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Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin

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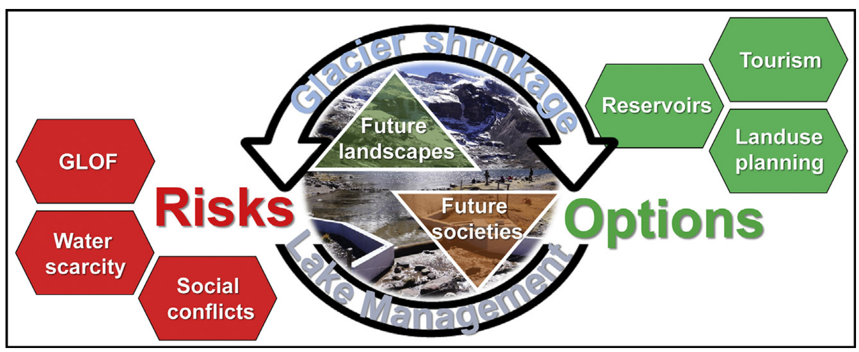
HIGHLIGHTS

- Glacier contribution to river discharge would be negligible until 2100.
- Current and future key hotspots of water risks challenge local water management.
- Future impacts from increasing water demand could outweigh changes in water supply.
- Future water management requires an integrated disaster and water risk framework.

GRAPHICAL ABSTRACT

Options and risks resulting from developing lakes in the context of glacier shrinkage considering future landscapes and societies. Photography: Lake Ausangatecocha (Cordillera Vilcanota), taken in 08/2016.



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ABSTRACT

Rapidly growing lakes in deglaciating mountain regions represent both: emerging risks and options for human livelihoods. In the Andes of Peru, seasonal water scarcity and Glacial Lake Outburst Floods (GLOF) pose a serious threat for highly exposed and vulnerable people. In addition, water demand is growing due to increasing irrigated agriculture, population and hydropower production. In this context, we assess current and future water risks and management options for the Vilcanota-Urubamba basin, Southern Peru. Therefore, the GLOF susceptibility of glacier lakes and the potential maximum reach of damaging flow were analysed. Eighteen out of 134 current and another six out of 20 future glacier lakes were identified as potentially highly susceptible to GLOF. A total of eight existing and one possible future lakes indicate very high risk potentials. Furthermore, a comprehensive surface water balance scheme for five selected subcatchments reveals that future river discharge could be reduced by some 2–11% (7–14%) until 2050 (2100). Particularly in headwaters and during dry seasons, glacier contribution representing roughly 15–25% to total streamflow is crucial and would substantially decrease to below 4–22% (1–3%) until 2050 (2100) with strong glacier shrinkage under intense warming (scenario RCP8.5). In the middle and lower basin, long-term water availability could be jeopardized by growing irrigated agriculture and hydropower capacity. Combining a GLOF and water shortage risk assessment, three key hotspots of current and future water risks were identified. In the context of the identified risks and complex intertwining of water users involving conflict potentials, robust adaptation planning is necessary within an integrative water and risk management framework. Therefore, it is crucial to incorporate ancestral and local knowledge for long-term management

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planning and implementation. This process should take place beyond temporarily limited governmental and project agency and strengthen broad acceptance of corresponding measures for adapting to hydroclimatic and socioeconomic changes.

1. Introduction

In the Andes of Peru and adjacent arid lowlands, human subsistence often depends on year-round streamflow from glaciers and lakes, particularly in the dry season (May–September). As seasonal snow cover is missing and pronounced hydroclimatic seasonality prevails in the outer tropics, perennial glacial streamflow represents a critical buffer to water shortages, annual discharge variability, and river contamination. However, global change impacts increasingly affect local hydrology and associated livelihoods (Kaser et al., 2010; Rabatel et al., 2013; Vuille et al., 2018). Rapidly shrinking glaciers and growing lakes as well as the expansion of irrigated agriculture and hydropower schemes, population growth and increasing energy demand might enhance water-related risks and scarcity, in both: quantity and quality (Drenkhan et al., 2015; Vuille et al., 2018). While water quantity might be strongly affected at spatiotemporal level, i.e. seasonally (e.g. pronounced dry season) and locally (e.g. deglaciation in headwaters), water quality can be 'naturally' jeopardized by e.g. acid rock drainages (ARD) from exposed bedrock and sediments in recently deglaciated areas (Drenkhan et al., 2015).

In rapidly changing high mountain environments, such as the tropical Andes, Himalayas and Alps, Glacial Lake Outburst Floods (GLOFs) represent imminent risks (Bajracharya et al., 2007; Cook et al., 2016; Emmer et al., 2015; Frey et al., 2016; Huggel et al., 2002). Hazards emerge from over-steepened ice, rocks and moraines, permafrost degradation, and de-buttressed slopes. In this context of increasing hazard conditions, detaching ice and rock masses might have a higher probability to reach glacier lakes growing at the foot of icy peaks, induce impact waves and trigger GLOFs affecting exposed people and assets further downstream in areas often characterized by urban expansion (Colonia et al., 2017; Haeberli et al., 2017). Furthermore, multidimensional human vulnerabilities (e.g. poverty, weak institutionality, political setting, and cultural aspects) enhance water-related risks (Lynch, 2012).

In the Andes of Peru, robust mechanisms for both (disaster) risk reduction and adaptation to changing hydrological conditions in these catchments of complex human-natural systems are urgently needed. However, current knowledge is quite limited due to scarce and inconsistent socioeconomic and hydroclimatic datasets which particularly result from complex topography, climatic setting, and limited in-situ monitoring and data processing (Drenkhan et al., 2015, 2018).

In this context, new (here defined as developed after 1988) and potential future (here defined as developing after 2016) glacier lakes in Peru bear important needs and options for integrated disaster risk management (IDRM) and integrated water resources management (IWRM) (Haeberli et al., 2016a), e.g. for the domestic, agriculture and hydropower sectors in adjacent downstream areas. These lakes potentially attenuate deglaciation-driven increasing discharge variability and scarcity, particularly in the dry season (Drenkhan et al., 2015). Additionally, new lakes could offer important attractions for tourism (Drenkhan et al., 2018; Haeberli et al., 2017).

Here, we make a first attempt to combine current and future high-flow (GLOFs) and low-flow (water scarcity) risks and management options for the upper Vilcanota-Urubamba basin (hereafter: 'VUB') in Southern Peru comprehensively analysing four main aspects: i) GLOF risk assessment focusing on dangerous glacier lakes, human vulnerabilities and exposure, ii) water balance and critical low-flows for selected catchments, iii) analysis of key hotspots of hydrological risks, and iv) suggestions for integrative disaster risk and water management at the interface of science and policy.

2. Regional setting and context

Our study region covers the upper Vilcanota-Urubamba basin (VUB) with a total area of 11,048 km^2 between 6372 m asl. (Ausangate, Andean altiplano) and 1180 m asl. (outlet at Santa María, transition towards the Amazon rainforest) in the Central Andes of Southern Peru (Cusco region). It belongs to the Administrative Water Authority (AAA) XII Urubamba-Vilcanota which is managed by three Local Water Authorities (ALA) of the National Water Authority (ANA) as part of the new water law from 2009 (Fig. 1). According to a previous study by Drenkhan et al. (2018), the VUB includes a glacier extent of 141.7 km^2 area (1.3% of total basin area) and ~6.457 km^3 volume (based on ice thickness estimations with a related uncertainty range of $\pm$30%), distributed within three main mountain ranges (in downstream running order): Cordillera Vilcanota (66.0 km^2, ~3.463 km^3) including Quelccaya ice cap (18.4 km^2, ~1.186 km^3), Cordillera Urubamba (18.1 km^2, ~0.553 km^3), and Cordillera Vilcabamba (39.2 km^2, ~1.254 km^3). A total of 544 lakes (26.9 km^2, ~0.699 km^3) and two large reservoirs, Sibinacocha (Cordillera Vilcanota) and Langui Loy (province of Acomayo) with a total area of 83.4 km^2 and about 0.130 km^3 useful volume, can be identified. For a more detailed water risk analysis of the basin we defined five subcatchments (total area: 4144 km^2) including high glacier extent (137.2 km^2) and several new lakes (in downstream running order): Salcca–Sibinacocha (01-SS), Pitumarca–Tigre (02-PT), Ccochoc–Chicón (03-CC), Aobamba–Santa Teresa (04-AST) and Runtumayu–Hualancay (05-RH) (Fig. 1). According to census data for the covered ten provinces in 2017, total population in the VUB was estimated at 838,500 inhabitants who are distributed in mostly small cities (by far largest city: Cusco with 447,900 people) and settlements (INEI, 2017a). Around 1318 km^2 of the basin are covered by agricultural land from which about the half (673.8 km^2) is irrigated (INEI, 2013). Particularly in the lower basin, energy production from hydropower is important, accounting for total installed capacity of >290 MW including the hydropower plants Machu Picchu I/II (190 MW) and Santa Teresa I (98 MW), see Fig. 1.

2.1. Socioeconomic development and cultural values

The region includes strong multidimensional human vulnerabilities which can be at least to some extents assessed by using indicators of e.g. poverty, education, and life conditions. The Human Development Index (HDI) which takes into account basic variables of life expectancy, education, and family income, is partially suitable for this purpose. In 2012 the ten VUB provinces indicated a HDI of 0.49, close to Peru's average of 0.51. The average of the five selected subcatchments only is considerably lower with 0.39. Generally, strong spatial and gender disparities persist with lowest HDI values in rural Paucartambo (0.16) and highest in urban Cusco (0.61) and with a clearly reduced index for women indicating higher life expectancy but considerably lower education and income values (PNUD, 2013). Poverty has been specifically assessed for Peru defined by basic food basket needs at ~3.4 USD/day/capita for 'general' and ~1.8 USD/day/capita for extreme poverty, respectively (INEI, 2017b). In 2016, general (extreme) poverty in the region of Cusco varied between 20.6% and 24.7% (1.3%–2.5%) of the population which corresponds to a ~50% (~500%) reduction in the last decade (2007–2016). Furthermore, nearly half (44.5%) of the inhabitants of Cusco do not have access to drinking water via the public network which is considerably over the national average of 36.4% (INEI, 2016). Hence, although some improvements have been achieved particularly in

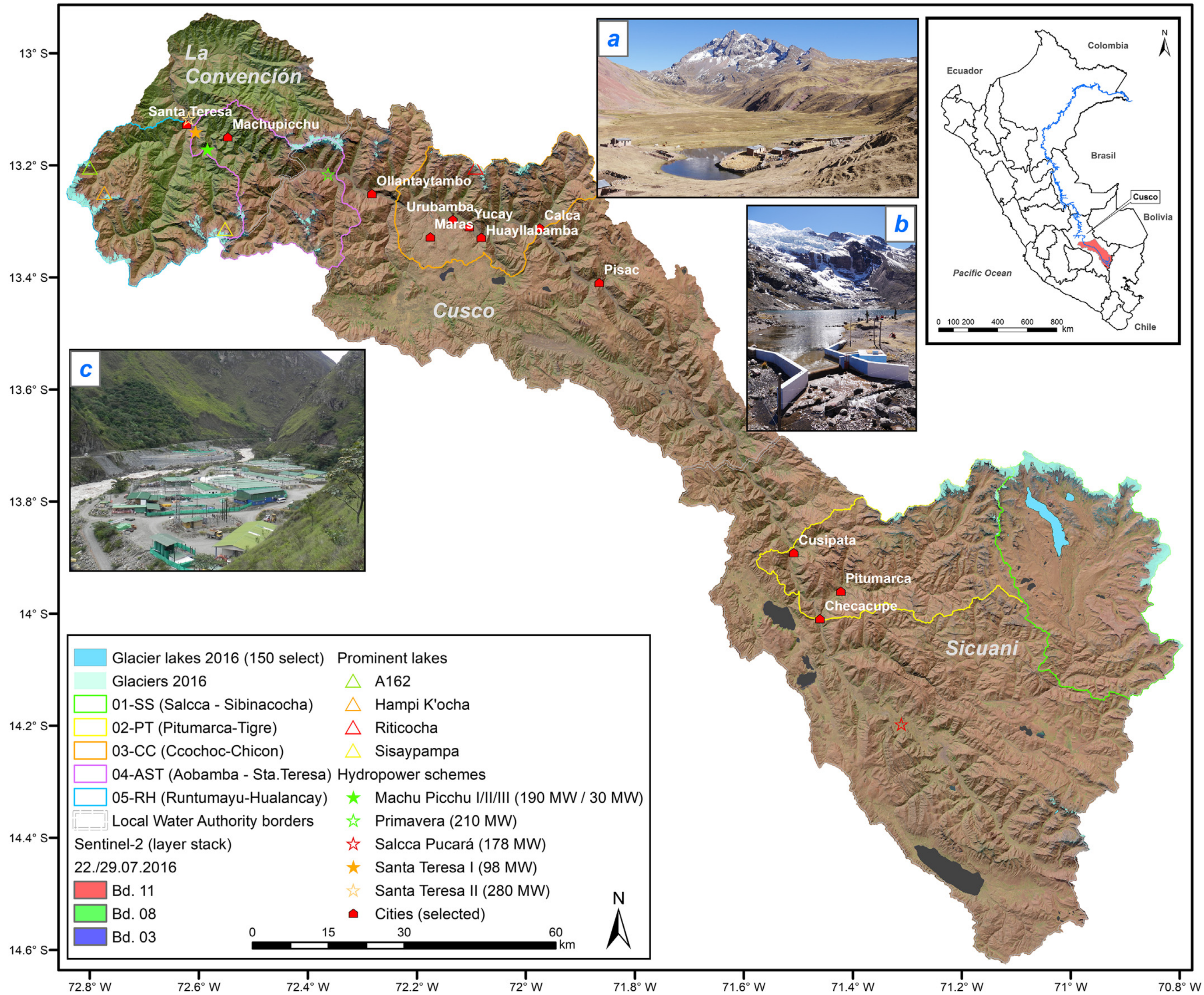

Fig. 1. Overview of the VUB. Small pictures: a) Central Valley of Pitumarca (02-PT), b) Lake Ausangatecocha (02-PT) with water intake, c) Santa Teresa I hydropower facilities (04-AST).

reducing extreme poverty, Cusco and the VUB still represent a low-developed region with high vulnerabilities with respect to Peru and probably to the Tropical Andes.

The Andes and their landscape features (e.g. glaciers, lakes, rivers) bear strong cultural significance including multiple deities for indigenous and peasant communities. Glacier shrinkage and socioeconomic changes are not only impacting in the physical availability of water resources but shaping culture, beliefs, and narratives (Carey et al., 2017; Jurt et al., 2015). These cultural values are increasingly under transformation and threat. One of the most prominent examples is the famous pilgrim ritual Qoyllur Rit'i at Ausangate glacier in the Cordillera Vilcanota which consisted in carrying down ice blocks from the glacier to a central shrine. The procession of ice removal was already questioned and successively restricted by the indigenous leaders in the early 2000s in order not to 'harm' the glacier more than necessary (Bolin, 2009). Today the ritual is being performed using stones instead of ice blocks.

2.2. Water risks and use

While for the Cordillera Blanca (Ancash) several historic and recent disastrous GLOF events with some thousand fatalities have been comprehensively documented (Carey, 2005; Carey et al., 2012b; Haeberli et al., 2017), only a few were reported in other glaciated regions in Peru. The VUB has been affected by large glacier-related mass movements, such as the repeated outburst events at Lake Sisaypampa (Fig. 1) due to ice avalanches from Salcantay glacier (Orcospampa-Aobamba valley, Cordillera Vilcabamba) on July 12, 1996 and November 22, 1998 (Carlotto et al., 2007; Frey et al., 2016) causing the loss of several human lives and assets in Yanatile and Santa Teresa. Later and further upstream, ice detachment from Chicón glacier provoked a GLOF at Lake Riticocha (Cordillera Urubamba, Fig. 1) on October 17, 2010 destroying around 50 houses on the way to Urubamba (Portocarrero, 2014).

Water risks in the VUB result not only from GLOF and other mass flow potentials but also from water scarcity. The latter is not only an expression of the hydroclimatic and physical state of a basin but also determined by political and market priorities, power relations, and, hence, allocation (Lynch, 2014; Savenije et al., 2014). Particularly the upper basin could already be in a situation of precipitation decline since the 2000s (cf. Drenkhan et al., 2018) which could even aggravate in view of a potential future 'aridification' of the Altiplano in the headwater region of the VUB (Neukom et al., 2015). This situation would have negative repercussions on long-term discharge with potential water shortages for different water sectors, including hydropower, particularly in the dry season (Kronenberg et al., 2016).

Cusco and the VUB are traditionally an important region of agriculture. Particularly water-intense agriculture is expanding due to growing export-crop markets. According to the last two agricultural census, total agricultural area has slightly grown from 273 km^2 in 1994 to 293 km^2 in 2012 within the 13 districts of the five defined subcatchments in the VUB (INEI, 1995, 2013). However, this increase is characterized by a doubling of irrigated areas from 77 km^2 to 154 km^2, respectively, while rainfed agriculture has decreased from 196 km^2 to 138 km^2 in the same period. Domestic water consumption is rising due to sustained population growth and urbanization processes (INEI, 2018). This development leads to extensions of the water network and, thus, to higher per capita water consumption (Miranda Sara and Baud, 2014) including considerable water leakages in the order of 30–45% (97 l/capita/day out of a total consumption of ~220–250 l/capita/day) (Liemberger and Wyatt, 2018). In the period 1993–2017 population in the VUB has increased by 1.3%/year with highest growth in urban (e.g. Cusco: 2.9%/year) and negative trends in the most rural (e.g. Acomayo: −0.2%/year) areas. Nearly half (47.4%) of national energy production is supported by hydropower (21,568 GWh) which is currently being extended. In the period 2004–2014 Peru's Gross Domestic Product has risen by 6.1%/year and, related to this economic upswing, energy demand has grown by 6.2%/year (MINEM, 2015). Several hydropower capacity extensions are planned in the VUB, such as, in downstream running order, Salcca Pucará (178 MW with a required flow of 64 m^3/s for full production) in the southwestern VUB, Primavera (210 MW, 62 m^3/s), and Machu Picchu III (30 MW, 10 m^3/s), both situated in 05-RH, and Santa Teresa II (280 MW, 105 m^3/s) at the outflow of 04-AST and 05-RH (Fig. 1) (Vergara, 2017).

3. Data and methods

Data presented in this study draw on the baseline of recent research, regarding current (1988–2016) and future (2050/2100) glacier and lake development in the VUB. For this, monthly Coupled Model Intercomparison Project Phase 5 (CMIP5) scenario runs were derived from the Royal Netherlands Meteorological Institute's (KNMI) Climate Explorer, based on the 1981–2005 mean. Two Representative Concentration Pathway (RCP) scenarios from the IPCC, were used in order to represent the full range of potential impacts from low (RCP2.6) and high (RCP8.5) emission trajectories (Drenkhan et al., 2018). Here, we further develop the existing datasets and put them into a context of emerging risks from shrinking glaciers and growing lakes as well as of feasible options for future water management. All data and methods applied for the current and future glacier and lake baseline mentioned before and the risks assessed in this study are drawn in Fig. 2. The term 'risk' used in this study, is conceived at the intersection of climate-related hazards, exposure and vulnerabilities of people and their assets (IPCC, 2012).

3.1. Glacier and lake changes

The VUB is characterized by strong glacier shrinkage with high spatiotemporal variability. As indicated by Drenkhan et al. (2018), between 1988 and 2016 glacier area has reduced from 226.1 km^2 to 141.7 km^2 (−37.3%) with corresponding ice (water) volume decrease of 20.5% from 8.122 km^3 (7.310 km^3) to 6.457 km^3 (5.811 km^3). Lakes adjacent to glaciers were considered if located ≥4000 m asl. with ≥2700 m^2. Between 1988 and 2016 these lakes have grown from 23.3 km^2 to 26.9 km^2 (+15.6%), including 84 new lakes (+18.3%). Corresponding total volumes increased from 0.637 km^3 to 0.699 km^3 (+9.7%). Using a freezing-level approach in combination with global climate model data (Fig. 2), future glacier areas would substantially decrease between 40.7% (RCP2.6) and 44.9% (RCP8.5) within the next decades (2031–2060) and between 41.4% and 92.7%, respectively, towards the end of this century (2071–2100). Hence, the transformation towards mostly glacier-free Andean regions below ~6000 m asl. would imply a considerable loss of permanently stored water. Above this altitudinal belt, predominantly steep slopes covered by mostly thin glaciers with reduced water storage could be found. Future lake development was previously assessed with the Glacier bed Topography (GlabTop) model (Linsbauer et al., 2009, 2012) in combination with several selection criteria from glacier morphology (Drenkhan et al., 2018). Between 14 (RCP 2.6) and 16 (RCP8.5) as well as 14 (RCP2.6) and 20 (RCP8.5) future lakes are estimated to possibly develop towards 2050 and 2100, respectively, in glacier-bed over-deepenings that will become exposed as glaciers retreat. Corresponding areas would increase by 0.9 km^2 (3.2%) and 1.1 km^2 (4.0%) until 2050 as well as by 0.9 km^2 (3.2%) and 1.6 km^2 (6.0%) until 2100. Associated volumes would rise by 0.032 km^3 (4.6%) and 0.037 km^3 (5.3%) until 2050 as well as by 0.032 km^3 (4.6%) and 0.041 km^3 (5.9%) until 2100, respectively.

3.2. GLOF risk assessment

In the following section, we describe the GLOF risk assessment approach for 134 glacier lakes (6.3 km^2, ~0.158 km^3 additionally

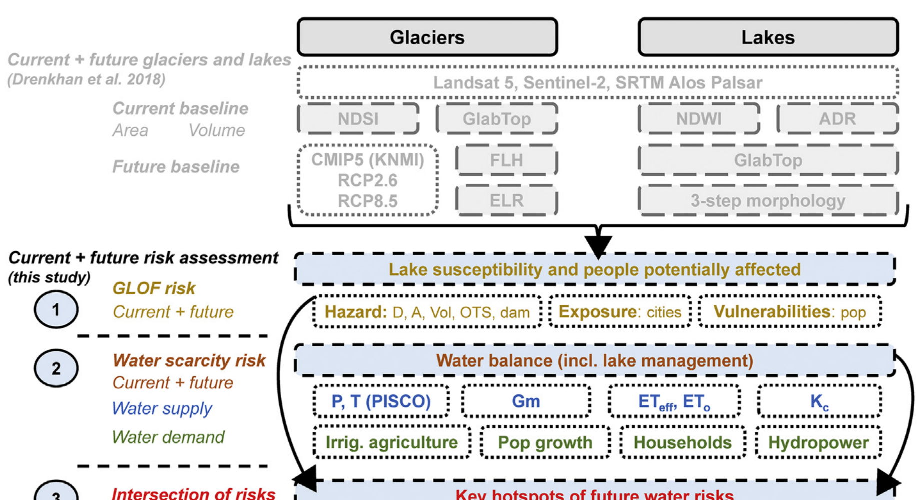

Fig. 2. Workflow of the applied methods for current and future glacier and lake assessment (upper part in grey, baseline from Drenkhan et al., 2018) and the current and future risk assessment. Abbreviations for this study: D = distance, A = area, V = volume, OTS = overall trajectory slope; pop = population; P = precipitation, T = temperature; Gm = glacier melt contribution; ET_{eff} = effective evapotranspiration; ET_o = reference evapotranspiration.

considering the reservoir Sibinacocha with 28.4 km^2 and ~0.110 km^3) in the five defined subcatchments of the VUB. Glacier lakes are here defined by a horizontal maximum distance of 2000 m to the next glacier terminus. This threshold has been determined using an automated GIS model of flow paths considering that most lakes below the 2000 m reach are still in direct downstream contact with current glacier extent. Additionally, we analyse all 20 identified potential future lakes (cf. Drenkhan et al., 2018) and their development over time by intersecting future glacier and lake areas, and classifying them as 'imminent' (next years), 'next decades' (~10–30 years) and 'after 2050' (2nd half of this century).

For lake inventories, based on remote sensing data in high mountain regions all over the world, common critical geometric features of dam and lake characteristics are described which determine hazard and risk potentials of lake outbursts (Bajracharya and Mool, 2009; Emmer and Vilímek, 2014; Hoffmann and Weggenmann, 2013; Huggel et al., 2004; McKillop and Clague, 2007a; Worni et al., 2013). Several approaches exist for stepwise index-based hazard assessment, pointing to critical lake area, volume, and terrain slope thresholds (Aggarwal et al., 2017; Allen et al., 2016a; Bolch et al., 2011; Fujita et al., 2013; Rounce et al., 2016). Approaches, mainly based on area change assessments, might be misleading (Kapitsa et al., 2017) and thresholds for different lake parameters could be fairly subjective. Nonetheless, a combination of lake growth, lake-glacier geometry, and the overall slope of potential ice and rock avalanche trajectories might provide stronger indicators for an appropriate hazard evaluation (cf. Fig. 11 in Haeberli et al., 2017). Additional criteria of downstream impacts including potentially affected people and assets are included in some studies (Allen et al., 2016a; Bajracharya et al., 2007; Rounce et al., 2016) which enhance the perspective towards more integrative risk analysis.

In a first step, we estimate the GLOF susceptibility of all 134 current glacier lakes. GLOF susceptibility is understood as a measure of how prone a lake is to failure and GLOF (Huggel et al., 2002). For a more objective and robust automated identification of susceptible lakes, a multi-criteria sensitivity analysis was developed. Sensitivity analyses have so far barely been applied to GLOF assessments but potentially provide considerably improved results for somehow subjectively selected critical thresholds for GLOF modelling (Kougkoulos et al., 2018). For this, multiple lake outburst parameter thresholds were iteratively tested and best estimates were defined using as proxies the lakes Riticocha (03-CC) and Sisaypampa (04-AST), which had historically been involved in GLOF events (Section 2.2). Furthermore, the lakes Hampi K'ocha (04-AST), which was classified as dangerous by Frey et al. (2016), and A162 (04-AST), which was identified with high risk potential by Guardamino and Drenkhan (2016), were considered. The following five primary hydro-geometric parameters were tested (Fig. 2, Table 1): a) Two-dimensional Distance (2DD), b) Relative Total Lake Area Growth (RAG), c) Absolute Lake Volume (AV), d) Overall Trajectory Slope (OTS), and e) Lake Dam Type (DT). The parameter 2DD is defined as horizontal distance in the main flow channel between the glacier terminus and the upper lake border. A proximity <500 m was defined as very high lake susceptibility potential (cf. Cook et al., 2016; Kapitsa et al., 2017; Wang et al., 2015). For the definition of RAG and AV no clear consensus can be found in the literature. For high (very high) RAG a change >150% (>250%) was assumed for the whole study period 1988–2016. Similar values around 100% have been described by e.g. (Bolch et al., 2011). High (very high) AV values were finally set at 100,000 m^3 (1,000,000 m^3). The OTS corresponds to the average terrain slope of the main flow channel network between the glacier's ablation area and upper lake border. It was iteratively computed with an automated GIS model of flow paths and corresponding network filters using the average glacier Elevation Line Altitude (ELA) for each mountain range as upper and corresponding lake levels as lower boundary conditions. Current (future RCP8.5 until 2100) ELA values were estimated at 5409, 5399, 5108 and 5109 m asl. (5680, 6010, 5739 and 5962 m asl.) for Quelccaya ice cap, Cordillera Vilcanota, Cordillera Urubamba and Cordillera Vilcabamba, respectively (Drenkhan et al., 2018). We defined the OTS at >11° (>20°) for high (very high) lake susceptibility potential excluding mass movements types, such as avalanches. This is in line with several studies which defined a critical threshold for debris flows at >11° (Bolch et al., 2011; Haeberli, 1983; Huggel et al., 2002). For DT classification, the presence of bedrock (moraine) dam was considered to represent medium (high) lake susceptibility potentials. For each parameter, a total of 1–4 points (1 = lowest, 4 = highest susceptibility, except for DT: 2 = medium and 3 = high) was allocated which, summed up, leads to a maximum achievable

Table 1
Thresholds of the sensitivity analysis for five lake outburst susceptibility parameters: two-dimensional glacier-lake distance (2DD, m), relative lake area growth (RAG, %), absolute lake volume (AV, m^3), overall trajectory slope (OTS, °) and dam type (DT; b = bedrock, m = moraine). The parameters assessment is divided into four susceptibility classes (L = low, M = medium, H = high, VH = very high) providing the total score of all 134 lakes for three possible threshold combinations (A, B, C). For the sensitivity analysis, four proxy lakes (Sisaypampa, Hampi K'ocha, Riticocha and A162) were used. The maximum achievable score (1–4 points per parameter) is 19 points for each lake. Please note that for Hampi K'ocha no significant RAG (between +5% and −5% for A and between +30% and −5% for B and C) has been observed. TOTAL: total number of lakes for the given susceptibility classes and threshold combinations.

	2DD			RAG			AV			OTS			DT			TOTAL		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
L	1.5k - 2k	1.5k - 2k	1.5k - 2k	<-5	<-5	<-5	<10k	<5k	<5k	3 - 10	3 - 8	3 - 11				9	8	7
M	600 - 1.5k	500 - 1k	1k - 1.5k	5 - 100	30 - 150	30 - 150	100k – 500k	15k – 100k	50k – 100k	10 - 12	8 - 11	11 - 14	b	b	b	65	66	57
H	300 - 600	0 - 500	500 - 1k	100 - 200	150 - 250	150 - 250	500k – 2000k	100k – 500k	100k – 1000k	12 - 14	11 - 14	14 - 20	m	m	m	56	47	52
VH	<300	<50	<500	>200	>250	>250	>2000k	>500k	>1000k	>14	>14	>20				4	13	18
Sisaypampa	3	3	4	4	4	4	2	3	3	4	4	4	3	3	3	16	17	18
Hampi K'ocha	4	3	4	-	-	-	3	4	4	4	4	4	3	3	3	14	14	15
Riticocha	4	4	4	4	4	4	2	3	3	4	4	4	2	2	2	16	17	17
A162	4	4	4	4	4	4	2	3	3	4	4	4	2	2	2	16	17	17

score of 19 for each lake. Finally, the qualitative GLOF susceptibility level was defined as 'moderate' (≥08 points), 'high' (≥13 points) and 'very high' (≥17 points). For future lakes, only 2DD, AV and OTS (scaled to 1–4) have been assessed in view of the uncertainty of lake extent (both area and volume) of the modelled lakes. In a second step, the hazard score of all 134 current lakes was normalized to the range 1–4 and those lakes with high outburst potential, together with all future lakes, were submitted to a more comprehensive GLOF assessment. We then used the Modified Single-Flow-direction (MSF) model developed by Huggel et al. (2003). This GIS model calculates pixel-based outburst flow direction following a central flowline of steepest descent from a defined starting point (lake dam) until a maximum runout distance determined by a user-defined overall trajectory slope. A probability for each cell to be affected by a mass flow was computed, including flexible diverging and converging flow networks. MSF has been widely used for GLOF modelling and assessments in high mountain areas, such as in the Alps, Himalayas, and Andes (Allen et al., 2016a; Bolch et al., 2011; Colonia et al., 2017; Frey et al., 2010). This model provides a quick and robust first insight of potential GLOF flow paths and corresponding reach without considering associated triggering mechanisms, volume, and density of the involved flow material or resulting flow velocities and deposition depth (Colonia et al., 2017; Rounce et al., 2016). If needed, more complex hydrodynamic, physically-based models, such as RAMMS (Frey et al., 2016), IBER (Schneider et al., 2014) and the open source solution r.avaflow (Mergili et al., 2018), can be used to compute flow depth and velocity which is, however, out of scope of this study. MSF model results are considerably affected by Digital Elevation Model (DEM) quality and spatial resolution for realistic flow modelling (Huggel et al., 2003; Kapitsa et al., 2017). For our modelling we used an adapted version of the global Shuttle Radar Topographic Mission (SRTM) 1° DEM for Alos Palsar (hereafter: 'SRTM AP') which is artefact- and void-corrected and downsampled from originally 30 m to 12.5 m spatial resolution (ASF, 2015). According to the type of mass flow, the maximum distance of debris flow type GLOF has been found not to fall below an average terrain slope of 11° (19.4%) (Haeberli, 1983; Huggel et al., 2002; McKillop and Clague, 2007b), while water- and sediment-dominated hyper-concentrated flows were observed to cause (primarily infrastructure) damage until a reach corresponding to an average slope of 2–3° (Frey et al., 2010; Haeberli, 1983; Kapitsa et al., 2017). For our purpose and corresponding maximum reach for worst-case scenarios, the lower boundary slope was set at 2° (3.5%).

In a third step, the damage potential of corresponding GLOF reach is analysed. Thereto, additionally to the physical GLOF susceptibility, we evaluate further components of risk. These include human exposure, here defined as people potentially affected, and human vulnerabilities, mostly referred to sensitivities and response capacities of population, here simplified as the level of HDI (PNUD, 2013), *see* Section 2.1. The analysis of human exposure and vulnerability for potential future lakes was performed using current values due to high spatiotemporal uncertainty about future population growth and human development. For human exposure evaluation in the valleys, simulated GLOF paths from the MSF model were intersected with the population and town register for the Cusco region (INEI, 2017a). As there are no bigger population centres in the subcatchments 01-SS and 04-AST, population had to be roughly estimated for these zones. Then, a scale of 1–4 points (1 = lowest, 4 = highest exposure level) was applied according to the individual number for each lake of people potentially affected. Human vulnerabilities were individually derived from weighted district-wide HDI averages and again 1–4 points (1 = lowest, 4 = highest vulnerability level) were allocated. For the determination of best estimates of vulnerability (HDI) and exposure (people potentially affected) thresholds, a sensitivity analysis was applied again using the proxy lakes mentioned above (Table 2). Finally, the combined GLOF susceptibility, exposure, and vulnerabilities assessment (achievable total score: 3–12 points) was normalized to the original score (1–4), weighted and translated into a qualitative index of 'low' (1), 'moderate' (2), 'high' (3) and 'very high' (4) GLOF risk. The best weight was achieved allocating a major importance to lake susceptibility (60%) and exposure (30%), while vulnerability which is only assessed by general HDI values is weighted with a low influence (10%), see risk combination 3 in Table 2.

3.3. Water balance and critical low-flows

A comprehensive surface water supply and demand scheme was developed for the selected five subcatchments and the whole VUB. A full water balance was calculated on a monthly scale for current (2016) and potential future (2050/2100) conditions based on observed and estimated hydroclimatic and socioeconomic data (Fig. 2). Groundwater flows were not considered due to insufficient data and process understanding in the region. Seasonal parameter values were defined for five dry season (May–September) and seven wet season (October–April) months. The water balance scheme for the entire VUB had been manually adapted with monthly gauging data from km105 (1981–2015), situated a few kilometres upstream of the VUB outflow. Then, simulated flow was validated for 2016. For each subcatchment, water losses from evaporation, transpiration, and corresponding vegetation coefficients were defined according to their climatic differences and slightly adjusted in a simple calibration procedure. Furthermore, options for lake management and dry-season discharge buffering were included, additionally considering the large reservoirs Sibinacocha and Langui Loy.

On the water supply side, precipitation (P), glacier melt contribution (Gm), and effective Evapotranspiration (ET_{eff}) were included. P was computed using the 0.1° (~10 km) gridded monthly precipitation baseline Peruvian Interpolated data of SENAMHI's (National Meteorology and Hydrology Service of Peru) Climatological and hydrological Observations (PISCO) v2.1. This dataset was produced using quality-controlled meteorological station, reanalysis and satellite data and complemented with rainfall datasets from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for the period 1981–2016 (Aybar et al., 2017). Solid P (perennial snow), which contributes to Gm within the accumulation area of each glacier, here defined as 70% of the entire glacier extent according to the Accumulation Area Ratio (AAR) for tropical glaciers of ~0.7 (Kaser and Osmaston, 2002), was separately calculated. Gm was then determined with an adapted degree-day glacier melt coefficient as water equivalent (w.e.) for the wet (6 mm/day w.e.) and dry (2 mm/day w.e.) season according to Wagnon et al. (1999). The lower amount for the dry season takes into account higher sublimation rates of 1–5 mm/day w.e. over the glacier (Vuille et al., 2018) and, hence, proportionately lower melt rates (Vuille et al., 2008).

For the estimation of ET_{eff}, in a first step reference evapotranspiration (ET_o) was calculated. Therefore, monthly minimum and maximum temperature (T) from PISCO v1.0 (1981–2015 average) and daily relative humidity (RH) datasets from five adjacent stations of SENAMHI (Ayaviri, Sicuani, Pisac, Abancay and Quillabamba, 2002–2008 monthly average) were added using the software ET_o Calculator based on the standard FAO Penman-Monteith equation (Allen et al., 1998a). Resulting values vary within a range of 3.4 mm/day during dry austral winter (JJA) and 4.2 mm/day in wet austral summer (DJF).

Then, monthly crop coefficients (K_c) were estimated for each subcatchment based on dominant land cover types according to the National Inventory of Land Cover of the Environmental Ministry of Peru (MINAM, 2015) and reference K_c from FAO (Allen et al., 1998b). Therefore, annual vegetation phenology was considered allocating lowest K_c values during JJA (0.2–0.4) and highest coefficients for DJF (0.5–0.7). ET_{eff} was finally calculated from the product of ET_o and K_c. In case monthly ET_{eff} (driven by ET_o) would exceed corresponding precipitation (typical for semi-arid regions with high insolation), *P* values have been taken instead (at 10%, considering at least 90% for infiltration). Additionally, monthly evaporation from lakes (E_{lake}) was estimated in relation to ET_o trajectories indicated before, defined here as 7.2–9.2% of

Table 2
Thresholds the GLOF risk analysis including lake outburst susceptibility (SUS), vulnerability (VUL) (Human Development Index) and exposure (EXP) (number of people potentially affected). For lake susceptibility, five parameters are considered: two-dimensional glacier-lake distance (2DD, m), relative lake area growth (RAG, %), absolute lake volume (AV, m^3), overall trajectory slope (OTS, °) and dam type (DT). The parameters assessment is divided into four susceptibility classes (L = low, M = medium, H = high, VH = very high) providing the total score of all 134 lakes for three possible threshold combinations (A, B, C). The risk components are weighted in three different combinations (1: SUS = 50%, VUL = 25% and EXP = 25%; 2: SUS = 50%, VUL = 20% and EXP = 30%; 3: SUS = 60%, VUL = 10% and EXP = 30%). For the sensitivity analysis, four proxy lakes (Sisaypampa, Hampi K'ocha, Riticocha and A162) were used. The maximum achievable score was normalized to the range 1–4 for each lake. Please note that for Hampi K'ocha no significant RAG (between +30% and −5%) has been observed.

	SUSCEPTIBILITY					VULNERABILITY			EXPOSURE			RISK		
	2DD	RAG	AV	OTS	DT	A	B	C	A	B	C	1	2	3
L	1.5k - 2k	<-5	<5k	3 - 11		>0.45	>0.45	>0.50	<501	<3k	<2k	0	0	0
M	1k - 1.5k	30 - 150	50k – 100k	11 - 14	b	0.35 - 0.45	0.29 - 0.45	0.29 - 0.50	501 - 2k	3k - 10k	2k - 5k	51	60	57
H	500 - 1k	150 - 250	100k – 1000k	14 - 20	m	0.25 - 0.34	0.21 - 0.29	0.24 - 0.29	2k - 15k	10k - 25k	5k - 20k	76	69	69
VH	<500	>250	>1000k	>20		<0.25	<0.21	<0.24	>15k	>25k	>20k	7	5	8
Sisaypampa	4	4	3	4	3	1	1	1	3	3	2	3	3	3
Hampi K'ocha	4	-	4	4	3	3	2	2	3	3	2	3	3	3
Riticocha	4	4	3	4	2	1	1	1	4	4	3	3	3	4
A162	4	4	3	4	2	3	2	2	3	3	2	3	3	4

all lake areas (=2.3–3.0 mm/day) for JJA and 6.5–8.2% (= 2.2–2.7 mm/day) for DJF. For an entire overview of all parameter values within the selected subcatchments see Table 3.

On the water demand side, agricultural water consumption is included based on irrigated areas from the 2012 census (INEI, 2013). Therefore, an average irrigation relationship of 1,769,100 m^3/km^2/year (01-SS, 02-PT) and 1,217,500 m^3/km^2/year (03-CC, 04-AST and 05-RH) was derived from estimated data in the region (ANA, 2015). These values roughly correspond to traditional irrigation systems in the Andes of Peru, which include mainly gravity and to a small extent spray irrigation considering an irrigation efficiency of 35% and 50%, respectively (MINAGRI, 2010). Domestic demand is determined using a constant value of 120 l/capita/day which has been found to be reasonable approximately reflecting average urban and rural water consumption in the Peruvian Andes (Drenkhan et al., in prep). Nonetheless, it must be noted that values vary considerably between socioeconomic groups of water users. For instance, in Lima people use between ~50 l/capita/day (for the poorest in suburban/rural areas) and ~500 l/capita/day (with access to water network and water-intense infrastructure) (cf. Miranda Sara and Baud, 2014). Additionally, water leakages in the order of 45% (97 l/capita/day) were considered, see Section 2.2. The main hydropower schemes Machu Picchu I/II and Santa Teresa I are included assuming year-round full capacity discharge needs. Furthermore, we consider a 5% environmental flow requirement (i.e. minimum necessary streamflow to sustain ecological processes) of average monthly natural discharge (without demand) based on the national methodology recently defined by ANA (2016).

The comprehensive water balance is calculated as a function of water supply from precipitation and glaciers, water losses from lake and terrestrial surface evaporation, and vegetation transpiration as well as withdrawals for domestic and agricultural water demand. Hydropower needs are added separately, as they represent non-consumptive water use. Therefore, the 5% environmental flow requirement was deducted from current water availability and the remaining monthly discharge not meeting needed minimum streamflow for hydropower production at full capacity, was highlighted (yellow fields, Table 6b). Lake management options are included interconnecting monthly water balance between the adjacent subcatchments. Therefore, maximum lake discharge (here defined as the double of the theoretical monthly streamflow average from entire lake volume) is used for the manual allocation of monthly lake storage (wet season) and drainage (dry season) in order to prevent critical low-flows if possible. The thresholds for these low-flows at the outflow of each subcatchments have been determined according to observed historical discharge data defining 'critical' as ~50% of the multi-year absolute minimum flow. For 01-SS where river discharge is mainly controlled by the reservoir outflow from Sibinacocha (7–12 m^3/s) the minimum threshold was set at 5 m^3/s. For all other subcatchments the only available long-term reference is the gauge km105 (monthly data for 1958–2015, minimum: 19.5 m^3/s) and the threshold was defined at 10 m^3/s.

In a next step, the potential future water balance is estimated for 2050 and 2100. The modelling approach is simplified using 'worst-case' (RCP8.5) corresponding glacier area reduction and lake growth until 2050 (with only slight differences between RCP8.5 and RCP2.6) and until 2100 (potential development of RCP8.5 far beyond RCP2.6), *see* Section 3.1. For simplicity, future P, Gm, ET_{eff} and E_{lake} values are supposed to be constant due to high uncertainty about current (cf. Salzmann et al., 2013) and future change trends. For a more realistic determination of future agricultural area change, a simple sensitivity analysis was applied using a wide range of potential agricultural growth rates considering a maximum point of carrying capacity (here defined as 50% of total catchment area) in each subcatchment. Most reasonable values for irrigated agriculture growth were found to be at 2.0%/year (2016–2050) and 0.5%/year (2050–2100). For domestic demand, reduced population growth of 1.1%/year (2016–2050) and 0.9%/year (2050–2100) in combination with increasing water consumption towards 2050 (140 l/capita/day) and 2100 (160 l/capita/day) are assumed. These estimations are based on current population trends (INEI, 2009, 2017a) and the fact that future water network extensions in the context of urbanization processes and potential economic increase would boost water consumption. Additionally, new hydropower capacities are included until 2050 considering the planned 520 MW additional capacity (Primavera, Machu Picchu III and Santa Teresa II), neglecting potential social tensions and economic feasibility that may adversely affect the implementation of these new plants.

Table 3
Overview of main water balance parameters and characteristics for each subcatchment and the entire VUB.

		01-SS			02-PT			03-CC			04-AST			05-RH			VUB		
Basin area	*km²*	**1155.24**			**948.78**			**701.47**			**727.70**			**610.74**			**11047.85**		
Glacier area	*km²*	60.89			22.08			5.42			35.15			10.91			**141.68**		
Glacier area (2050)		*51.52*			*13.17*			*1.22*			*8.91*			*1.38*			***78.00***		
Glacier area (2100)		*4.79*			*3.42*			*0.11*			*1.37*			*0.45*			***10.31***		
Glacier-basin fraction	*%*	5.3			2.3			0.8			4.8			1.8			**1.3**		
Glacier-basin fraction (2050)		*4.5*			*1.4*			*0.2*			*1.2*			*0.2*			***0.7***		
Glacier-basin fraction (2100)		*0.4*			*0.4*			*0.0*			*0.2*			*0.1*			***0.1***		
Glacier contribution	*%*	25.1	6.2	14.4	19.9	4.7	10.8	17.2	4.2	9.7	14.9	7.0	11.0	12.7	3.9	7.9	**7.7**	**1.7**	**4.2**
Glacier contribution (2050)		*22.1*	*5.2*	*12.5*	*16.2*	*3.7*	*8.7*	*13.3*	*3.2*	*7.4*	*4.2*	*1.8*	*3.0*	*8.9*	*2.7*	*5.5*	***4.4***	***0.9***	***2.3***
Glacier contribution (2100)		*2.5*	*0.5*	*1.3*	*2.4*	*0.5*	*1.2*	*1.9*	*0.4*	*1.0*	*0.7*	*0.3*	*0.5*	*1.3*	*0.4*	*0.7*	***0.6***	***0.1***	***0.3***
Lake area	*km²*	11.34			1.50			1.58			1.19			0.20			**26.90**		
Lake area (2050)		*12.57*			*1.62*			*1.58*			*1.24*			*0.20*			***27.98***		
Lake area (2100)		*12.64*			*1.78*			*1.58*			*1.24*			*0.20*			***28.53***		
Lake volume	*km³*	0.3310			0.0138			0.0168			0.0147			0.0014			**0.6991**		
Lake volume (2050)		*0.3698*			*0.0150*			*0.0168*			*0.0153*			*0.0014*			***0.7359***		
Lake volume (2100)		*0.3707*			*0.0195*			*0.0168*			*0.0153*			*0.0014*			***0.7405***		
Temperature (T)	*°C/month*	2.8	6.4	5.2	5.8	9.0	7.9	10.8	13.5	12.6	9.1	11.0	10.5	10.4	12.5	11.9	**7.8**	**10.5**	**9.6**
Precipitation (P)	*mm/month*	10.4	150.5	68.8	10.8	147.1	72.4	7.8	79.6	37.7	18.9	124.3	67.2	26.0	133.7	75.7	**9.9**	**138.5**	**66.0**
Relative humiditiy (RH)	*%*	36.3	67.7	52.6	48.0	70.5	59.3	54.1	68.5	60.9	62.6	77.3	69.9	62.6	77.3	69.9	**57.2**	**75.2**	**66.2**
Crop coefficient (K_c)	*coefficient*	0.2	0.5	0.3	0.3	0.5	0.4	0.3	0.6	0.4	0.4	0.7	0.5	0.4	0.6	0.5	**0.3**	**0.6**	**0.4**
Reference evapotranspiration (ET_o)	*mm/day*	3.4	3.7	3.7	3.5	3.9	3.8	3.8	4.2	4.2	3.4	3.7	3.7	3.5	3.8	3.8	**3.5**	**3.9**	**3.8**
Effective evapotranspirtion (ET_{eff})		0.0	1.7	0.9	0.0	1.9	1.0	0.0	2.3	0.8	0.1	2.4	1.3	0.1	2.3	1.3	**0.0**	**2.1**	**1.1**
Lake evaporation (E_{lake})		2.3	2.2	2.2	2.5	2.3	2.4	3.0	2.6	2.7	2.7	2.7	2.7	2.8	2.7	2.8	**2.9**	**1.5**	**2.1**
Population	*No.*	2656			14121			59552			6154			11843			**838500**		
Population (2050)		*3811*			*20261*			*85445*			*8830*			*16992*			***1203071***		
Population (2100)		*5965*			*31711*			*133734*			*13820*			*26596*			***1882997***		
Irrigated agriculture	*km²*	12.45			51.60			71.57			17.39			1.06			**673.76**		
Irrigated agriculture (2050)		*26.41*			*109.52*			*151.90*			*36.91*			*2.26*			***1429.91***		
Irrigated agriculture (2100)		*33.90*			*140.54*			*194.92*			*47.37*			*2.89*			***1834.90***		
Hydropower	*m³/s*	–			–			–			–			61.50			**61.50**		
Hydropower (2050/2100)		–			–			–			–			*105.00*			***105.00***		
Human Development Index (HDI)	*coefficient*	0.266			0.238			0.436			0.472			0.405			**0.399**		

The three columns for Glacier contribution, temperature (T), precipitation (P), relative humidity (RH), crop coefficient (K_c), reference evapotranspiration (ET_o), effective evapotranspiration (ET_{eff}) and lake evaporation (E_{lake}) refer to dry season (JJA), wet season (DJF) and average annual values, respectively. Population data is estimated from (INEI, 2017a). HDI data is estimated from (PNUD, 2013).

Finally, results from the integrated analysis of current and future GLOF risks are manually intersected with computed potential water shortages from the water balance estimations for 2050 and 2100 within each subcatchment. We define those intersections of critical future low-flows and GLOF potentials as 'key hotspots' of future water risks. The term 'water shortage' is applied to each situation, where simulated monthly discharge falls below the critical low-flow level. Additionally, current and future lake volumes are considered in order to compare their potential to attenuate possible water shortages in the context of glacier shrinkage and growing water demand.

4. Results

In the following section results are at first separately shown for the GLOF risk and water balance assessment and then integratively presented for the identified potential 'key hotspots' of water risks.

4.1. Current and future GLOF risks

Out of 134 current glacier lakes in the VUB, a total of 70 lakes (2.5 km^2, 0.035 km^3) was evaluated as potentially susceptible to lake outbursts indicating high (52) and very high (18) levels of lake susceptibility (Table 1). Combined with the vulnerability (HDI) and exposure (people potentially affected) assessment, a total of 77 lakes (2.6 km^2, 0.035 km^3) with high (69) and very high (8) risk levels were identified (Table 2). Lakes with highest risk are L103 and Riticocha (both within 03-PT, Ccochoc-Chicón), Azulcocha, Qomercocha, L369 and L162 (all within 02-PT, Pitumarca-Tigre) as well as A162 (04-AST, Aobamba-Santa Teresa) and L122 (05-RH, Runtumayu–Hualancay). They are situated at 4571–5043 m asl. and include a total area (volume) of 0.43 km^2 (0.005 km^3) (Table 4). Some of these lakes have rapidly developed within the last decade, as the case of A162 in 04-AST (Aobamba–Santa Teresa) illustrates (Fig. 3).

Table 4
Combined risk potential for all current lakes with very high and selected lakes with high risk.

Lake name	X	Y	Z	Area (m^2)	Volume (10^3 m^3)	Dam type	Catchment	Cordillera	Glacier	PPA	HDI	SUS	EXP	VUL	TOT	RISK
L101	−72.07	−13.22	4691	2700	8	Rock	03-CC	Urubamba		29,986	0.535	3	4	1	3	H
L206	−71.01	−13.77	5062	21,088	144	Rock	01-SS	Vilcanota	Sorañaño	500	0.211	4	1	4	3	H
L370	−70.92	−13.83	5195	14,300	83	Moraine	01-SS	Vilcanota	Pucasalla 2	500	0.211	4	1	4	3	H
L178	−71.24	−13.82	4933	10,200	51	Rock	02-PT	Vilcanota	Ausangate 2	12,532	0.211	3	3	4	3	H
L379	−71.14	−13.81	5007	33,500	277	Moraine	02-PT	Vilcanota		12,532	0.211	3	3	4	3	H
L381	−71.14	−13.81	4968	3000	9	Moraine	02-PT	Vilcanota		12,532	0.211	3	3	4	3	H
L390	−71.14	−13.80	5053	51,700	513	Moraine	02-PT	Vilcanota		12,532	0.211	3	3	4	3	H
L392	−70.98	−13.79	5127	16,000	97	Moraine	01-SS	Vilcanota	Huilayorc 2	500	0.211	4	1	4	3	H
L396	−71.17	−13.78	5005	7600	34	Moraine	02-PT	Vilcanota		12,532	0.211	3	3	4	3	H
L398	−71.09	−13.78	5252	21,300	146	Moraine	01-SS	Vilcanota	Japujapu	500	0.211	4	1	4	3	H
L400	−71.12	−13.78	5093	10,400	53	Moraine	02-PT	Vilcanota		12,532	0.211	3	3	4	3	H
L401	−71.03	−13.77	5050	111,000	1518	Moraine	01-SS	Vilcanota	Cuncapata	500	0.211	4	1	4	3	H
L402	−71.12	−13.77	4999	4800	18	Moraine	02-PT	Vilcanota		12,532	0.211	3	3	4	3	H
L472	−72.04	−13.22	4538	44,000	408	Moraine	03-CC	Urubamba		29,986	0.385	3	4	2	3	H
L62	−71.32	−13.86	4695	92,500	1172	Moraine	02-PT	Vilcanota	Inka	4769	0.209	4	2	4	3	H
Sisaypampa	−72.53	−13.32	4554	18,700	121	Moraine	04-AST	Vilcabamba	Salcantay	6384	0.596	4	3	1	3	H
L187	−71.29	−13.83	4833	14,300	83	Moraine	02-PT	Vilcanota		4769	0.211	4	2	4	3	H
L122	−72.39	−13.29	4896	43,600	403	Rock	05-RH	Vilcabamba	Planchayoc	14,810	0.345	4	3	2	4	VH
A162	−72.78	−13.20	4573	30,000	237	Rock	04-AST	Vilcabamba	Chaupimayo	6384	0.348	4	3	2	4	VH
L162	−71.21	−13.81	4852	127,399	1847	Moraine	02-PT	Vilcanota	Ausangate	12,532	0.211	4	3	4	4	VH
L369	−71.13	−13.86	5043	13,600	77	Moraine	02-PT	Vilcanota		12,532	0.211	4	3	4	4	VH
Qomercocha	−71.19	−13.81	4817	54,600	554	Moraine	02-PT	Vilcanota	Ausangate	12,532	0.211	4	3	4	4	VH
Azulcocha	−71.20	−13.81	4923	98,900	1289	Moraine	02-PT	Vilcanota	Ausangate	12,532	0.211	4	3	4	4	VH
Riticocha	−72.07	−13.21	4842	4900	110	Rock	03-CC	Urubamba	Chicón	21,310	0.535	4	4	1	4	VH
L103	−72.01	−13.21	4571	53,200	534	Moraine	03-CC	Urubamba	Cancha	22,276	0.385	4	4	2	4	VH

X = Longitude (decimal degrees); Y = Latitude (decimal degrees); Catchments: 01-SS = Salcca–Sibinacocha, 02-PT = Pitumarca–Tigre, 03-CC = Ccochoc–Chicón, 04-AST = Aobamba–Santa Teresa and 05-RH = Runtumayu–Hualancay; PPA = People potentially affected; HDI = Human Development Index; SUS = Lake susceptibility; EXP = Human exposure level; VUL = Human vulnerability level. RISK level: H = high; VH = very high.

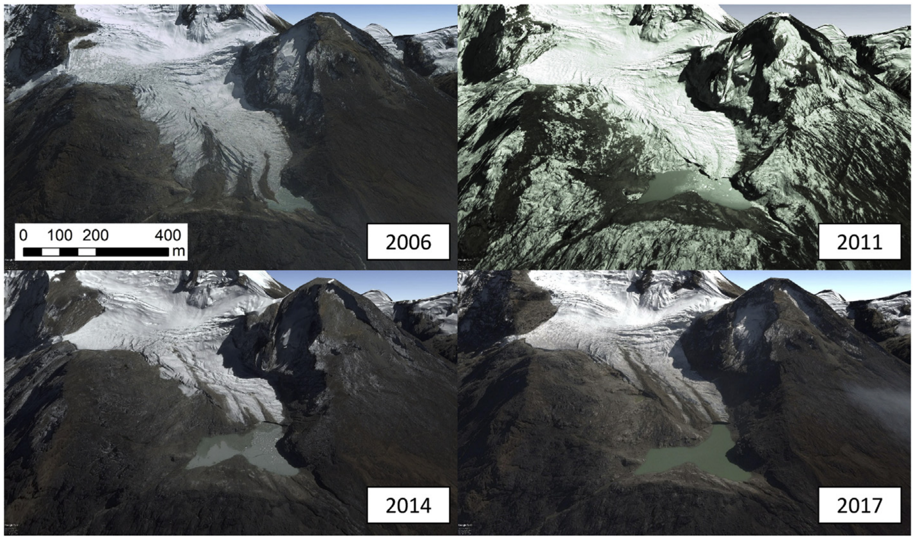

Fig. 3. Development of the lake A162 (−72.78 W, −13.20S, 4573 m asl.), classified with very high risk potential, in the period 2006–2017. Imagery: CNES Airbus/Digital Globe (Google Earth).

The 20 possible future lakes (1.6 km^2, 0.046 km^3) were classified with high (11) and very high (6) lake susceptibility potentials as well as with moderate (3), high (16) and very high (1) levels of risk (Table 5). According to modelled glacier shrinkage rates they would most likely develop imminently (7), within the next decades (7) and after 2050 (6). The latter six lakes could only form under scenario

Table 5
Combined risk potential for all potential future lakes.

Lake formation	X	Y	Z	Area (m^2)	Volume (10^3 m^3)	Catchment	Cordillera	Glacier	PPA	HDI	SUS	EXP	VUL	TOT	RISK
After 2050	−70.85	−13.94	5228	243,125	4715	01-SS	Quelccaya	Morojani	500	0.295	2	1	3	2	M
After 2050	−70.86	−13.97	5273	35,469	391	01-SS	Quelccaya	Paco Loma	500	0.295	2	1	3	2	M
After 2050	−71.07	−13.75	5250	8750	29	01-SS	Vilcanota	Osjollo Anante	500	0.211	2	1	4	2	M
Imminent	−71.01	−13.76	4998	115,000	2987	01-SS	Vilcanota	Soranano	500	0.211	3	1	4	3	H
Imminent	−71.07	−13.76	5053	342,500	18,894	01-SS	Vilcanota	Osjollo Anante	500	0.211	3	1	4	3	H
After 2050	−71.05	−13.77	5196	22,031	103	01-SS	Vilcanota	Cuncapata	500	0.211	3	1	4	3	H
After 2050	−71.09	−13.76	5395	232,656	4318	01-SS	Vilcanota	Japujapu	500	0.211	3	1	4	3	H
Imminent	−71.31	−13.85	4891	43,281	307	02-PT	Vilcanota	Inka	4769	0.209	3	2	4	3	H
Imminent	−72.73	−13.36	4764	28,594	466	04-AST	Vilcabamba	Padreyoc	6384	0.348	3	3	2	3	H
Imminent	−72.79	−13.25	4869	5781	29	04-AST	Vilcabamba	Sacsara	6384	0.348	3	3	2	3	H
Next decades	−72.77	−13.28	5050	10,313	64	04-AST	Vilcabamba	Sacsara	6384	0.348	3	3	2	3	H
Next decades	−72.72	−13.37	5117	8125	43	04-AST	Vilcabamba	Padreyoc	6384	0.348	3	3	2	3	H
Imminent	−71.00	−13.78	5022	118,281	4260	01-SS	Vilcanota	Japupunta	500	0.211	4	1	4	3	H
Imminent	−71.04	−13.77	5065	76,094	2233	01-SS	Vilcanota	Cuncapata	500	0.211	4	1	4	3	H
Next decades	−71.18	−13.80	5084	16,719	80	02-PT	Vilcanota	Ausangate	12,532	0.211	3	3	4	3	H
Next decades	−71.11	−13.78	5138	162,500	4491	02-PT	Vilcanota	Jatunhuma	12,532	0.211	3	3	4	3	H
Next decades	−70.94	−13.81	5149	39,844	783	01-SS	Vilcanota	Alccachaya	500	0.211	4	1	4	3	H
Next decades	−70.93	−13.81	5191	38,906	572	01-SS	Vilcanota	Imata	500	0.211	4	1	4	3	H
After 2050	−70.91	−13.82	5491	21,719	397	01-SS	Vilcanota	Pucasalla	500	0.211	4	1	4	3	H
Next decades	−71.21	−13.80	5008	55,156	850	02-PT	Vilcanota	Ausangate	12,532	0.211	4	3	4	4	VH

X = Longitude (decimal degrees); Y = Latitude (decimal degrees); Catchments: 01-SS = Salcca–Sibinacocha, 02-PT = Pitumarca–Tigre, 03-CC = Ccochoc–Chicón, 04-AST = Aobamba–Santa Teresa and 05-RH = Runtumayu–Hualancay; PPA = People potentially affected; HDI = Human Development Index; SUS = Lake susceptibility; EXP = Human exposure level; VUL = Human vulnerability level. RISK level: M = moderate; H = high; VH = very high.

RCP8.5 until 2100. The possible future lake with highest risk (0.1 km^2, 0.001 km^3) might emerge within the next years at 5008 m asl. at the retreating foot of the glacier Ausangate. A potential enhanced future threat would be the exposed situation of lake Ausangate within the flow channel around 300 m above the current lake L162. This would create a potential for cascading effects combined with GLOF risk from Ausangate impacting L162 and running further down the valley.

The MSF assessment for all 8 current (with very high risk) and 20 possible future (Table 5) dangerous lakes shows a broad reach of areas potentially affected by GLOF events (Fig. 4). Most current and future lakes of highest risk potentials are situated within the 02-PT (Cordillera Vilcanota) and 03-CC (Cordillera Urubamba) subcatchments. At the lower GLOF reach (2° slope) of these lakes, around 20–45 km further downstream, several cities are potentially exposed, such as Pitumarca and perhaps Checacupe (02-PT) with >12,000 inhabitants, as well as Urubamba, Huayllabamba and Yucay (03-CC) with >30,000 inhabitants (Fig. 4). Lake susceptibility and vulnerability levels are particularly high (4 points) in the low-populated Quelccaya-Vilcanota region (e.g. 01-SS) while strongest potential exposure exists further downstream where people live in larger cities, such as Calca and Urubamba in the Sacred Valley (03-CC). Generally, an increasing terrain steepening can be observed for surrounding future lakes. While all 134 glacier lakes indicate OTS of 17.9° on average, the value for the 20 modelled future lakes would be at approximately 22.1° on average.

4.2. Current and future water shortages

The water balance estimation for all five subcatchments and the entire VUB at monthly scale reveals a closer spatiotemporal insight into current patterns of water availability and potential future shortages as well as challenges as a function of glacier shrinkage, agricultural and population growth and hydropower extensions until 2050 and 2100 (Table 3).

For current conditions, water availability without any lake management (buffering months of lowest discharge) is generally critical during most months of the dry season for domestic and agricultural supply (Table 6a), except for 05-RH. Highest glacier fraction (5.3%) of all subcatchments can be found in 01-SS where glacier contribution to river discharge is strong (JJA: 25.1%, DJF: 6.2%). On the other hand, 02-PT has a smaller glacier-basin fraction (2.3%), and, consequently, lower relative glacier streamflow contribution. Nonetheless, highly growing water demand, particularly due to irrigation (>50 km^2), considerably reduces total water availability and already generates pressure under current conditions. This means that already at present, hydropower (mostly situated at the outflow of 04-AST and 05-RH) is only producing maximum energy output with additional streamflow from reservoirs or has to adjust with energy production rationing during several dry season months.

Considering further lake management and using, hypothetically, the buffer function of all selected lakes in this study (Table 6b), the threat of

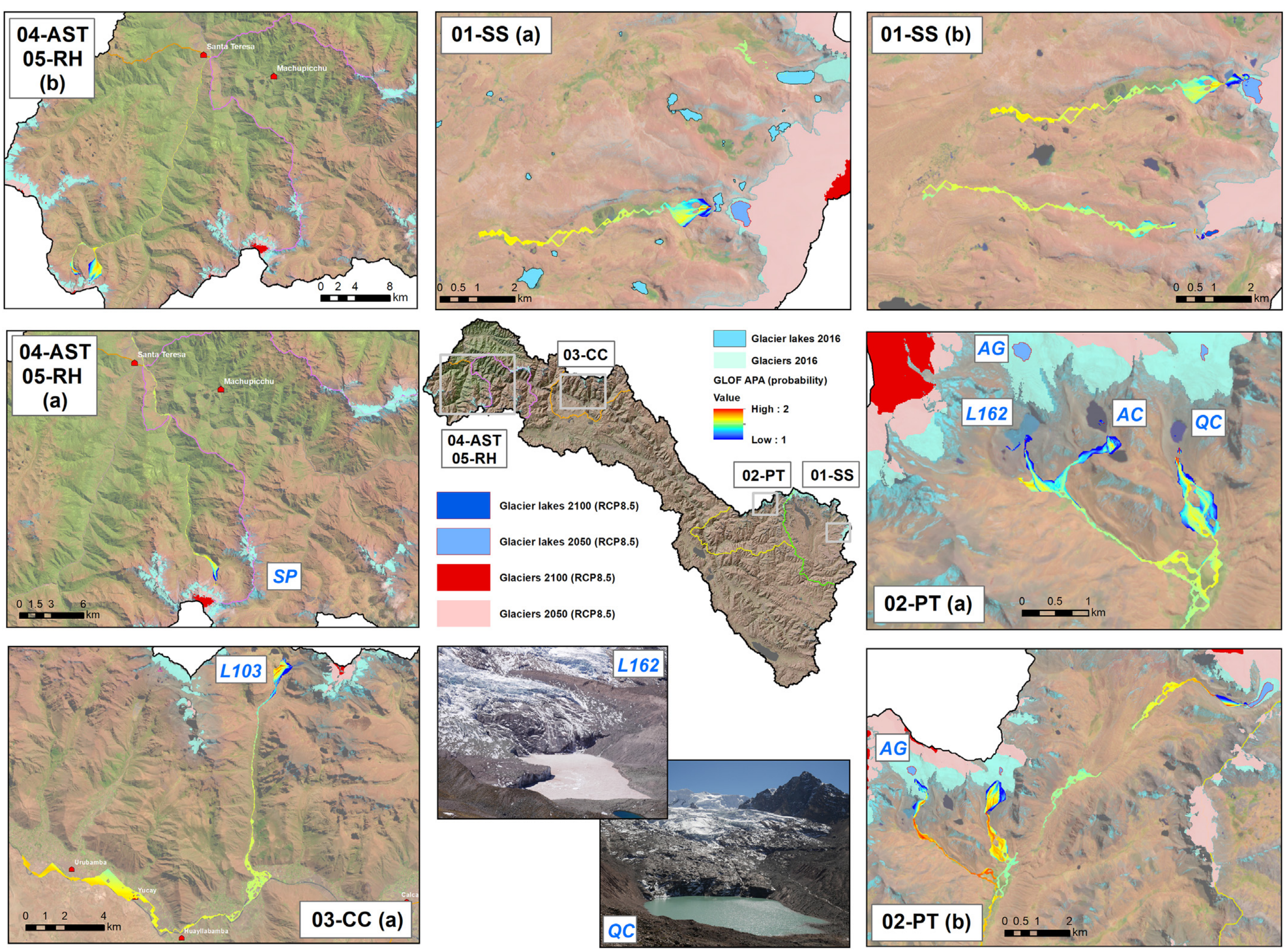

Fig. 4. MSF modelling results for areas potentially affected (APA) under maximum GLOF reach (2–3°) for selected (a) current and (b) future critical lakes in the five selected subcatchments (01-SS = Salcca–Sibinacocha; 02-PT = Pitumarca–Tigre; 03-CC = Ccochoc–Chicón; 04-AST = Aobamba–SantaTeresa; 05-RH = Runtumayu–Hualancay). Selected lakes with (very) high risk are labelled (current lakes: L103, L162, AC = Azulcocha, QC = Qomercocha, SP = Sisaypampa; potential future lake: AG = Ausangate).

Table 6
Current and future water balance and critical low-flows without (a) and with (b) lake management.

	01-SS			02-PT			03-CC			04-AST			05-RH			VUB		
a)	2016	2050	2100	2016	2050	2100	2016	2050	2100	2016	2050	2100	2016	2050	2100	2016	2050	2100
January	43.88	43.61	42.15	81.27	79.73	76.98	80.33	78.22	73.76	22.57	21.78	21.54	118.54	114.62	109.73	350.64	347.77	344.08
February	44.72	44.46	43.11	83.37	81.83	79.19	83.83	81.38	76.53	17.64	16.73	16.45	115.32	111.50	106.32	369.31	365.50	361.41
March	30.51	30.11	28.17	54.95	54.07	50.46	53.81	52.23	62.05	18.85	17.81	17.48	84.83	81.73	91.16	236.69	230.44	224.63
April	17.60	17.06	14.63	31.03	29.71	25.33	36.25	34.27	29.54	3.13	1.65	1.19	47.24	43.34	38.08	56.95	49.01	41.84
May	6.11	5.84	4.89	9.25	8.70	8.30	12.39	12.21	12.17	5.98	5.50	5.34	25.26	24.48	24.25	44.55	40.00	35.78
June	3.30	3.01	1.98	5.70	5.11	4.66	9.93	9.20	8.87	4.24	3.71	3.55	22.21	20.83	20.30	28.21	23.67	19.42
July	3.72	3.43	2.40	6.90	6.28	5.84	10.43	9.60	9.23	4.23	3.69	3.51	20.98	19.45	18.86	26.90	21.72	17.13
August	5.45	5.17	4.19	8.13	7.51	7.08	11.65	10.45	9.90	7.16	6.62	6.42	26.13	24.90	24.26	40.96	33.58	27.84
September	11.47	11.23	10.46	19.01	17.61	15.88	20.65	18.35	16.10	5.79	5.15	4.91	35.14	32.09	29.55	77.51	69.03	62.80
October	5.91	5.31	2.60	14.45	13.30	12.47	22.88	20.85	19.54	2.21	0.72	0.25	30.36	26.40	24.55	15.84	6.33	−1.68
November	17.41	16.90	14.55	29.37	28.26	24.68	41.45	39.98	36.19	3.92	2.61	2.22	53.02	49.83	45.59	106.23	100.64	94.91
December	50.06	49.80	48.53	72.19	72.60	69.94	75.31	75.46	71.42	7.33	6.16	5.82	92.74	91.35	86.91	246.18	242.41	238.03
Average (avg)	***20.01***	***19.66***	***18.14***	***34.64***	***33.73***	***31.74***	***38.24***	***36.85***	***35.44***	***8.59***	***7.68***	***7.39***	***55.98***	***53.38***	***51.63***	***133.33***	***127.51***	***122.18***
Δ avg (%)		***−1.76***	***−9.37***		***−2.62***	***−8.37***		***−3.64***	***−7.32***		***−10.62***	***−13.96***		***−4.65***	***−7.77***		***−4.37***	***−8.36***
DJF avg (m^3/s)	***46.22***	***45.96***	***44.60***	***78.94***	***78.05***	***75.37***	***79.82***	***78.35***	***73.91***	***15.85***	***14.89***	***14.60***	***108.86***	***105.82***	***100.99***	***322.04***	***318.56***	***314.51***
DJF change (%)		***−0.57***	***−2.96***		***−1.13***	***−3.44***		***−1.84***	***−5.67***		***−6.04***	***−1.94***		***−2.79***	***−4.57***		***−1.08***	***−1.27***
JJA avg (m^3/s)	***4.16***	***3.87***	***2.86***	***6.91***	***6.30***	***5.86***	***10.67***	***9.75***	***9.33***	***5.21***	***4.67***	***4.49***	***23.11***	***21.73***	***21.14***	***32.03***	***26.32***	***21.46***
JJA change (%)		***−7.02***	***−26.15***		***−8.83***	***−7.01***		***−8.60***	***−4.30***		***−10.38***	***−3.84***		***−5.97***	***−2.70***		***−17.80***	***−18.46***

	01-SS			02-PT			03-CC			04-AST			05-RH			VUB		
b)	2016	2050	2100	2016	2050	2100	2016	2050	2100	2016	2050	2100	2016	2050	2100	2016	2050	2100
January	43.88	42.61	40.15	78.27	76.43	73.48	79.91	77.34	72.73	20.07	19.03	18.79	118.44	114.52	109.63	270.52	267.65	263.96
February	44.72	43.46	41.11	80.37	78.33	75.19	82.00	79.38	74.53	13.64	12.73	12.45	115.12	111.30	106.12	339.31	335.50	331.41
March	30.51	30.11	26.97	53.17	52.24	47.93	53.81	52.23	62.05	16.95	15.81	15.48	84.77	81.67	91.10	289.27	285.36	279.84
April	17.60	17.06	13.36	31.03	29.71	25.33	36.25	34.27	29.54	4.07	2.62	2.16	47.24	43.34	38.08	109.53	103.92	97.05
May	5.01	5.01	5.01	10.60	10.66	10.81	12.39	12.21	12.17	6.92	6.47	6.32	25.35	24.57	24.34	97.13	90.00	85.19
June	5.01	5.01	5.01	7.84	7.33	7.17	11.00	10.27	9.94	5.17	4.68	4.52	22.30	20.93	20.39	80.79	73.67	69.42
July	5.01	5.01	5.01	9.04	8.50	8.34	11.50	10.67	10.30	5.17	4.66	4.48	21.07	19.54	18.95	41.90	37.21	32.62
August	5.01	5.01	5.01	10.28	9.73	9.58	11.76	11.20	10.80	8.10	7.59	7.39	26.22	24.99	24.35	45.96	38.58	32.84
September	11.17	10.30	8.96	19.01	17.61	15.88	20.65	18.35	16.10	6.73	6.12	5.88	35.14	32.09	29.55	47.51	39.03	32.80
October	5.75	5.41	5.29	14.45	13.30	12.47	22.88	20.85	19.54	3.14	1.69	1.22	30.36	26.40	24.55	49.64	40.14	32.12
November	17.41	17.00	14.05	29.37	28.26	24.68	41.45	39.98	36.19	4.85	3.58	3.19	53.02	49.83	45.59	76.23	70.64	64.91
December	49.06	49.94	47.73	72.19	72.60	69.94	75.31	75.46	71.42	8.27	7.14	6.79	92.74	91.35	86.91	152.18	148.41	144.03
Average (avg)	***20.01***	***19.66***	***18.14***	***34.64***	***33.73***	***31.74***	***38.24***	***36.85***	***35.44***	***8.59***	***7.68***	***7.39***	***55.98***	***53.38***	***51.63***	***133.33***	***127.51***	***122.18***
Δ avg (%)		***−1.76***	***−9.37***		***−2.63***	***−8.37***		***−3.64***	***−7.32***		***−10.62***	***−13.97***		***−4.65***	***−7.77***		***−4.37***	***−8.36***
DJF avg (m^3/s)	***45.89***	***45.34***	***43.00***	***76.94***	***75.79***	***72.87***	***79.07***	***77.39***	***72.90***	***13.99***	***12.96***	***12.68***	***108.76***	***105.72***	***100.89***	***254.00***	***250.52***	***246.47***
DJF change (%)		***−1.20***	***−6.30***		***−1.50***	***−5.29***		***−2.13***	***−7.81***		***−7.35***	***−9.41***		***−2.79***	***−7.24***		***−1.37***	***−2.97***
JJA avg (m^3/s)	***5.01***	***5.01***	***5.01***	***9.05***	***8.52***	***8.37***	***11.42***	***10.71***	***10.34***	***6.15***	***5.64***	***5.46***	***23.20***	***21.82***	***21.23***	***56.22***	***49.82***	***44.96***
JJA change (%)		***−0.11***	***−0.07***		***−5.87***	***−7.60***		***−6.19***	***−9.42***		***−8.18***	***−11.10***		***−5.95***	***−8.48***		***−11.38***	***−20.03***

All monthly values in m^3/s. Shaded areas in red indicate critical low-flow levels (<10 m^3/s, except 01-SS: <5 m^3/s), cells shaded in yellow show critical months of insufficient streamflow for full hydropower capacity (considering 5% environmental flow requirement). DJF = wet season, JJA = dry season.

dry season shortages considerably reduces for the subcatchments 01-SS, 02-PT, 03-CC and the entire VUB under current conditions. Nonetheless, future water availability would considerably reduce by some 2–11% (7–14%) until 2050 (2100). This decline in water availability could provoke additional pressure for several dry season months until 2050 and the entire dry season or even several wet season months (04-AST) until 2100. Only 01-SS shows different patterns as water demand remains low and lake reservoir contribution is high. Strongest impacts would result in the upper basin, e.g. in 01-SS and 04-AST where average annual discharge could be reduced by 1.8% and 10.6%, respectively, until

2050 and by 9.4% and 14.0%, respectively, until 2100. With ongoing glacier shrinkage in 01-SS and 04-AST, glacier contribution to streamflow could decrease to 22.1% and 4.2% (JJA) as well as to 5.2% and 1.8% (DJF), respectively, until 2050 and substantially diminish to 2.5% and 0.7% (JJA) as well as 0.5% and 0.3% (DJF), respectively, until the end of this century (Table 3). Future lake management would not by any means meet the entire demand for hydropower energy, including the potential 520 MW hydropower extensions (Primavera, Machu Picchu III and Santa Teresa II) in the lower VUB (cf. 05-RH, Table 6b). For the hydropower sector, high risk of water shortages and reduced energy production during most months of the year would have to be expected.

4.3. Key hotspots of future water risks

The intersection of current and future GLOF risks with potential water shortages and further hydroclimatic and socioeconomic data provides a clear picture of critical locations within the VUB where risk potentials are strongly enhanced. We identified three key hotspots of current and future water risks (Fig. 5) which are presented in the order from highest to lowest magnitude:

4.3.1. Key hotspot 1

This most significant hotspot is located at the outflow from 02-PT. At current conditions, four lakes with very high GLOF susceptibility and risk potential (Azulcocha, Qomercocha, L369 and L162) are present. Around 12,500 highly exposed inhabitants, mostly situated in the cities of Pitumarca, Checacupe and around, indicate strong vulnerabilities (HDI: 0.238). Already under current conditions, water shortages are a serious problem for domestic and irrigated agriculture (>50 km^2) water supply during at least three months (JJA) of the year. In this context, substantial glacier contribution to river streamflow (JJA: 19.9%, DJF: 4.7%) is crucial, particularly for dry-season water supply.

Future conditions could aggravate this situation towards the end of the century. One lake with very high lake outburst potential would develop within the next decades and could particularly threaten exposed people downstream. It would develop within the flow channel of the current lake L162 about 300 m further upstream and, thus, represent a potential for cascading effects combined with GLOF risk (Section 4.1). More than 30,000 inhabitants could be highly exposed and vulnerable. Water shortages would further increase with up to four months which would jeopardize particularly the growing irrigated agriculture (>140 km^2) sector. Strongly decreasing glacier contribution to river streamflow (JJA: 2.4%, DJF: 0.5%) would enhance the pressure and competitions over water resources.

4.3.2. Key hotspot 2

The second hotspot of potentially strong water risks is situated at the outflow of 04-AST and 05-RH. Currently, a few hundred people with a medium vulnerability level (HDI: 0.472 and 0.405, respectively) might be affected by very high GLOF susceptibility and risk from one

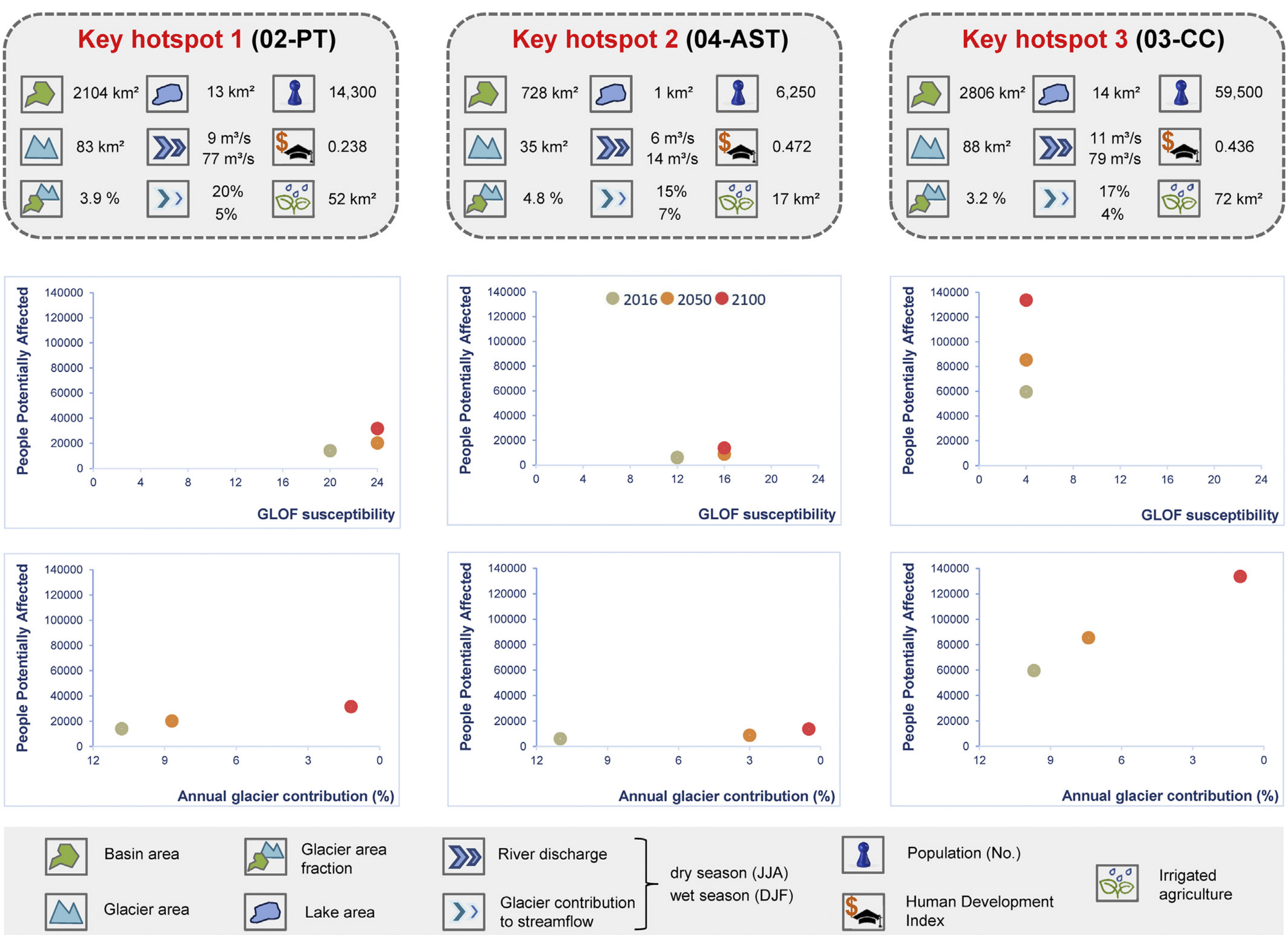

Fig. 5. Key hotspots (with main catchment characteristics) of current and future water risks. For each key hotspot people potentially affected are delineated in relation to GLOF susceptibility and annual glacier contribution to discharge for current (grey points), and future (2050 = orange points; 2100 = red points) conditions.

prominent lake (A162) only (Fig. 3). Nonetheless, hydropower infrastructure (Santa Teresa I: 98 MW installed capacity and 62 m^3/s discharge needed) and tourism in the region (Machu Picchu) are highly sensitive. Water shortages of several months represent a clear risk particularly for hydropower production. In this context, high glacier contribution to river streamflow (JJA: 14.9% and 12.7%, DJF: 7.0% and 3.9%, respectively) is crucial, particularly for dry-season water supply.

Until the end of this century ~6400 people could be affected by increasing exposure due to four potentially developing lakes (two of them within the next years, another two in a few decades) with high GLOF susceptibility. Increasing water shortages of up to nine months represent an important threat. This would be particularly true for the hydropower sector a few kilometres further downstream where total installed capacity of Santa Teresa I/II would grow to 388 MW implying a required discharge of 105 m^3/s. Pressure over water resources, particularly in the dry season, would be enhanced by strongly reduced glacier contribution to river streamflow (JJA: 0.7% and 1.3%, DJF: 0.3% and 0.4%, respectively).

4.3.3. Key hotspot 3

This hotspot is located at the outflow of 03-CC. At current conditions, two lakes (L103 and Riticocha) with very high GLOF susceptibility and risk levels would potentially affect >29,000 exposed people, mostly situated in the cities of Urubamba, Huayllabamba and Yucay (and at the lower bound probably Ollantaytambo further downstream), with a medium vulnerability level (HDI: 0.436). Here, water shortages are currently not representing a serious problem for domestic and irrigated agricultural (>70 km^2) water supply. Glacier contribution to river streamflow (JJA: 17.2%, DJF: 4.2%) plays a considerable but smaller role for local water supply than in the upper catchments.

Until the end of this century, there is a low probability of significant new lake developments and corresponding enhanced future GLOF susceptibility around the low-lying and flat Urubamba glaciers. Nonetheless, water shortages for at least one month during the dry season would now persist which could affect about 133,000 inhabitants and >190 km^2 of irrigated agriculture in the area. Already strongly reduced glacier contribution to river streamflow (JJA: 1.9%, DJF: 0.4%) would further enhance dry season water shortfalls.

In summary, the integrative analysis of a diverse range of water risks within three key hotspots provides some tangible results. While in the upper and middle basin particularly large irrigated agriculture (key hotspot 1) and population (key hotspot 3) sectors might be affected on the long term, especially hydropower and tourism (the latter not further assessed within the scope of this study) could be threatened by serious water shortages (key hotspot 2) until the end of this century.

5. Discussion and perspectives

5.1. GLOF risk assessment and related uncertainties

The presented GLOF risk assessment approach with free remote sensing data is effective in terms of data use and costs, particularly in view of challenges from persistent data scarcity in the VUB and the Andean region. Nonetheless, for a more detailed risk analysis with clearly communicated consequences for decision-making and further local lake management, more variables related to critical dam characteristics (e.g. freeboard and width-to-height ratio) and permafrost degradation (e.g. slope instabilities) need to be incorporated. Several lakes, such as those below Quelccaya ice cap (01-SS), had been assessed with high GLOF susceptibility (3–4 points) e.g. due to rapid area growth and huge lake volumes. However, they do not seem to pose a major threat due to low valley trajectory slopes and short runout distances (cf. Fig. 4). The overall score for these lakes is relatively low due to reduced human exposure (1 point) in this scarcely populated subcatchment.

The entire risk assessment applied here, provides a thorough and to some extent robust picture of GLOF risks considering that the applied thresholds have been derived from sensitivity analyses which are barely been used in this field. For instance, a field survey in the Pitumarca region (02-PT) conducted by the authors in 2016 corroborates the critical state of the three current lakes assessed with very high risk level (L162, Azulcocha and Qomercocha). However, more in-situ data would be needed to validate and adapt this semi-automatic approach. Notwithstanding, for the evaluation of the agreement between our assessment, field and previous surveys, it is important to consider that inconsistencies between remote sensing based lake hazard analysis, observed events and field assessments are quite common (Aggarwal et al., 2017; Allen et al., 2016b; Worni et al., 2013).

Glacier lake outburst floods often show flow transformation, with varying degrees of water-sediment concentration along the flow trajectory. Flow transformation between less mobile flows with higher sediment concentration and more mobile hyper-concentrated flows with less sediment concentration depend, among other, on overall trajectory slope, discharge, and available and erodible sediment. For instance, extreme floods have been reported for the Cordillera Blanca which are characterized by an overall trajectory slope of <8°, a reach of >10 km and erosion, transport and deposition volumes in the order of 10^6 m^3 (Emmer, 2017). Our analysis is in line with a first-order assessment but even with more sophisticated physically based flow models, exact identification of flow transformation and, thus, reach can be difficult. Whether a GLOF reaches 2° or 3° average slope is therefore difficult to define and within the range of uncertainty. We therefore apply a 2° approach as a lower worst-case limit. The GLOF risk scheme used here is particularly appropriate for future conditions where we lack more detailed information (e.g. on lake dam characteristics, topography) that could justify the application of more sophisticated models (Frey et al., 2010). Furthermore, the approach allows to consistently apply a regional-scale modelling and assessment across different periods of time. Follow-up studies may focus in more detail on identified critical zones and on additional large mass flow processes, such as landslides causing impact waves and/or turning into massive debris flows, as observed in 1998 in the lower VUB (Frey et al., 2016). There is a need to improve understanding of related upstream-downstream impacts. An important question in that context is whether future magnitude and risk of such disasters are driven by climate change impacts on the hazard component in headwaters or by socioeconomic effects on exposure and vulnerability in downstream areas or both. Huggel et al. (2015) found e.g. that the increasing number of people affected by disasters in the Andean region of Peru is rather driven by rising vulnerabilities than exposure. Finally, the analysis of changes in future exposure and vulnerability could enhance the understanding of the drivers of future risks and facilitate adequate risk management strategies.

5.2. Water shortages and related uncertainties

The estimated water balance depicts a complex picture of current and potential 'business-as-usual' water availability until 2050 and 2100. Therefore, a range of simplified assumptions based on current and possible future trends of glacier reduction, lake development and population, domestic, agricultural and hydropower growth was used in a context of high data scarcity and limited knowledge. The water balance simulation should be understood as a first-order assessment including potential worst-case future trajectories (RCP8.5 scenario) in a context of high uncertainty. Uncertainties arise from multiple inputs, e.g. the glacier and lake outline mapping (in the order of ~5–10%) (Cook et al., 2016), GlabTop's ice thickness distribution (~30%) (Linsbauer et al., 2012), PISCO precipitation input data (~20%) (Aybar et al., 2017) and, basically, non-assessable (high) uncertainties for the water demand sectors.

On the supply side, for example, the combined PISCO precipitation product includes uncertainty (bias ~±20%, root mean square error ~±15 mm/month) related to the merge and interpolation of the global dataset CHIRPS and quality-checked in-situ stations

(Aybar et al., 2017). Nonetheless, this new gridded dataset represents an important alternative to the inconsistent in-situ station data network in the region. Precipitation, the main input for the water balance, is highly variable in the study area and observation period (1986–2016) extending from 453 mm/year (03-CC) to 908 mm/year (05-RH). The degree-day glacier melting scheme assumes seasonally determined uniform melting over the whole glacier area. Additionally, and important to consider, our study also assesses the loss of glacier volume. We found the highest existing glacier volumes for the Cordillera Vilcanota and Quelccaya Ice Cap while Cordillera Urubamba and Vilcabamba only account for ~27% of total water volume from glaciers, yet with 40% of total glacier area with respect to the whole study region. Furthermore, the lowlying glaciers of Cordillera Urubamba and partially also of Cordillera Vilcabamba could be more affected by atmospheric warming and corresponding ELA rise which, in turn, could enhance melting rates (Drenkhan et al., 2018). The FAO Penman-Monteith standard method for estimating ET_o gives a general idea of regional but not necessarily local climatic conditions and must, thus, be taken with caution. Losses from ET_o might exceed those from glacier melt and errors applying the Penman-Monteith method are indicated in the magnitude of 30% (Vuille et al., 2018). Important is also to mention that, with a transformation from ice to glacier-free surfaces, evapotranspiration rates increase. However, this effect only applies to headwaters and might be negligible further downstream (Vuille et al., 2018). It is difficult to assess a full range of uncertainty when nearly no comprehensive datasets exist of any of the determinant variables. Nonetheless, good correlation of some defined parameters and simulated runoff can be observed. For the VUB, yearly ET_{eff} was determined at 411 mm/year which is only slightly lower than evaporation calculated by Andres et al. (2014) (443 mm/year) for the same region with reanalysis data and a semi-distributed hydrological model. The comparison of simulated monthly discharge (with lake management) for the entire VUB (Table 6b) with monthly averaged observations from gauging data from km105 (1958–2015) shows good agreement. Here it should be considered that the adjustment of multiple parameters in the water balance scheme, such as gridded precipitation values, losses from evaporation, agricultural demand or water allocation due to lake management, may considerably shift values and affect corresponding correlations. In that context, it is also important to mention the crucial but also complex role of groundwater. In the highly glaciated Santa basin (Cordillera Blanca), groundwater has been found to be a major contributor to river streamflow controlled by geomorphic setting (Glas et al., 2018) with a fraction of up to 80% in the dry season (Baraer et al., 2015). However, in the VUB and most other Andean basins groundwater contribution and flow characteristics still need to be sufficiently quantified and comprehensively understood in order to enable the inclusion of groundwater processes. Finally, it is also important to mention that the catchment area between the upper (01-SS and 02-PT), middle (03-CC) and lower basin (05-RH) has not been analysed due to reduced or missing glacier extent, and, thus, uncertainty of discharge simulation increases further downstream.

On the demand side, there is no comprehensive data or knowledge in Peru about current water demand trends in important sectors, such as agriculture and households. Last agricultural (domestic) census data are from 2012 (2018) and they do not cover water consumption but irrigated areas, population growth and water sources used. This represents a critical limitation and, in order to overcome this gap, other reasonable (general) correlations had to be used to relate irrigated areas and population data with water consumption. Additionally, in spatiotemporal terms, growth will not happen homogenously. Population will most probably grow more strongly in urban areas and could further decrease in the most rural areas. This would require a more detailed spatiotemporal analysis which is beyond the scope of this study. From this perspective, seasonal and monthly variations are difficult to assess. In summary, results for absolute runoff estimation at the outflow of each subcatchment must be taken with caution due to high uncertainties (cf. Buytaert et al., 2017).

A key question for several deglaciating regions is whether the growth of lake volumes has the potential to considerably attenuate or even compensate future negative effects of deglaciation on water streamflow and availability. The analysis of glacier and lake development in the VUB for 1988–2016 shows that total lake volume increased by 0.062 km^3 which corresponds to the small fraction of 3.72% of the estimated water equivalent of glacier volume loss (1.666 km^3) in the same period. Furthermore, total potential water volume from possible future lakes until 2100 is between 0.032 km^3 (RCP2.6) and 0.041 km^3 (RCP8.5) which corresponds to a fraction of 0.6% and 0.7%, respectively, of currently estimated water from glacier ice (5.811 km^3) (Drenkhan et al., 2018). This is in line with the new future lake inventory for Peru compiled by Colonia et al. (2017) who estimated the fraction of possible future lakes as 0.5–1.0% of the current glacier volume. Although not all lakes in the VUB are considered in our study, this clearly illustrates that future lake development alone would not allow for storing a major part of melting water from glacier shrinkage. Furthermore, the ratio of glacier and lake volume probably decreases substantially in future due to continued loss of flat glacier parts with potential bed-overdeepenings. This highlights even more the urgency for water storage measures in a timely manner. Lakes and reservoirs in fact play an important role because their water retention function buffers and regulates river flow. For example, Machu Picchu I/II operator EGEMSA controls the main reservoir Sibinacocha (Cordillera Vilcanota, 01-SS) via floodgates and is able to add 7–12 m^3/s of discharge to the Vilcanota-Urubamba river in the dry season which corresponds to an energy capacity of up to 62 MW, necessary for the hydropower plants Machu Picchu I/II and Santa Teresa I. Although water scarcity might be reduced through smart lake management at catchment level, as illustrated within this study, it is important to consider that local water scarcity might probably not be mitigated by a few (large) reservoirs. On the one hand, the storage of permanently released water from glacier shrinkage, estimated in the order of 2800–5500 10^6 m^3 for the entire VUB until 2100 (Drenkhan et al., 2018), is technically challenging. The currently largest reservoirs Sibinacocha and Langui Loy only buffer about 130 10^6 m^3. On the other hand, the social acceptance for large projects is generally low leading to strong social conflicts on the long term (Carey et al., 2012a; Drenkhan et al., 2015). Therefore, decentralised options could be more effective and at least compensate for a certain fraction of water from glacier ice (see following Section 5.3).

Our analysis of current and future water balance and related key hotspots of potential water shortages illustrates the complex interactions and intertwining of both: water supply and demand drivers. Reduced (future) water availability can be a combined consequence of shrinking glaciers and growing demand with a more important role of (relative) glacier contribution in headwaters which rapidly decreases with downstream distance (cf. Buytaert et al., 2017) and as a critical function for e.g. agriculture further downstream. Continued growth of population and e.g. water-intense agro-export crops might enhance the major role of increasing water demand which could outweigh impacts from shrinking glaciers and potential meteorological drought conditions. Current climate change and adaptation debates, however, primarily focus on water supply with an important prevailing lack of studies concerning changing water demand in the Tropical Andes (cf. Vuille et al., 2018).

5.3. Options for future water management

The current environmental and socioeconomic conditions and future changes, as analysed in this study, pose important challenges to water resource management in Peru and other regions. In Peru, the water management architecture has been changing in the context of the political-administrative regionalization (2002) and the implementation of a new water law (2009). This process explicitly incorporates principles of IWRM and attempts to promote a 'new water culture' aiming at a more efficient use of water resources with less contamination (ANA, 2009). Therefore, Water Resources Management Plans (WRMP) foresee a participative process incorporating local water users and stakeholders in order to provide a tool for water resources planning and management promoting intersectoral and sustainable water use at basin scale. The Water Resources Councils (WRC) are responsible for the implementation of each WRMP and, thus, for the coordination among different water users and council members, such as regional and local governments, agricultural users and peasant communities. However, so far only 12 WRC have formed at the national level, mostly located at the Pacific coast. The recently formed WRC Vilcanota-Urubamba represents one of the first comprehensively managed Andean basins in Peru (cf. http://goo.gl/cBubpJ) and is now in charge to develop the WRMP for the entire basin. If effective, WRC could represent an important mechanism to mitigate and contain social conflicts over water. From 539 social conflicts identified in 2011–2014 at national level, 153 (12 in Cusco) were directly related to water resources. Only 29 water conflicts entered into a dialogue and were, thus, put into a framework for long-term solving, highlighting the need for effective and inclusive governmental structures to manage water resources and conflicts (DDP, 2015). In Cusco, examples include unsolved conflicts of local communities, hydropower operators and local governments regarding the planned hydropower plant and reservoir construction in Salcca Pucará (in the province of Canchis, southwestern VUB) or in Santa Teresa II (downstream of 04-AST and 05-RH). Conflicts typically center around the distribution of water, and eventually make these projects socially and economically unfeasible (Drenkhan et al., 2015).

This study clearly indicates that stress on water resources will further increase with growing water demand, shrinking glaciers and transformation of future landscapes, raising concerns about water availability and access with considerable conflict potential. Competing demand over water and multiple risks have to be addressed by appropriate IWRM, and a stronger linkage between water resources and risk management needs to be developed. Our study is a first approach to develop the scientific evidence for more integrated approaches, considering that so far flood risk and water availability are typically addressed separately by the scientific community. The rapid environmental and socioeconomic transformation calls for more adaptive water management regime, essentially with a paradigm shift from a centralized prediction-and-control to a participatory social-learning-process approach, including all major water user groups (Pahl-Wostl, 2007). While socioeconomic and cultural disparities as well as institutional weaknesses are a limitation for this transformation, remarkable initiatives have recently emerged in the VUB.

EGEMSA, a major hydropower company in the region, has recognized that their deficit in dry-season water flow cannot just be compensated by constructing additional dams and water reservoirs as it has been done in the past. Awareness has risen that more integrative solutions are needed that not only include hydraulic engineering but increasing efficiency in water distribution and irrigation systems, participative water allocation and management and strong institutional coordination mechanisms. Specifically, in view of dwindling water resources and increasing multiple demand, multi-use of water projects have recently been promoted in the VUB. EGEMSA, together with various governmental, non-governmental and civil society stakeholders, is evaluating the potential for multi-purpose projects of water use in the headwater catchments of the VUB. These water retention structures can buffer future decreasing glacial melt water flow during the dry season and serve multiple users, such as local communities and agriculture, hydropower, households or tourism. While multi-purpose projects are not a new concept, they have rarely been implemented in high-mountain regions. Now, under rapid socio-environmental change initiatives are being promoted in regions, such as in the Himalayas (Bhattarai, 2009), tropical Andes (Barriga et al., 2018; Haeberli et al., 2016b) or in the Alps (Haeberli et al., 2016a). Our study has identified hotspots of increasing potential future water risks related to climate change impacts on glaciers and water resources. In this context, multi-purpose projects could be a feasible approach to integratively address GLOF risks and water supply and allocation problems by providing flood retention space and stored water volume for release during the dry season. For instance, following the 2010 GLOF at lake Riticocha in Chicón, Urubamba, studies and coordination have been undertaken to identify adaptation options that can address GLOF risk, decreasing glacial meltwater flows and rising water demand in an integrative way. The experiences available so far in the VUB and elsewhere indicate that the main challenge with water multi-purpose approaches is not primarily of technical nature but related to governance. Coordination within and between stakeholders (e.g. local governments, private sector and peasant communities), trust-building measures, such as full transparency, information exchange, or joint workshops are crucial. These long-term projects must gain social and political acceptance outlasting governmental changes and frequent turnover of decision makers in order to achieve sustainability. For any implementation of multi-purpose projects or other integrative water management frameworks, it is critical to adopt planning horizons beyond common governmental (4–5 years) and development project (3–5 years) timeframes probably in the order of 10–20 years.

A second important initiative is based on decentralised, small infrastructure with reduced socioenvironmental impacts: the reactivation of ancestral technologies by constructing micro-reservoirs ('qochas') and ancient stone canals ('amunas') for local water harvesting (storage), sowing (groundwater recharge) and distribution. These efforts recognize the role of local knowledge and its combination with technical and scientific approaches of adaptation (Bolin, 2009), which may have particular importance in data-scarce environments, such as the VUB. Total storage volume of all the 'qochas' planned in the Sibinacocha and Pitumarca catchments comprises 0.004 km^3 (IMA, 2016), which is about one order of magnitude smaller than the total volume of future lakes in these catchments as analysed in this study. Hence, total 'qocha' as well as potential future lake water volume by far does not compensate for water lost by shrinking glaciers. Nonetheless, locally they can contribute to sustain livelihoods, livestock and important ecosystems, such as Andean peat bogs ('bofedales'). Furthermore, the construction of 'qochas' is embedded in a national policy of 'siembra y cosecha de agua' (water sowing and harvesting), and national and international investments in green infrastructure, as part of climate adaptation strategies (Buytaert et al., 2017; Vuille et al., 2018). Additionally, new glacier lakes could increase the potential for alpine tourism and recreational activities which are an important source of income in the VUB. The exploration of new routes to these lakes and other sites might be favoured by increasingly rapid access to ice-free mountain environments (Vuille et al., 2018).

6. Conclusions

This study provides an integrative insight into emerging water risks and the need for adaptive management of potential disasters and water resources in the context of current and future glacier shrinkage and lake growth. The following main messages can be summarized from this study:

- Several key hotspots of water risks related to potential glacier lake outburst disasters and (future) water shortages have been identified in the VUB which provide a thorough picture of long-term impacts for growing irrigated agriculture, population and hydropower production
- While current river flow regimes in the dry season already reach critical levels, our future scenarios suggest widespread streamflow

reductions in the order of 2–11% (7–14%) until 2050 (2100) and, thus, substantial water scarcity, unless effective Integrated Water Resources Management beyond single-purpose lake management will be implemented
- Upstream-downstream relationships must be considered for the evaluation of risks and potentially affected people taking into account the importance of glacier streamflow contribution and potential reductions in future supply in headwaters as well as domestic, agricultural and hydropower demand increase in the middle and lower catchment
- Glacier contribution to river discharge is particularly important in headwaters and during dry seasons (~15–25%), but is likely to substantially decrease towards 2050 (~4–22%) and become mostly insignificant (~0.7–2.5%) until 2100
- Water demand, an under-researched field in many countries, could outweigh impacts from shrinking glaciers within the next decades, stressing the need for more socioeconomic studies and a stronger focus on more efficient and equitable water use
- Current and potential future natural lakes represent an important component for water resources management but cannot by any means compensate the loss of water reserve due to glacier shrinkage
- This study provides for the first time a combined analysis of low-flow (water scarcity) and high-flow (GLOF) risks and encourages strengthening of inter- and transdisciplinary water research including potential developments of and impacts from future landscapes and societies
- Complex interactions between drivers of water supply and demand must be critically reflected as well as data availability improved in order to enable better assessments of current and future water availability
- Ancestral and local knowledge should play a more visible role in current adaption planning and co-production of knowledge, also in view of water storage as well as allocation options considering current and potential future social conflicts
- A stronger move is proposed towards an integrated disaster and water risk framework combining complex and interconnected needs in e.g. multi-purpose projects

The catchment in Southern Peru is to a large extent comparable with socioenvironmental basin conditions in other parts of the Tropical Andes and the findings presented here therefore bear relevance beyond the study region.

Conflict of interest

All authors declare no conflicts of interest for this article.

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