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LETTER

From dwindling ice to headwater lakes: could dams replace glaciers in the European Alps?

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Abstract

The potential exploitation of areas becoming ice-free in response to ongoing climate change has rarely been addressed, although it could be of interest from the water management perspective. Here we present an estimate for the potential of mitigating projected changes in seasonal water availability from melting glaciers by managing runoff through reservoirs. For the European Alps we estimate that by the end of the century, such a strategy could offset up to 65% of the expected summer-runoff changes from presently glacierized surfaces. A first-order approach suggests that the retention volume potentially available in the areas becoming deglacierized is in excess of the volume required for achieving the maximal possible mitigation by more than one order of magnitude. Obviously, however, such a strategy cannot compensate for the reduction in annual runoff caused by glacier ice depletion. Our estimates indicate that by 2070–2099, 0.73 ± 0.67 $\mathrm{km}^3\ \mathrm{a}^{-1}$ of this non-renewable component of the water cycle could be missing in Alpine water supplies.

1. Introduction

Environments significantly influenced by the presence of seasonal snow or glaciers are hotspots regarding the impacts on water availability in response to expected climate change (e.g. Beniston 2003, Viviroli *et al* 2011, Mankin *et al* 2015). With warmer temperatures, both the duration and the spatial extent of the seasonal snow cover are projected to decrease (e.g. Barnett *et al* 2005, Steger *et al* 2013, Brutel-Vuilmet *et al* 2013) and glaciers are expected to retreat significantly (e.g. Zemp *et al* 2006, Radić and Hock 2011, Cogley *et al* 2012). This is anticipated to have influences on water resources at different time scales, and to affect runoff seasonality in particular (for reviews, see de Jong *et al* 2005, Schaner *et al* 2012, Radić and Hock 2014): while increased discharge is expected during the winter and spring time, a significant decrease is projected for summer and fall (e.g. Bavay *et al* 2009, Huss 2011, Berghuijs *et al* 2014). Glacier recession, moreover, is known to have an effect on longer-term water availability, with an initial phase of increased water yields in response to increased melt rates, and a later stage of decreased runoff due to the reduction in actual glacier size (e.g. Hock *et al* 2005, Farinotti *et al* 2012, Bliss *et al* 2014).

Glacier recession has generally been connoted negatively, with concerns emerging from the impacts of reduced water yields in summer (Piao *et al* 2010, Immerzeel *et al* 2010), the impacts of a changed landscape in touristic regions (Scott 2006, Scott *et al* 2007), or the hazards induced by the destabilization of formerly frozen grounds (Carey 2005, Kääb *et al* 2005, Fischer *et al* 2006) and the associated potential for more frequent glacier lake outburst floods (Richardson and Reynolds 2000, Dussaillant *et al* 2010). Water-availability related concerns are particularly prominent in arid regions, such as Central Asia or parts of Southern America, in which the dependence on snow and glacier melt for regional supply is most important

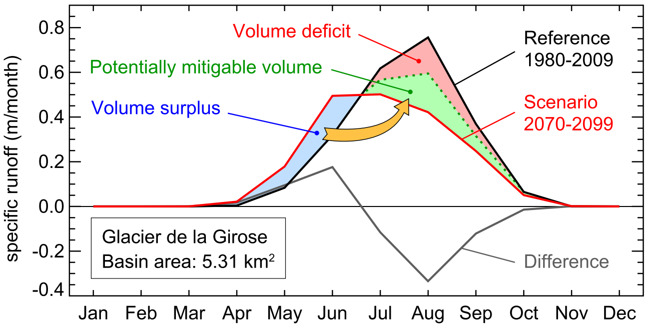

Figure 1. Illustration of the potential mitigation through water management. *Volume surplus* (light blue) is the runoff volume that, according to the projection, will be in excess to the runoff in the reference period during late spring and early summer. This volume could potentially be transferred into late summer and early autumn (arrow) in order to partially compensate (light green) the runoff reduction caused by glacier depletion. *Volume deficit* (light red) is the net reduction in annual runoff. The example refers to Glacier de la Girose, France.

(Hagg and Braun 2005, Kaser *et al* 2010). Such regions, moreover, often coincide with economically less developed areas, thus lacking the potential capability of mitigating the impacts through engineering solutions (Orlove 2009).

The potential of exploiting newly deglacierized areas has not often been addressed, although it was suggested earlier that new proglacial lakes, likely to form in such environments, could take over important roles in hydropower production or the management of both water resources and natural hazards (Frey *et al* 2010, NELAK 2013). In support of such a possible utilization, the supposed 'neutrality' in terms of ecological value of the surfaces becoming ice-free is sometimes mentioned: Since the exposed forefields are bare, non-vegetated and relatively simple in their ecosystem structure (e.g. Nemergut *et al* 2007, Hodson *et al* 2015), a potential exploitation could result in comparatively limited ecological impacts. Similarly, it could be argued that an intervention in the uppermost part of a given river stretch would have only minimal consequences on river continuity.

This opens the admittedly provocative question on whether newly deglacierized areas could be used to mitigate, at least partly, the hydrological effects caused by the shrinkage of glaciers and the snow cover. Postulating that preserving the current natural runoff regime is a desirable target, the additional water expected during spring time under changed climate conditions could in fact be temporarily stored and seasonally transferred in order to compensate for the reduction in summer water yields (figure 1). In such a scenario, reservoirs would replace part of the hydrological effect currently provided by glaciers and the seasonal snow pack.

In this study we focus on the European Alps, a region expected to be significantly affected by future changes in snow- and glacier-fed water resources (e.g. Beniston *et al* 2011, Huss 2011), and use a first-order approach in order to assess whether 'replacing glaciers with dams' is an option theoretically worth considering. For doing so, we use the output of a global glacier model (GloGEM) (Huss and Hock 2015) in combination with latest climate projections (Taylor *et al* 2012) to assess the evolution of both glacier extent and runoff until the end of the century. We then compute storage capacities required for achieving the maximal possible mitigation, and compare these results to an estimate of retention volumes that could hypothetically be installed in newly deglacierized forefields. While we don't discuss the technical feasibility or any of the actual ecological implications of such a hypothetical way of action, we provide a first assessment of the maximal effect that such a strategy could potentially achieve.

2. Methods

2.1. Runoff from presently glacierized surfaces

We define *glacier runoff* Q_{gl} as the sum of liquid precipitation (rain) that does not refreeze within a glacier, and snow- and ice-melt that stems from currently glacierized areas (*glacier runoff* as defined by *concept 1* in Radić and Hock (2014) neglecting evaporation). The individual components of Q_{gl} are taken from the GloGEM by Huss and Hock (2015) (see section 2.2) and evaluated within individual catchments defined by present glacier extent. Presently glacierized areas are discerned with the glacier outlines provided by the Randolph Glacier Inventory (Pfeffer and The Randolph Consortium 2014) version 4.0 (RGIv4.0; Arendt *et al* 2014), which refers to the year 2003 for Central Europe (Paul *et al* 2011). For all analyses, the area contributing to Q_{gl} is fixed to the glacier extent given by the RGI. This is to avoid suggesting misleadingly large reductions in future water yields in case of shrinking catchment area due to glacier retreat.

For quantifying the relative importance of glacier contributions to total runoff, we consider the percental runoff share that stems from presently glacierized surfaces, that is

$$RS_{\mathrm{gl}} = 100 \cdot Q_{\mathrm{gl}}/Q_{\mathrm{tot}}. \quad (1)$$

Here, Q_{tot} is the total runoff at the considered location, and is estimated through a weighted flow accumulation operation (e.g. Pistocchi and Pennington 2006, Pistocchi 2014) of the climatological monthly composite runoff fields provided by the University of New Hampshire/Global Runoff Data Center (Fekete *et al* 2002). The analysis is performed on the *GTOPO30* digital elevation model (DEM) provided by the *HYDRO1k* data base (https://lta.cr.usgs.gov/HYDRO1K). The DEM has a resolution of 30 arc-seconds (about 1 × 1 km), which is maintained in all our results.

In principle, RS_{gl} is defined for any time aggregation, but only summer (July, August, September) and annual values are considered in the following. Meltwater transit-time along the considered streams (in the order of some days to a few weeks; Huss 2011) are therefore neglected.

Derived values of both Q_{tot} and RS_{gl}, are validated against independent estimates based on station measurements (supplementary figures S.1 and S.2). The general agreement is satisfactory although a tendency to underestimate Q_{tot} in relatively small catchments (i.e. catchments with small runoff) emerges. This causes RS_{gl} to be overestimated in such cases. However, since RS_{gl} is only used for quantifying the relative importance of glacier runoff during the reference period 1980–2009 (and thus is irrelevant for the considerations on potential mitigation and storage volume), this has no effect on the presented interpretations.

2.2. Glacier and climate evolution

GloGEM (Huss and Hock 2015) computes glacier mass balance and associated glacier geometry changes on a glacier-by-glacier basis. Glacier outlines are obtained from the RGI v4.0 and are intersected with the DEM provided by the shuttle radar topography mission (Jarvis *et al* 2008) in order to derive relevant topographical information (glacier hypsometry, aspect, and slope in particular). For each glacier, the information is aggregated into 10 m elevation bands, which is the resolution at which the model operates. The initial ice thickness distribution for every glacier is calculated with the method presented by Huss and Farinotti (2012), updated to the RGIv4.0 (Huss and Hock 2015). The climatic glacier mass balance—that is the balance of snow accumulation, snow- and ice-melt, and refreezing (Cogley *et al* 2011)—is calculated at monthly resolution based on air temperature and precipitation time series (Huss and Hock 2015). These time series are taken from ERA-Interim reanalysis (Dee *et al* 2011) for the past (period 1979 to present) and from the 5th phase of the coupled model intercomparison project (CMIP5; Taylor *et al* 2012) for the future (present to 2099). For CMIP5, results from 14 different Global Circulation Models (GCMs) and 3 different representative concentration pathways (RCP 2.6, 4.5, and 8.5; Meinshausen *et al* 2011) are considered (supplementary figure S.3). The so-computed glacier mass balance is then used in combination with the parametric approach by Huss *et al* (2010) for adjusting glacier surface elevation and extent on a yearly basis.

The model is calibrated at the regional scale with the consensus glacier mass-change estimates by Gardner *et al* (2013), and is validated against observations of both glacier mass balances (*in situ* and geodetic measurements; WGMS 2012) and glacier area changes (Fischer *et al* 2014). For Central Europe, model performance is high, with average deviations in the calculated glacier-wide (point) mass balance of ± 0.04 (± 0.16) m water equivalent a^{-1}, and average area-change rates reproduced within ± 0.04% a^{-1} (see supplementary tables 5–7 in Huss and Hock 2015).

For additional details on the glaciological modelling, including details on the downscaling of the climatological data, and the calibration and validation procedures, refer to Huss and Hock (2015).

2.3. Computation of mitigable volume change

We compute the *maximal potentially mitigable volume change* for a given scenario period as the sum of all positive volume differences with respect to the mean runoff volume during the reference period 1980–2009 (figure 1). All calculations are performed using monthly values. We present results for a near-term (2010–2039), a medium-term (2040–2069), and a long-term horizon (2070–2099). The monthly differences are computed on a glacier-by-glacier basis for simulations appertaining to the same GCM ensemble member, and aggregated to the resolution of the HYDRO1k DEM (1 × 1 km). The same DEM is used for deriving flow directions with which the aggregated values are accumulated downstream. Both the derivation of the flow directions and the downstream flow accumulation follows Jenson and Domingue (1988).

Presented results refer to the mean of all available GCMs, while individual RCPs are considered separately. We use the standard deviation between individual GCM results in order to quantify the uncertainty linked to climate model choice, and the standard deviation of the time series of a given GCM in order to quantify internal year-to-year variability. Presented uncertainties refer to the combination of both effects (added in quadrature). The uncertainty introduced by GloGEM (see previous section) is assumed to be included in this range as typical year-to-year variations in glacier mass balance are larger than the associated uncertainties by about one order of magnitude.

Table 1. Projected changes in total runoff from presently glacierized surfaces for the European Alps. Changes are given with respect to the reference period 1980–2009 and refer to yearly totals (first block), summer (July–September) totals without intervention (second block), and summer totals with implementation of the maximal potential mitigation (third block). Values are in km^3. Mean runoff volumes for the reference period are given at the end of the table. Confidence intervals refer to the 95% level.

Period	RCP 2.6		RCP 4.5		RCP 8.5	
ANNUAL TOTALS						
2010–2039	$+1.00 \pm 0.74$	(+18%)	$+1.05 \pm 0.75$	(+19%)	$+1.14 \pm 0.76$	(+21%)
2040–2069	-0.10 ± 0.69	(−1%)	$+0.05 \pm 0.74$	(0%)	$+0.32 \pm 0.80$	(+6%)
2070–2099	-0.74 ± 0.62	(−14%)	-0.73 ± 0.67	(−13%)	-0.93 ± 0.89	(−17%)
SUMMER—WITHOUT INTERVENTION						
2010–2039	$+0.55 \pm 0.56$	(+13%)	$+0.61 \pm 0.58$	(+15%)	$+0.60 \pm 0.59$	(+15%)
2040–2069	-0.61 ± 0.53	(−15%)	-0.64 ± 0.58	(−16%)	-0.62 ± 0.63	(−15%)
2070–2099	-1.16 ± 0.48	(−29%)	-1.48 ± 0.53	(−37%)	-2.21 ± 0.71	(−55%)
SUMMER—WITH MAXIMAL MITIGATION						
2010–2039	$+1.68 \pm 0.75$	(+42%)	$+1.83 \pm 0.77$	(+46%)	$+1.90 \pm 0.77$	(+47%)
2040–2069	$+0.21 \pm 0.69$	(+5%)	$+0.44 \pm 0.74$	(+11%)	$+0.84 \pm 0.81$	(+21%)
2070–2099	-0.57 ± 0.57	(−14%)	-0.52 ± 0.65	(−13%)	-0.75 ± 0.84	(−18%)
1980–2009	ANNUAL TOTAL: 5.28 ± 0.48				SUMMER TOTAL: 3.97 ± 0.36	

3. Results

Presently glacierized surfaces in the European Alps (ca. 2050 km^2 on 3800 glaciers) contributed an average runoff volume of 5.28 ± 0.48 km^3 a^{-1} during 1980–2009 (table 1). About 75% of this volume (3.97 ± 0.36 km^3 a^{-1}) occurred between July and September (*summer* hereafter). The spatial distribution of the resulting runoff share is shown in figures 2(a) and (b). Regions with very important glacier contributions are found across the whole Alpine Ridge, with two main clusters around the common borders of France/Italy/Switzerland (Mont Blanc Massif and Pennine Alps) and Austria/Italy/Switzerland (Bernina and Adamello–Presanella Ranges, as well as Ortler Alps and Ötztal Alps).

In terms of relative importance, the picture is similar for both annual and summer values (figures 2(a) and (b) respectively), although the actual magnitude can largely differ. For the Mont Blanc region, for example, the annual runoff-share from glacierized surfaces is estimated to be around 20%, whereas this share increases to more than 60% during the summer months.

Also for the major low-lying rivers, the runoff-share from presently glacierized surfaces can be significant. Summer (annual) values for the Rhône at Chancy, the Inn at Innsbruck, the Po at Pontelagoscuro and the Rhine at Basel (see figures 2(a) and (b) for locations) are in the order of 53 (15), 38 (14), 11 (2) and 6% (2%), respectively, with uncertainties in the range of 25% of the estimated values. At its confluence with the Danube at Ingling, the Inn is estimate to still have an annual (summer) glacier runoff share of 3% (10%). These values compare well with the results by Huss (2011), although the observed tendency of overestimating the share of glacier runoff in smaller basins seems to re-emerge (see section 2.1).

At the Alpine scale, the total runoff yield from presently glacierized surfaces is expected to increase significantly in the short term ($+1.05 \pm 0.75$ km^3 a^{-1} by 2010–2039 according to RCP 4.5) and to decrease in the long term (-0.73 ± 0.67 km^3 a^{-1} by 2070–2099, RCP 4.5). The general evolution is similar for other RCPs although differences occur as a result of differing temperature and precipitation projections (see table 1 and supplementary figure S.3).

Without any intervention, the temporal evolution of the summer runoff contributions ($Q_{\mathrm{gl}}^{\mathrm{JAS}}$) is similar to the annual ones, although appreciable reductions in the total water yield are expected in the mid-term already (table 1). It is important to note, however, that at the local scale such effects are visible even in the short term: figures 2(a)–(c) presents projected changes in $Q_{\mathrm{gl}}^{\mathrm{JAS}}$ for RCP 4.5 (results for RCPs 2.6 and 8.5 are given in supplementary figures S.4 and S.5, respectively) and shows that significant reductions are expected in the easternmost and westernmost parts of the Alps in particular (figure 2(a)). Such a decrease in water availability becomes widespread in the mid term (figure 2(b)) and is virtually ubiquitous for the long term (figure 2(c)).

Reductions in $Q_{\mathrm{gl}}^{\mathrm{JAS}}$ are substantially less important when surplus volumes occurring in the former part of the year are virtually transferred to the summer months through temporary storage in hypothetical reservoirs (figures 2(d)–(f)). On the Alpine scale, the expected decrease in summer runoff could even be offset entirely in the mid term for all considered RCPs (table 1), although the statement does not hold true at the local scale (figure 2(e)). On average for the period 2070–2099, the results suggest that about two thirds (65%) of the change in summer runoff from presently glacierized surfaces could be mitigated through active water management. Also at the local scale the impacts of such a strategy are significant. Figures 2(g)–(i) show the differences between runoff reductions in the case

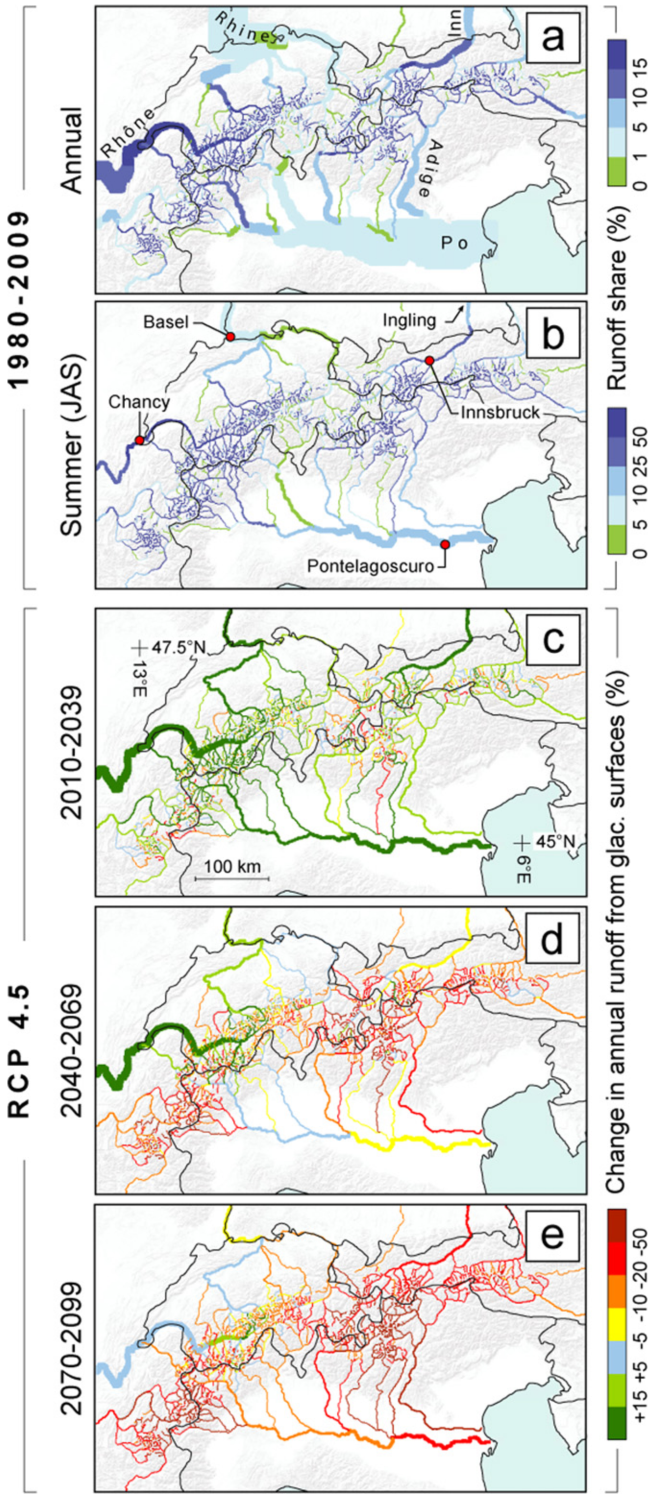

Figure 2. Past and future runoff contribution from presently glacierized surfaces. The mean annual (a) and summer (b) runoff share form presently glacierized surfaces (see section 2.1 for definition) is given for the reference period 1980–2009. The expected change in annual runoff from the same surfaces for 2010–2039 (c), 2040–2069 (d), and 2070–2099 (e) is expressed as a relative change with respect to the reference period. Changes (means over all considered GCMs) refer to RCP 4.5. Results for RCPs 2.6 and 8.5 are shown in supplementary figure S.6. In (a) and (b), river-width is proportional to the annual and July–August–September (JAS) runoff estimated from the UNH/GRDC data set, respectively. In (c)–(e) the width is proportional to the estimated annual runoff contribution from glacierized surfaces.

without intervention and the case with maximal potential mitigation (that is the effectively mitigable change), and highlight that the largest potential is available in regions that currently have high degrees of glacierization. This observation, which might seem contra-intuitive at first, can be explained by the fact that these regions are also expected to experience the largest changes in annual runoff regime, which is the pre-requisite for the mitigation strategy defined here (see figure 1).

4. Discussion

The potential for mitigating the runoff reduction in the summer months is significant, and possibly of importance for individual regions. An estimate on the actual feasibility of such a water management strategy is thus of interest. This opens the question about how much of the required storage volume—in the order of 1 km^3 over the European Alps by the end of the century—could potentially be installed. In order to minimize the impact of such important technical infrastructure, one strategy could be to focus on areas that are becoming ice-free due to glacier retreat. This would be in line with the general idea of artificially sustaining the effect that glaciers have in the hydrological cycle, and possibly result in smaller ecological and socio-economic impacts when compared to placing storage volumes in lower lying—and thus typically vegetated and inhabited—valleys.

We perform such a first-order assessment by virtually placing dams at the locations of current glacier terminus (determined through the RGI v4.0), and calculate the water volume of each individual lake being formed. We do this by making use of the subglacial bedrock topography provided by Huss and Farinotti (2012) and using watershed delineation as described by Jenson and Domingue (1988). Dams are initially placed perpendicularly to the glacier centre lines provided by Machguth and Huss (2014) and are iteratively rotated in 5° steps in order to minimize the ratio between required dam-wall area (product of crest length and average dam height) and obtained reservoir volume. Dam heights and widths are limited to a maximum of 280 m and 800 m, respectively (the dimensions of the largest dam currently installed in the Alpine area) and 'grown' to the maximal size allowed by the local topographical conditions. Note that this procedure aims at estimating the maximal installable total reservoir volume, and is not intended to designed reservoirs capable of accommodating the volume surplus of individual glaciers only.

According to our analysis, the potentially installable volume over the entire Alps exceeds the required volume by more than one order of magnitude (figure 4(a)). In general, the hypothetically available volume is largely in excess to the locally required one also at the sub-regional scale. Figure 4(b) shows the spatial distribution of the storage volume hypothetically available as the percentage of the volume required for achieving the maximal potential mitigation at a given location (see figure 3). As expected, the excess in potentially available storage increases when moving downstream of the river network.

Clearly, such a widespread installation is neither desirable, nor technically or economically viable. Figure 4(a) highlights, however, how a relatively small set of the virtually created installations could already provide the required total storage volume—assuming these installation being fed by the surplus water volumes of all surrounding glaciers. According to the results, less than a dozen of the largest virtual reservoirs would be sufficient for providing the total volume required for achieving the maximal potential mitigation for the period 2070–2099 under the RCP 4.5 scenario. This is true even when considering the relatively large uncertainties introduced by the GCM spread, the RCP choice and the year-to-year variability (grey band in figure 4(a)). The total uncertainty, in fact, influences the required total storage volume by a factor of 2 at most (table 1).

The necessity of collecting the surplus water volumes of surrounding glaciers into centralized reservoirs would clearly be a major technical challenge when adopting the described strategy. Figure 4(b), however, suggests that sufficient storage volume is potentially installable also at the sub-regional scale, which would reduce the difficulty in centralizing the water from individual glaciers. Obviously, this decentralization of reservoirs would significantly increase the total number of required installations, and—on a par—the ecological and socio-economic impacts.

Four visualization examples (one for each major Alpine country) of the virtually installed reservoirs are shown in figures 4(c)–(f). In this respect we would like to emphasise that it is not our intention to suggest that these particular locations could indicate a priority for installation. Our analysis, in fact, clearly neglects a whole series of factors—linked to ecological, environmental, economical, and technical considerations amongst others—that would need to be considered when compiling an actual priority list. Similarly, our analysis does not take into account already-installed infrastructure—the exploitation of which should be first choice when considering an actual implementation of the strategy—and does not consider potential competing interests, that would likely arise in case of a widespread installation of artificial reservoirs. In this respect, in fact, it should be noted that the typical seasonal production cycle of current hydropower infrastructure installed in the Alpine region, is exactly anticyclical with the mitigation strategy proposed here (current hydropower operators with storage typically accumulate water during summer in order to produce energy during winter).

Besides the limitations above, it has obviously to be noted that seasonally transferring a given runoff volume cannot compensate a reduction in the total annual runoff (see figure 1). Even assuming unchanged annual precipitation in the future, and neglecting increased evapotranspiration losses due to higher air temperatures, such a runoff decrease has to be expected for high alpine catchments in response to glacier retreat. This is because glaciers losing large parts of their ice volume will largely reduce their contribution to runoff by ice melt. The water that contributes to runoff during the glacier recession phase can, hence, be considered as a non-renewable water contribution to the water cycle: once depleted, the water volume

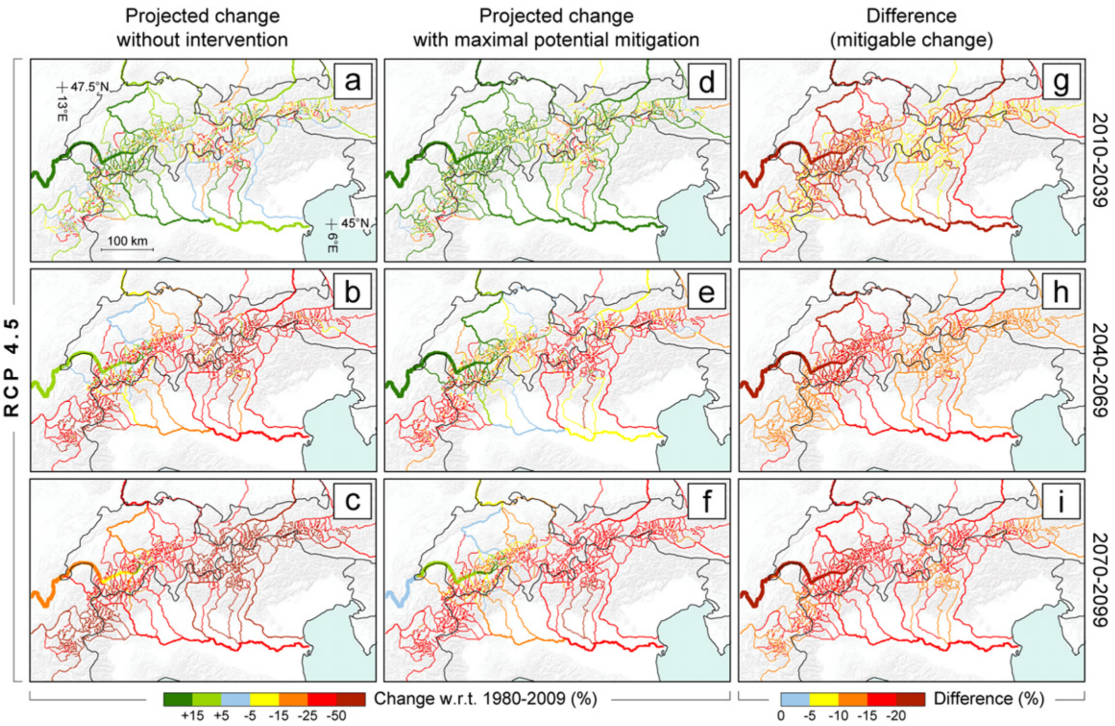

Figure 3. Projected changes in mean summer (JAS) runoff form presently glacierized surfaces. The changes are expressed as relative differences with respect to (w.r.t) 1980–2009 and refer to the situation without any intervention (a)–(c), and the situation in which the maximal potentially mitigable volume (see figure 1 for definition) is realized (d)–(f). The difference between the two cases, that is the potentially mitigable change, is presented separately (g)–(i). Results are given for three different time periods (rows) and refer to RCP 4.5. Results for RCPs 2.6 and 8.5 are given in supplementary figures S.4 and S.5, respectively. River width is proportional to the estimated summer runoff.

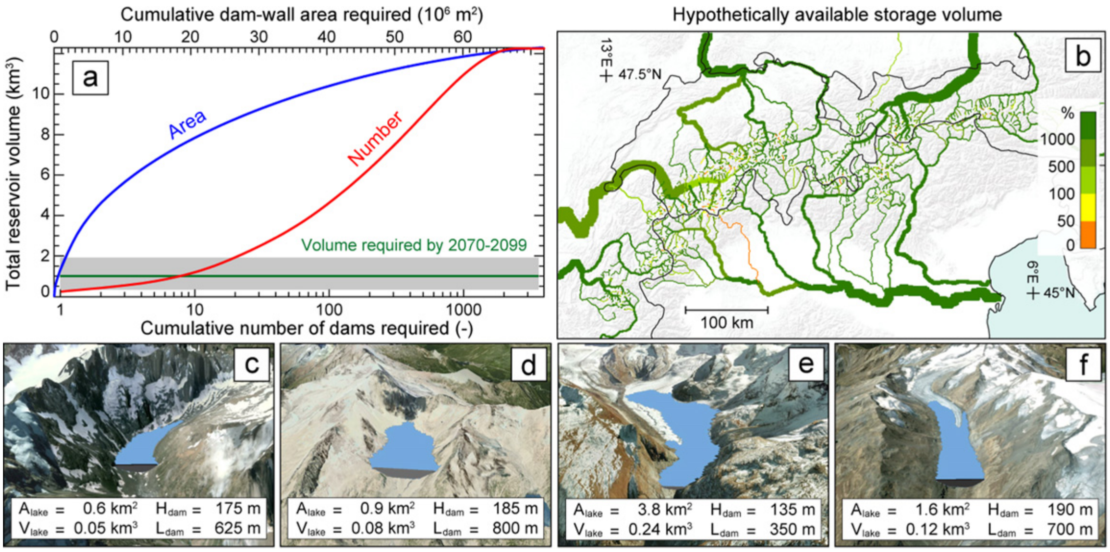

Figure 4. Comparison of required and hypothetically available storage volume. (a) Cumulative number of dams (red) and wall-dam area (blue) required for achieving a given total storage volume according to the virtual set of constructed reservoirs. The storage volume required for achieving the maximal potential mitigation during 2070–2099 is shown (green). The grey band represents the uncertainty due to GCM spread, considered RCP, and year-to-year variability. (b) Ratio between (1) the maximal hypothetically available storage volume along a given river stretch and (2) the storage volume required for achieving the maximal potential mitigation (see figure 1 for definition) in summer runoff change at a given location (figures 3(d)–(f)). The results refer to the period 2070–2099 and RCP 4.5. The widths of the rivers are proportional to the hypothetical storage volumes cumulated along a given river stretch. Four hypothetical reservoirs are visualized for examples in the (c) French, (d) Italian, (e) Swiss, and (f) Austrian Alps. For each example, the area (A_{lake}) and volume (V_{lake}) of the generated lake, as well as the maximal height (H_{dam}) and the length of the crest of the required dam (L_{dam}) is given (for comparison: Grande Dixence, the largest dam currently installed in the European Alps, has $A_{\mathrm{lake}} = 0.40\ \mathrm{km}^3$, $V_{\mathrm{lake}} = 3.7\ \mathrm{km}^2$, $H_{\mathrm{dam}} = 285$ m, $L_{\mathrm{dam}} = 700$ m). Topographical imagery is from Google™ Earth.

previously stored as ice will require decades to centuries, and drastically changed climatic conditions, to re-form.

The change in this non-renewable contribution is shown in figures 2(c)–(e) for the three considered time horizons and RCP 4.5 (see supplementary figure S.6 for RCP 2.6 and 8.5). According to these results, a total of 0.73 ± 0.67 km^3 of water per year could be missing across the European Alps on average between 2070 and 2099 (see table 1). This is equivalent to roughly 80% of today'(s) annual freshwater consumption in Switzerland (SFSO 2014), and highlights the need of alternative water management strategies in addition to the hypothetical one presented above. A part from the obvious need of curbing current greenhouse gas emissions in order to minimize changes in global temperature, concepts aiming at a more efficient use of water resources are required.

5. Conclusions

Surfaces presently covered by glaciers are important water sources across the European Alps. During the period 1980–2009, glaciers provided an average 5.28 ± 0.48 $\mathrm{km}^3\ \mathrm{a}^{-1}$ of freshwater. About three quarters of this volume occurred during July–September, resulting in significant glacier contributions also in large low-lying rivers including the Po, the Rhine, and the Rhône.

Important decreases in both annual and summer glacier runoff contributions are anticipated in response to ongoing climatic change. For an average emission scenario (RCP 4.5), annual runoff contributions from presently glacierized surfaces are expected to decrease by 16% by 2070–2099—despite of nearly unchanged contributions from precipitation. The decrease is even more pronounced during the late summer months (JAS), for which a decrease of about 37% is projected. This highlights the need of adequate water management strategies in the future.

Here, we addressed the somewhat provocative question of whether replacing glaciers by dams could be an option theoretically worth considering in order to mitigate the projected changes in summer runoff. Postulating that keeping the past runoff regime of individual river stretches unaltered is a desirable target, we quantify the water volume that could seasonally be transferred by means of reservoirs in order to compensate for such runoff reductions. We estimate that by 2070–2099, roughly 1 $\mathrm{km}^3\ \mathrm{a}^{-1}$ of water could be seasonally redistributed, and that this volume would be sufficient to offset about two thirds of the expected changes in July–September runoff across the European Alps.

With a first-order assessment that neglects a series of environmental, ecological and economic considerations, we compute the storage volume that could hypothetically be installed in areas becoming ice-free due to glacier retreat. We estimate that this hypothetical volume is in excess of the required one by more than one order of magnitude, and that less than a dozen of large dams could theoretically provide the total required storage. Centralizing and redistributing the waters from the numerous glacierized catchments would, however, be a major technical challenge.

Obviously, the here addressed technocrat solution cannot compensate for the expected net reduction in annual water yields. For compensating this non-renewable component of the water cycle, alternative strategies aiming at a more efficient management of water resources are required.

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