2019. The effect of geotextile coverage has been isolated by subtracting elevation changes in uncovered areas.
models (Fig. 6). The saved volume computed with Eq. 1 is shown, including a range for the uncertainty in the efficiency of geotextiles.

300,000 m$^3$ along with covered areas (Fig. 6). The saved volume reached more than 0.04% of the overall Swiss ice volume loss was mitigated, although the temporal dynamics of the share of volume saved are interesting: In 2013, as much as 0.04% of the overall Swiss ice volume loss was mitigated, although the absolute volume saved by geotextile coverage was almost three times smaller than in 2018 and 2019. This is explained by regional glacier mass balance closer to equilibrium in 2013, compared to the most recent years (Fig. 9a).

For each year, we relate the ice volume saved by artificial melt reduction to the overall glacier volume loss in Switzerland. The latter is estimated based on a combination of annual departures of all direct mass balance observations from their long-term means, and spatial extrapolation to each Swiss glacier (GLAMOS). Between $<0.01\%$ and 0.04% of the total annual loss in glacier ice across Switzerland was mitigated by geotextiles (Fig. 9b). This clearly indicates that the effect of artificial melt reduction is vanishingly small at the mountain-range scale, although being considerable locally (Figs. 3 and 7). The temporal dynamics of the share of volume saved are interesting: In 2013, as much as 0.04% of the overall Swiss ice volume loss was mitigated, although the absolute volume saved by geotextile coverage was almost three times smaller than in 2018 and 2019. This is explained by regional glacier mass balance closer to equilibrium in 2013, compared to the most recent years (Fig. 9a).

Averaged across all sites, the ice height saved over the study period shows a general increase to around 2 m yr$^{-1}$ in the most recent years (Fig. 9c). This is explained by the much larger areas covered at sites experiencing high melt rates (Fig. 4), and by enhanced mass loss of all glaciers (Fig. 9a).

At the scale of the individual glacier, the impact on the overall mass balance strongly varies, depending on the fraction of glacier area covered (Fig. 10). For the relatively large Rhone-, Theodul- and Fee-getscher, the effect of artificial melt reduction on glacier-wide mass balance is smaller than 0.01 m w.e. yr$^{-1}$ as an average for the period 2010–2019. This is far below the typical uncertainties of mass balance series (Zemp et al., 2013), and thus not recognizable. Related to the entire glacier, less than 0.5% of the total mass loss was mitigated for these glaciers. For smaller glaciers, where the share of the geotextile coverage accounts for 2–8% of overall glacier area, the effect on glacier-wide annual balance can reach up to 0.06 m w.e. yr$^{-1}$, corresponding to a mitigated overall average volume loss of 1% (Titlis) to 7% (Gemsstock). This needs to be accounted for in mass balance assessments for these glaciers. The very small glacier at Diavolezza is a special case. It had practically disappeared before the coverage was installed, and has now been re-grown to its size of about 15 years ago (0.03 km$^2$). The entire surface is seasonally covered, leading to an effect of +1 m w.e. yr$^{-1}$ on glacier-wide mass balance compared to conditions without artificial measures. This is enough to accumulate glacier mass on the long term despite negative balances of surrounding glaciers over the last years.

4.4. The price for saving 1 m$^3$ of ice

According to the data collected during the structured interviews, material costs are 3.0 CHF m$^{-2}$ on average, including delivery and sinkers. Placement costs ($C_{\text{placem.}}$) estimated by the operators vary strongly between 0.3 and 3.9 CHF m$^{-2}$ (Table 3). Annual maintenance costs range between 3.3 and 9.9 CHF m$^{-2}$ yr$^{-1}$ for seasonally replaced geotextiles. For a permanent installation, maintenance costs of 0.3 CHF m$^{-2}$ yr$^{-1}$ are reported. We note that comparability between the individual cost estimates is difficult as different budgetary considerations by the individual operators are likely. According to the interviews, the typical lifetime of geotextiles is 3–8 years, which is also consistent with reports from other European countries (e.g., Senese et al., 2020).

We compute the price $P$ of saving 1 m$^3$ of glacier ice using Eq. 2. If the variables have not been reported for the considered site (two out of nine sites), we use the average of all sites with direct information (Table 3). The average price of saving 1 m$^3$ of glacier ice varies over one order of magnitude. On average of the last decade, it can be as low as 0.6 CHF m$^{-2}$ yr$^{-1}$ in case of high melt rates combined with low maintenance costs, and reach up to 7.9 CHF m$^{-2}$ yr$^{-1}$ when geotextiles are placed in the accumulation area, thus requiring labour-intensive maintenance (Fig. 11a). For non-permanent coverage, also the year-to-year variability in $P$ is high, as the costs for maintenance do not only scale with area but also with melt rates (i.e. saveable volume) and, hence, can strongly vary (Fig. 11a). Our considerations based on glacier areas covered with geotextiles and estimated costs per unit area indicate that in 2018 and 2019, a total of 700,000–900,000 CHF yr$^{-1}$ were invested to artificially prevent the melting of glacier ice across Switzerland. Individual operators of Swiss glacier ski resorts report annual investments into the technique of up to 200,000 CHF based on a direct assessment of all costs. Although the effect is very small at the regional scale (Fig. 9a), the large investments show how local benefits of melt reduction have a considerable economic value. This lends relevance to the approach.

Fig. 11a indicates a clear dependency of cost-efficiency of geotextile coverage on the location on the glacier (see also Fig. 1). Per unit of saved ice volume, coverage in the upper area of the glacier tends to be more costly than in the ablation area. Furthermore, costs of a permanent installation are seven times lower (on average) than for seasonal replacement. However, the former is not an option in glacier ski resorts, and the seasonal installation carries various advantages, e.g. in combination with snow grooming. In comparison to the late 2000s, the average price of saving 1 m$^3$ of ice across Switzerland has been substantially reduced (Fig. 11b). This is related to the recent extension of coverages in the ablation area of glaciers (which are more cost-efficient) but also to the higher frequency of years with high melt rates (when the effect of geotextiles is more pronounced).

5. Discussion

5.1. Scenarios of glacier melt reduction

The fast increase in the area covered by geotextiles and the corresponding rise in saved ice volume (Figs. 6 and 9) raise the question on the scalability. Could technical intervention for reducing melt become a relevant factor at the scale of the Swiss Alps, or other mountain ranges? With presently around 0.03% of mitigated volume loss in Switzerland, this is clearly not yet the case. In a hypothetical experiment, we assess the effect and compute the costs of placing geotextiles on a large number of Swiss glaciers. Since our results indicated that the efficiency for solely saving ice (i.e. irrespective of other factors relevant in a touristic context) is by far highest for permanent geotextile coverage close to the
glacier snout (Fig. 11a), we set up our experiment as follows: Melt reduction measures are simulated at the 10, 100 and 1000 largest Swiss glaciers. We focus our experiment on the past two decades with melt rates based on observed climatic conditions, as well as on the next 20 years relying on modelled glacier melt (Zekollari et al., 2019). Geotextiles are first placed only at the lowermost elevation of each glacier, and are then progressively extended upwards, until the entire glacier is covered. As we prescribe a permanent coverage, covering areas with positive mass balance would show no benefit (geotextiles would be buried by firn). We still model coverage up to 100% as many glaciers are expected to completely lose their accumulation area in a warmer climate, but we detect a critical percentage of covered area above which the further benefit is limited. We define this threshold as the geotextile extent at which a 1% increase in coverage has an effect of <0.2% on saved volume. Beyond this boundary, one would not apply coverage due to its negligible effect. Our experiment ignores any aspects of practical feasibility, such as crevassing, too steep slopes, natural hazards, areas under environmental protection and other legal restrictions.

Both for the 20-year period 1997 to 2017, and a future period 2020–2040 results on annual mass balance distribution are available from the Global Glacier Evolution Model (GloGEM, Huss and Hock, 2015) for all individual Swiss glaciers. Results for the median regional climate model run forced with the Representative Concentration Pathway 4.5 (Jacob, 2013; Zekollari et al., 2019) are employed for the future. In GloGEM, mass balance is constrained to correspond to observed ice volume change between 1980 and 2010 (Fischer et al., 2015) and changes in glacier extent are computed relying on a parameterization (see Huss and Hock, 2015, for details). We then apply Eqs. 1

![Figure 9](https://example.com/figure9.png)

**Fig. 9.** (a) Observed winter (blue) and summer (red) mass balance as an average of all studied sites (GLAMOS, 1881–2018). Dark grey bars show the annual mass balance. (b) Total ice volume saved in 2005–2019 by artificial glacier melt reduction using geotextiles, including uncertainties. The relative contribution of the artificially saved ice volume to each year’s total glacier volume loss in Switzerland is given in percent. Note that the total volume saved is strongly related to the area covered by geotextiles (see Fig. 5). (c) Annual ice height saved by geotextile coverage as an area-weighted average across all sites, including uncertainties. The signal depends both on annual melt rates and the efficiency of geotextiles.
The share of glacier area covered by geotextile
coverage plotted against the site’s location relative to the glacier’s elevation range. Horizontal bars indicate the variability in \( P \) (Eq. 2) in the individual years. The ranges are asymmetric as \( P \) is higher in years with lower surface melting. The size of the dots scales with the current area covered by geotextiles. The name of the sites along with the financial costs is not stated for some sites, resulting in a lower estimate for the individual sites.

Table 3
Parameters used for computing the cost-efficiency of geotextile coverage (Eq. 2) according to the operators responsible for artificial glacier melt reduction. The price \( P \) of saving 1 m$^3$ of ice is given as the average between 2010 and 2019, and is specified for both the case of permanent installation ("permanent"; 1 site), and of annual removal of the coverage in fall and replacement on top of the spring snow surface ("replaced"; 8 sites). The average and the range of individual sites is specified.

| Variable        | Average (Range) | Unit   |
|-----------------|-----------------|--------|
| \( C_{\text{material}} \) | 3.0 (2.7–3.5) | CHF m$^{-2}$ |
| \( C_{\text{placem.}} \) | 1.0 (0.3–3.9) | CHF m$^{-2}$ |
| \( \tau \) | 5 (3–8) | yr |
| \( \tau_{\text{material}} \) (permanent) | 0.3 | CHF m$^{-2}$ yr$^{-1}$ |
| \( \tau_{\text{placem.}} \) (replaced) | 6.0 (3.3–9.9) | CHF m$^{-2}$ yr$^{-1}$ |
| \( P \) (permanent) | 0.6 | CHF m$^{-3}$ yr$^{-1}$ |
| \( P \) (replaced) | 4.4 (1.9–7.9) | CHF m$^{-3}$ yr$^{-1}$ |

and 2 to compute ice volumes saved and costs when progressively extending the coverage from 0% to 100% of the glacier surface. Cost parameters (Eq. 2) are set to the values found for a permanent installation ("permanent"; 1 site), and of annual removal of the coverage in fall and replacement on top of the spring snow surface ("replaced"; 8 sites). The average and the range of individual sites is specified.

The overall modelled annual ice volume loss of all glaciers in Switzerland between 1997 and 2017 and 2020–2040, respectively, is taken as a benchmark for comparing the ice volume that could have been or could be saved hypothetically. Two clear conclusions emerge (Fig. 12): (1) The technique would neither have allowed for a complete mitigation of glacier mass loss in the past, nor would it allow for a complete mitigation during the coming two decades. Even if the largest 1000 Swiss glaciers (or 99% of the total area) would have been covered completely, only about two thirds of the average annual volume loss could have been avoided. (2) The costs for such an endeavour are exorbitant. For achieving a maximum effect – here defined as covering 1000 glaciers by 76% of their surface – Switzerland would need to commit about 1.4 billion CHF each year.

Such an annually recurring investment would be beyond reasonable regarding several aspects: For one, the ecological risk of such a large-scale intervention would be extremely difficult to assess. For another, the economic value of the endeavour seems questionable: From the touristic perspective, for example, it is very likely that the revenue of reducing but not stopping Swiss glacier retreat would be limited, although we acknowledge that no detailed studies are yet available on this subject. Being completely wrapped in blankets, we speculate that glaciers would largely lose their present touristic appeal, certainly in the long term. Regarding water resources, there would be some desirable temporal delay in the change of the hydrological regime caused by glacier retreat (see e.g., Gabbi et al., 2012). Still, artificially reducing glacier mass loss is unlikely to offset potential future water shortages. This is also because meltwater from (geotextile-covered) glaciers cannot reasonably be stored and released at the times when it is needed. Also putting the necessary financial expense into context with measures for reducing global CO$_2$-emissions (IPCC, 2019) is insightful: Given the current price of compensating CO$_2$-emissions through projects in developing countries (typically in the order of 30 CHF per ton of CO$_2$), more than the current total annual CO$_2$-emissions of Switzerland could be mitigated at a cost comparable to deploying artificial melt reduction.
5.2. Benefit, impacts and alternatives

Although the above analysis has shown that reducing glacier melt through geotextile coverage is not scalable unless enormous costs and impacts are accepted, there are benefits of such measures at the local scale. The economic revenue of protecting glaciers by geotextiles seems to be high enough as to have prompted glacier ski resorts in the Alps to intensify their investments during the last years (e.g., Fischer et al., 2016; Senese et al., 2020). Maintaining accessibility and quality of ski slopes, or in the case of Rhonegletscher, an ice cave, represents a challenge for the operability of the sites, and might therefore justify local interventions to preserve glacier ice.

The potential of artificial management of snow and ice melt is also increasingly discussed in the context of establishing seasonal reservoirs in the form of water frozen during wintertime through so-called ice stupas (Nüsser et al., 2019; Sharma, 2019). These structures are reported to be beneficial for local agriculture in dry regions, being particularly popular in Asia. However, the water volume stored in individual ice stupas is small, in the order of only a few thousands m$^3$, and discharge is correspondingly low (Nüsser et al., 2019). Geotextiles placed on seasonal snow or ice, as well as artificial snow production can act similarly as ice stupas by seasonally delaying melt water run off. By hydrological modelling it has been shown that geotextile coverage of snow fields can push back the meltwater peak by 1–2 months into the dry summer season (Nestler et al., 2014). Melt reduction can thus represent a way to store water over these time scales, making such approaches locally valuable but not efficiently scalable.

Glaciers are known to have a considerable impact on downstream biodiversity and ecology (Hotaling et al., 2017; Milner et al., 2017; Cauvy-Fraunié and Dangles, 2019). Geotextiles placed on glacier ice might have a suite of negative effects for the local environment and downstream water quality, although the exact processes and their reach are not yet fully understood. Weathering of geotextiles releases chemical substances that influence the cryobiota of snow and ice (Obwegereser, 2015; Els, 2016). Furthermore, plastic particles originating from material degradation might accumulate in the downstream hydrological system, with potentially cascading effects on aquatic organisms, and other fauna and flora. Whereas these impacts are expected to be limited for the presently small extent of geotextiles on glaciers in the Alps, the environmental sustainability would need to be far better assessed if larger areas were to be covered.

Several alternative approaches to reduce glacier melt have been discussed, sometimes being prominently exposed by the media: These include, for example, the blocking of katabatic winds or painting of the glacier surroundings in white (Spiegel, 2008). The effectiveness of such exploratory techniques is unproven, and their efficiency is very likely lower than the one of geotextiles as they only have some effect on less important components of the ice surface energy balance. Moreover, also their applicability at large scales is more than questionable. A more promising alternative is the technical production of snow on glaciers (Oerlemans et al., 2017; Carmagnola, 2018). This approach targets an amplification of accumulation. Due to snow albedo being higher than that of ice, a considerable melt reduction could also be achieved. No studies on the efficiency of this approach in direct comparison to that of geotextile coverage have yet been performed but the development of the technology is ongoing (Innosuisse, 2019). A planned potential application at the scale of a large glacier would involve major construction works, notably including cables for snow lances on top of the ice and a substantial water retention basin. Such interventions in a sensible high-alpine area with considerable ecologic and touristic value clearly represent serious drawbacks. Nevertheless, technical snow production on glaciers has both the advantage of a smaller impact on the downstream environment and a more natural vision of the protected glacier. However, it involves the building of permanent structures at high elevations which can be risky, both during construction and at the long-term due to potential hazard situations that might be evoked.

Fig. 12. Hypothetical experiment of progressively covering the 10, 100 and 1000 largest Swiss glaciers, respectively, from the terminus upwards to their entire area. The potentially saved ice volume is presented relative to the average annual ice volume loss between 1997 and 2017 (solid lines) and the modelled volume loss 2020–2040 (dashed lines). Dots indicate the percentage of covered glacier surface in 20% steps. Triangles and percent values refer to the share of coverage for the respective experiment beyond which the benefit becomes small (defined as 0.2% volume loss reduction for a 1% increase in coverage), and horizontal lines visualize the respective overall costs. See text for details on the cost computation.

on all glaciers, i.e. with an investment of about 1 billion CHF per year. These considerations demonstrate that measures to artificially reduce ice melt with the purpose of saving glaciers at the mountain-range scale are clearly unsustainable.

Fig. 12 reveals some interesting features, defining priorities in the case that an extension of areas for technically mitigating glacier mass loss were to be discussed. Covering the largest 10 instead of 1000 glaciers allows for achieving more than a third of the total possible effect. The smaller the percentage of geotextile coverage (extending upwards from the glacier terminus), the higher the cost-efficiency. For example, if only the lowermost 10% of the 10 largest Swiss glaciers would have been covered during the last two decades, 10% of the average ice volume loss could have been mitigated at a cost of about 60 million CHF yr$^{-1}$, or roughly 1 billion CHF cumulatively over the two decades. The more glaciers are covered and the higher the share of covered area per glacier, the smaller the benefit in terms of ice loss saved per invested capital. Covering more than the lowermost about 60% has a very limited benefit but could become relevant for smaller glaciers, and in a future climate (Fig. 12).

The experiment for covering glaciers over the period 2020–2040 indicates that, compared to the past 20 years, a slightly higher percentage of the expected ice loss could be mitigated (dashed lines in Fig. 12). This is explained by increased melt rates and thus more ice saved per unit area of geotextile. Overall, costs would be smaller than in 1997–2017 by 9–21% (depending on the considered number of covered glaciers) because of reduced glacier area. It is important to note, however, that a new glacier equilibrium would still not be reachable.
Furthermore, the management of these structures is inherently inflexible. In the specific case of Vadret da Morteratsch (Oerlemans et al., 2017), no integrative cost assessment is yet available but preliminary estimates (pers. comm., F. Keller, 2019) combined with the saveable ice volume indicate that cost-efficiency would probably be similar to that of permanent geotextile coverage.

Artificial snow production in French ski resorts involves 19 million m$^3$ of water annually distributed over 53 km$^2$ of equipped slopes (Spandre et al., 2015), and is increasingly also extended to glacierized areas for maintaining operability into the summer season. For example in Les 2 Alpes, 800,000 EUR were recently invested into snow making systems on glacier ice (Carmagnola, 2018). For melt reduction related to the operation of high-alpine ski resorts and the maintenance of ski slopes on glaciers, artificial snow, also in combination with snow farming (e.g., Pelto, 2009; Spandre et al., 2015; Fischer et al., 2016; Grünewald et al., 2018), is a competitor of geotextile coverage. The efficiency and profitability of the chosen technique will depend on both the specific situation and the objective of the operator. Intercomparison of the net effect and the revenue of glacier melt reduction using geotextiles or artificial snow production should be the focus of future studies.

5.3. Uncertainties

We note that the uncertainties in our computation of artificially saved ice volume and related costs are considerable (see Fig. 11). The available information is partly incomplete (e.g. regarding the exact management of the installed geotextiles), and the assessment of the costs per site is not homogenous as different factors might have been accounted for by the individual operators responsible for the coverage. Our study provides a first-order assessment of both the costs and the most important factors determining the variations in efficiency, which we consider as robust. It is likely that economies of scale would become relevant if increasingly larger areas were covered with geotextiles, however our dataset does not consider this effect.

An assessment of the transferability of our estimates to other sites in neighbouring countries is difficult. Previous studies have estimated costs for material and maintenance of between 1.5 and 3 EUR m$^{-2}$ in Austria and Italy (Fischer et al., 2016; Senese et al., 2020). This is less than a third when compared to our data on $C_{\text{material}}$, $C_{\text{glacem}}$, and $C_{\text{maint}}$. (Table 3). Besides the fact that different factors have likely been included in the computation, it must be noted that the price level in Switzerland is generally higher.

Most sites across the Alps are using the same type of geotextile with a first-year efficiency of around 60% (Table 2). Senese et al. (2020) presented experiments with a new generation of geotextiles that might yield a better performance. Such changes in technology have not been accounted for in our study but might become relevant in the near future.

6. Conclusion

This study provided the first estimate of the overall regional effect of active glacier melt reduction over decadal time scales. By mapping the temporal change in areas covered by geotextiles in all nine sites where the technique is currently applied in the Swiss Alps, a substantial increase in covered glacier areas was found since 2005. The area with geotextile coverage by the year 2019 is 0.18 km$^2$, equivalent to only 0.02% of the total Swiss glacier area. An efficiency in melt reduction of 59% beneath newly installed geotextiles was derived from a meta-analysis of previous studies. Combination with measured annual melt rates in uncovered areas and their year-to-year variations allows estimating the total ice volume saved by artificial intervention in Switzerland. We find that in 2018 and 2019, more than 300,000 m$^3$ yr$^{-1}$ of ice have been saved. In comparison to roughly 1 km$^2$ yr$^{-1}$ of total Swiss glacier mass loss in these years this is vanishingly small (0.03%).

Direct information on the costs of purchasing, installing and maintaining the geotextile coverage was collected for most sites. This allowed computing the price of saving 1 m$^3$ of glacier ice by artificial melt reduction. We find a high variability of between 0.6 and 7.9 CHF m$^{-3}$ per year (average 2010–2019), depending on the type of installation (permanent versus seasonally replaced) and the location of the coverage (ablation versus accumulation area). The high prices indicate the considerable economic value of glaciers in high Alpine areas, and clarify why major efforts are undertaken to protect them locally.

Our study demonstrates the presently considerable artificial glacier melt reduction at the local scale which can be crucial for the operability of ski slopes or other touristic attractions such as ice caves. In a hypothetical experiment, the scalability of geotextile coverage was investigated, and the potential of saving glaciers as a whole was assessed. The results show that such upscaling is neither feasible nor affordable, and would entail exceptional impacts on both the landscape and the environment. We thus advocate for a clear separation between reasonable and economically profitable local-scale glacier melt reduction, and theoretical, large-scale applications. We believe that such a distinction is particularly important in the communication with the broader public, as false hopes and contra-productive perceptions might arise in the current and pressing climate change debate. Seeking technocratic solutions for saving glaciers at the large scale cannot be a priority in comparison to efforts to mitigate CO$_2$-emissions. Abating greenhouse gas emissions is the only way of efficiently limiting future atmospheric warming and, hence, reducing the rates of glacier mass loss globally.

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Authorship

We confirm that the manuscript has been read and approved by all named authors including the order of authors listed.

Declaration of Competing Interest

The authors declare no conflict of interest related to the results presented in this paper.

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