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Landsystems of the tropical high Peruvian Andes: Glaciers, lakes, wetlands and water resources in the Cordillera Vilcanota

Bethan Davies¹  | Tom Gribbin^{2,3}  | Owen King¹  | Tom Matthews⁴  |
 Jan R. Baiker⁵  | Rike Becker⁶  | Wouter Buytaert⁶  | Jonathan Carrivick⁷  |
 Fabian Drenkhan^{8,9}  | Juan-Luis García¹⁰  | Nilton Montoya¹¹  |
 Baker Perry^{12,13}  | Jeremy Ely¹⁴ 

¹School of Geography, Politics and Sociology, Newcastle University, Newcastle-upon-Tyne, UK

²British Geological Survey, Environmental Science Centre, Keyworth, UK

³School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

⁴Department of Geography, Kings College London, London, UK

⁵ACEMAA (Asociación para la Conservación y Estudio de Montañas Andinas-Amazónicas), Cuzco, Peru

⁶Imperial College London, London, UK

⁷School of Geography and water@leeds, University of Leeds, Leeds, UK

⁸Geography and Environment, Department of Humanities, Pontificia Universidad Católica del Perú, Lima, Peru

⁹Grupo de Glaciología y Ecohidrología de Montañas Andinas (GEMS), Institute for Nature, Earth and Energy (INTE), Pontificia Universidad Católica del Perú, Lima, Peru

¹⁰Instituto de Geografía, Facultad de Historia, Geografía y Ciencia Política, Pontificia Universidad Católica de Chile, Santiago, Chile

¹¹Universidad Nacional San Antonio Abad del Cusco, Cusco, Peru

¹²Department of Geography, University of Nevada, Reno, Nevada, USA

¹³Research Institute for Environment, Energy, & Economics, Appalachian State University, Boone, North Carolina, USA

¹⁴School of Geography and Planning, The University of Sheffield, Sheffield, UK

Correspondence

Bethan Davies, School of Geography, Politics and Sociology, Newcastle University, Newcastle-upon-Tyne, UK.
 Email: bethan.davies@newcastle.ac.uk

Abstract

The water, food and energy security of millions of people is at risk in several regions of the tropical Andes because climate change is altering water storage in high Andean wetlands (*bofedales*), lakes and glacier ice. These features play a crucial role in delaying water release, particularly in many semiarid regions with pronounced seasonal precipitation, sustaining baseflows and water quality. Changing water availability impacts both high Andean pastoralist systems and other productive systems downstream, including bigger cities in the inter-Andean valleys. Here we outline the hydrological and geomorphological relationships between glaciers, lakes and *bofedal* wetlands, and the way in which catchment features such as moraines, talus slopes and sandar interact with catchment hydrology in the tropical Andes of Peru. We present a geomorphological map of catchment features in the Cordillera Vilcanota, Southern Peru, and explore how these features can impact hydrogeological processes. We suggest the ways in which well mapped and dated catchment features can provide a damming or groundwater/surface water exchange mechanism for *bofedal* development and sustenance. We find that glacial lakes will grow modestly as glaciers retreat, but will not provide an equivalent water storage to compensate for the loss of glacier ice. We find that *bofedales* are well developed within glacial limits, with glacial processes such as erosion and formation of moraines providing the poorly drained conditions suitable for their development. However, we find that the majority of the *bofedales* are largely hydrologically independent of contemporary glaciers, and could perhaps buffer water supply as glaciers dwindle and disappear. Such analysis enables an improved understanding of the timeframe for the formation of *bofedal* wetlands and for them to provide their key ecosystem services of water retention and remediation capacity, buffering drought, providing forage for high-Andean livestock herding, carbon storing and sequestration.

KEYWORDS

Andes, *bofedales*, Peru, tropical glaciers, wetlands

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1 | INTRODUCTION

In the outer tropics of the high Andes (including most of Peru and Bolivia), glaciers buffer drought and sustain baseflows for downstream ecosystems and communities (Immerzeel et al., 2020; Kaser, Großhauser, & Marzeion, 2010). However, current tropical glacier recession lowers dry season discharge (Baraer et al., 2012), especially after the passing of the 'peak water' threshold (Huss & Hock, 2018), and threatens water storage and buffering capacity, with implications for geopolitics, economies and biodiversity (Immerzeel et al., 2020), as well as social-cultural significance (Allison, 2015). Glaciers in the tropics are projected to have largely disappeared by 2100 CE (Rounce et al., 2023). Lakes formed in glacial forefields can act as natural reservoirs of water (Shugar et al., 2020). High Andean wetlands such as the *bofedales* of Peru and Bolivia, which can evolve through infilling these lakes (Emmer, 2024; INAIGEM, 2023a), also play a crucial role in delaying water release (Gribbin et al., 2024), sustaining baseflows (Wunderlich et al., 2023) and water quality (Monge-Salazar et al., 2022; Ross et al., 2023). *Bofedales* wetlands are perennially saturated peat-forming wetlands (Cooper et al., 2019), which are crucial for high Andean (indigenous) pastoralist communities (Verzija & Quispe, 2013; Yager et al., 2019), carbon sequestration (Cooper et al., 2015; Hribljan et al., 2015; Maldonado-Fonkén, 2014; Monge-Salazar et al., 2022) and host a range of (endemic) species (Domic et al., 2021; Herrera, Meneses, & Anthelme, 2015; Maldonado-Fonkén et al., 2024). Together, glaciers, lakes and *bofedales* wetlands are therefore crucial for water security in the tropical Andes (Ross et al., 2023) to sustain ecosystems and livelihoods in the high Peruvian Andes and further downstream (Drenkhan et al., 2019). The mechanism and timing of *bofedales* wetlands development is a critical question, as their capacity to provide ecosystem services as glaciers disappear is increasingly part of climate change adaptation efforts (Drenkhan et al., 2023; García, Prieto, & Kalazich, 2021; López-i-Gelats et al., 2015; Monge-Salazar et al., 2022; Squeo et al., 2006).

However, the hydrological and geomorphological relationships between glaciers and *bofedales* wetlands are complex. On the one hand, it has been argued that glaciers play a critical role in sustaining *bofedales* (Loza Herrera, Meneses, & Anthelme, 2015; Dangles et al., 2017; Polk et al., 2017; Vuille et al., 2018). On the other hand, other studies have asserted that the relationship is inconsequential, with groundwater flow and hillslope runoff being more important for *bofedales* wetlands than glacial meltwater (Cooper et al., 2019; Gribbin et al., 2024; Ross et al., 2023). The way in which glacial meltwater propagates through the system is in general not well understood (Buytaert et al., 2017), with previous studies being limited by a small spatial scale and focused on water source attribution. Catchment features, such as glaciers, glacial geomorphology, wetlands and groundwater, are frequently researched by disciplinary specialists in isolation

and the wider role each of these features plays in catchment hydrology is, therefore, highly uncertain (Navarro, MacDonell, & Valois, 2023; Ross et al., 2023). Variations in these geomorphic features could lead to distinct inter-valley and inter-region hydrogeologic processes (Glas et al., 2018). Well-mapped catchment features can give an insight, and, if chronological constraints are available, a timeframe for the length of time *bofedales* wetlands take to form and provide their key ecosystem services of buffering drought (Monge-Salazar et al., 2022), providing forage for livestock (Squeo et al., 2006) and storing carbon (Cooper et al., 2015; Wunderlich et al., 2023).

It is critical to comprehend with more clarity the relationship between glaciers, glacial geology and landforms, climate and *bofedales* wetlands, to improve our ability to understand current water resources, to improve sustainable management and to predict future glacier and wetland behaviour. This research therefore aims to use a landsystem approach to understand the current relationships between glaciers, lakes, geomorphology, climate and *bofedal* wetlands, and how these have evolved over time. Here, we first outline the key elements of the study area, before describing the key glacier, fluvial, lacustrine and paraglacial landforms, and then the study region's *bofedales* wetlands. The Discussion focuses on glacier and lake change and presents a new high-Andean tropical glacier, lake and *bofedal* landsystem, with the potential future drought-buffering capacity of glaciers and *bofedales* wetlands.

2 | STUDY AREA

We focus this study on the glacierised Cordillera Vilcanota range (71°W, 13.7°S; glacierised area is 50 km wide), covering 163.3 km² and Quelccaya Ice Cap (70.8°W, 13.9°S; 13 km wide, 38.8 km² in 2020 CE [INAIGEM, 2023b]), in the southerly part of the Vilcanota-Urubamba catchment in southern Peru (14°S) (Figure 1a,b). The main Cordillera Vilcanota massif, which includes the Ojollo Anante Ice Cap with Hatun Uma Mountain (6093 m asl), Nevado Ausangate (6384 m asl) and Chumpi massif (6106 m asl), is the second largest Peruvian icefield after Cordillera Blanca. Quelccaya Ice Cap is located at the southeastern margin of Cordillera Vilcanota and is one of the world's largest tropical ice caps (after Coropuna Ice Cap [72°38'W, 15°33'S], which covered 42.4 km² in 2020 [INAIGEM, 2023b]). The cordillera arcs around the large non-glacierised Sibinacocha Plateau (Figure 1c), the environs of which are the focus of this study. This 3000 km² study domain is shown in Figure 1c. The Sibinacocha Plateau occupies 359 km² (approximately 25 km west-east; 30 km south-north), with slopes generally below 5°, and ranges in height from 4600 m asl in the south, where fluvial incision has occurred, lowering the base of the river valley, to 4950 m asl in the north (Figure 1c).

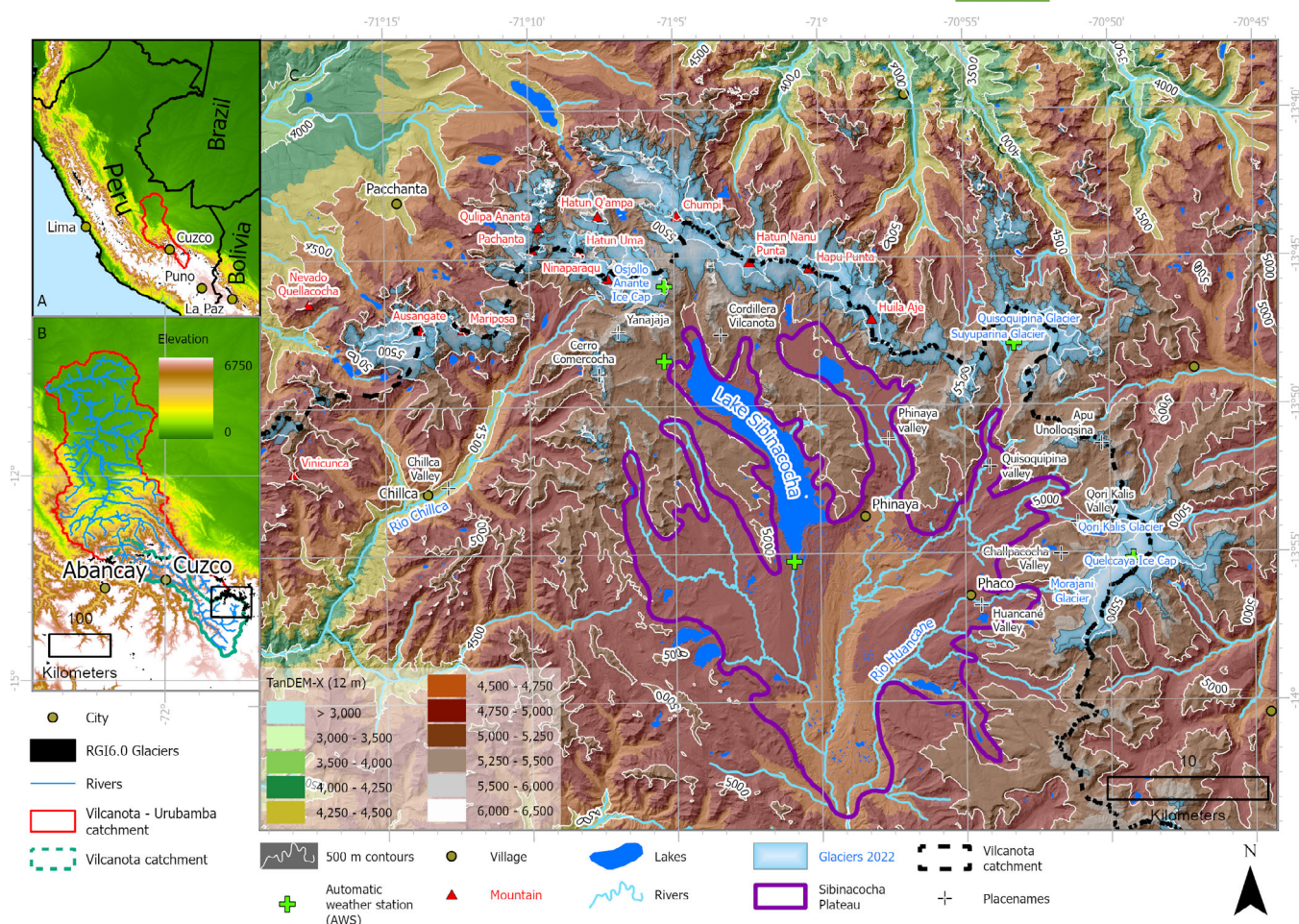


FIGURE 1 Study domain: Cordillera Vilcanota in the high Peruvian Andes. (a) The Vilcanota–Urubamba basin within Peru (red line). (b) The upper Vilcanota catchment (green dashed line) within the broader Vilcanota–Urubamba catchment, and significant cities. Black box shows location of Panel (c). (c) The study domain including the Sibinacocha plateau (purple). Location shown by box in Panel (b). Hydrological basins and basin-wide rivers from HydroSHEDS (Lehner, Verdin, & Jarvis, 2008).

The Cordillera Vilcanota range lies in the outer tropics. It has a pronounced precipitation seasonality, with a wet (October to April) and a dry (May to September) season, but limited temperature seasonality (Perry, Seimon, & Kelly Ginger, 2014). The low latitude and high radiation ensure high insolation, and the mean 0°C annual isotherm lies at about 5000 m asl (Schauwecker et al., 2017; Veettil & de Souza, 2017). Temperatures are at their minimum in the dry season. Increased cloud cover and atmospheric moisture content in the wet season increase the temperature seasonality with elevation (Fyffe et al., 2021). Annual precipitation (800–1000 mm) is mainly delivered by advective moisture transport from the Amazon basin (Drenkhan et al., 2015).

The range is drained by the Vilcanota River into the Amazon basin (Drenkhan et al., 2015). The Vilcanota catchment, defined as the area upstream of the Sacred Valley of the Incas (below which the name changes to the Urubamba River) (Figure 1b), is largely situated in the region of Cusco and is ~17 000 km² (Drenkhan et al., 2015). Within ~50 km of the mountain range, numerical modelling studies show that the glacial contribution to water in the Vilcanota River is above 50%, and can increase to 90% in dry periods (Buytaert et al., 2017). Down-valley from the glaciers, this river receives substantial contributions from lateral runoff of non-glacial origin, including orographic precipitation along the eastern slopes of the Andes, and the proportion of

glacial meltwater content in the river declines, though it remains important even hundreds of kilometres downstream in drought years (ibid.).

The Cordillera Vilcanota mountain range includes steep mountain glaciers that terminate at 4700–5000 m asl, with equilibrium line altitudes at 5105–5275 m asl (Salzmann et al., 2013) and median elevations of 5357 m asl (Mark et al., 2002; Taylor et al., 2022). The steep mountain glaciers are relatively thin, reaching a maximum of 270 m and many under 100 m (Millan et al., 2022). Quelccaya Ice Cap reaches up to ~200 m thickness (Thompson et al., 1982).

Glaciers in this region are currently receding (Drenkhan et al., 2018; Hanshaw & Bookhagen, 2014). Over the last six decades (1962–2020 CE), the Vilcanota glaciers have lost 50.86% (167.39 km²) of their area (INAIGEM, 2023b), corresponding to a shrinkage at $-0.9\% \text{ a}^{-1}$. Glaciers here are shrinking at about $1.8\% \text{ a}^{-1}$ (INAIGEM, 2018), only partially offset by a small increase in cumulative lake volume that does not provide an equivalent alternative water storage (Hanshaw & Bookhagen, 2014). The glaciers of Cordillera Vilcanota have lost $3.18 \pm 0.44 \text{ Gt}$ of ice from 2000 to 2020 CE, with accompanying thinning and a rise in glacier median elevation of 15.9 m per decade (Taylor et al., 2022). Following glacier recession, some valleys have become drier, driving changes in local flora and land-use practices (Thompson et al., 2011).

The south-eastern portion of the Cordillera Vilcanota catchment contains important high-altitude wetlands used for pasture, grazing and other ecosystem services (Fernandez-Palomino et al., 2021). These wetlands, locally named *bofedales*, or *oconales* (Maldonado-Fonkén, 2014), cover large parts of central and southern Peru, Bolivia, northern Chile and Argentina at an altitude of 3500–5200 m asl (INAIGEM, 2023a). They are typically only distributed within this elevational range, and can be found favouring headwaters and adjacent to springs, on flat or low-slope (0° to 15°) surfaces (Figure 2) (Monge-Salazar et al., 2022). They often develop over colluvial deposits (e.g., lacustrine plains, fluvioglacial kettles or bedrock hollows) and in infilled lakes (Emmer, 2024). There is a high seasonality in the productive *bofedal* areas between the wet and dry seasons in Cordillera Vilcanota (Ross et al., 2023). In some places, manual management then seeks to redistribute waters via artificial channels to produce wider grass areas for livestock (Figure 2d). However, the characteristics of these ecosystems are poorly described, especially with reference to their geomorphological and topographical constraints.

Bofedales wetlands comprise a diverse set of low-growing hydrophytic and cushion plants, dominated by species in the Juncaceae family, most commonly *Distichia muscoides* in Peru (Maldonado-Fonkén et al., 2024), which form dense clonal cushions (Oyague & Cooper, 2020) (Figure 2). They are resilient ecosystems, often exposed to strong winds, large diurnal thermal contrasts, pronounced dry seasons and high solar radiation (Ross et al., 2023). Peat

thicknesses vary considerably between *bofedales*, with thicknesses of up to 7 m at some locations in Cordillera Vilcanota (Perez & Loisel, 2023), thus acting as a potentially significant store of carbon (Cooper et al., 2019; Hribljan et al., 2015; Monge-Salazar et al., 2022; Wunderlich et al., 2023). The year-long growing season results in high carbon accumulation rates ($37\text{--}47\text{ g m}^{-2}\text{ a}^{-1}$), with reported volumes of carbon of 572 to 1040 metric tonnes of carbon stored per hectare (0.01 km^2) (Hribljan et al., 2015). A combination of mechanisms acts on different timescales in *bofedales* wetlands to slow the transit of water through the catchment, including the dense structure of individual cushion plants, and the properties of the peat soil and underlying units. This forms a natural dam and isolated pool systems seasonally disconnect from the surface water network, preventing and slowing drainage (Gribbin et al., 2024; Oyague & Cooper, 2020; Wunderlich et al., 2023) (Figure 2).

Receding glaciers may drive expansion of *bofedales* wetlands by providing more accommodation space and by temporarily increased meltwater supply (Polk et al., 2017). However, the decreasing glacierised area may decrease the availability of water resources to sustain *bofedales* (Baraer et al., 2012; Buytaert et al., 2017; Immerzeel et al., 2020; Milner et al., 2017) and drive further fragmentation of *bofedales* (Polk et al., 2017), ultimately driving a decrease in wetland area (Dangles et al., 2017; Polk et al., 2017). However, others have argued that *bofedales* wetlands are mostly supported by non-glacial sources such as groundwater springs from the valley sides (Cooper et al., 2019; Glas et al., 2018; Gribbin et al., 2024). The vulnerability of



FIGURE 2 Examples of different *bofedales* wetlands types of Cordillera Vilcanota, distinguished by dominant vegetation type and intensity of anthropogenic management: (a) *Bofedal* with peaty meadow and pooled water, in the Quisoquipina valley. (b) *Bofedal* dominated by *Distichia muscoides* cushions in Quisoquipina valley. (c) *Distichia* peatland down-valley of Quelccaya Ice Cap, with sediment-rich glaciofluvial meltwater flowing around the plants. Quelccaya Ice Cap in the distance. (d). Highly managed *bofedal* with an artificially cut dyke used for alpaca and sheep grazing. (e) The Qori Kalis valley, with alpaca foraging on *Distichia* peatland, which are seasonally dry. (f) *Bofedal* on valley floor above river, with Quelccaya Ice Cap in the distance.

these peatlands to glacier loss under climate change is therefore largely contingent on the degree to which they are supported by glacial meltwater versus groundwater recharged from precipitation (Cooper et al., 2019). However, since water availability is fundamental for *bofedales* wetlands evolution and maintenance, any factor influencing water availability, including changing temperatures and evapotranspiration under a changing climate and water management by local communities, is crucial for their viability.

3 | METHODS

3.1 | Landform mapping

We mapped landforms across the study region in a GIS, building on field surveys conducted in September 2023 and April 2024. Data sources for remote sensing include a range of recent optical satellite imagery including 1-m DigitalGlobe imagery, part of the ESRI™ World Imagery, and 1.5-m resolution SPOT-6 imagery (provided as part of Bing maps). Elevation data were derived from TanDEM-X 12-m DEM (data acquisition in 2015 CE). The TanDEM-X DEM was visualised using hillshades and slope maps as well as elevation datasets. Current glaciers and ice marginal and subglacial features (such as moraines, ice-scoured bedrock, flutes and drumlins) are presented in detail in Davies et al. (2026). The sedimentology of specific landforms is described, as it can clarify processes of formation and post-depositional deformation.

We used these data sets to produce a new geomorphological map in ESRI ArcMap Pro of the Cordillera Vilcanota and Quelccaya area, focusing on lacustrine and fluvial landforms and *bofedales* wetlands, alongside the glacial geomorphology. This map was refined using field surveys (September 2023 and April 2024) and imagery derived from uncrewed aerial vehicles (UAVs) following standard protocols (Chandler et al., 2018). Mapping was conducted at a scale of 1:10000. Landforms in the field were mapped using a handheld GPS with a documented accuracy of ± 5 m. Landforms were identified, classified, and manually mapped in a GIS according to established glacial geomorphological and sedimentological criteria (Davies et al., 2022; Lee et al., 2022; Małeck et al., 2018; Martin, Davies, & Thorndycraft, 2019; McCerery et al., 2024), based on their visual appearance on satellite imagery, sedimentary characteristics as observed in the field, and their significance for process understanding (Table 1). Lakes first mapped in Davies et al. (2026) are here further categorised and analysed. Hydrological basins were obtained from HydroSHEDS v1 (Lehner, Verdin, & Jarvis, 2008).

In order to assess recent glacier shrinkage, we used glacier outlines from the Randolph Glacier Inventory (RGI) V.6.0 (Randolph Glacier Inventory Consortium et al., 2017), mapped from satellite imagery acquired in 2003. These outlines were then manually edited to reflect glacier extent as observed in the 2022 Sentinel image (Table 1), providing 19 years of glacier shrinkage data. Outlines and ice divides were visually checked against the INAIGEM 2020 inventory (INAIGEM, 2023b) and found to be consistent. These glacier extents are the same as those presented in Davies et al. (2026). This up-to-date inventory also allowed geomorphological mapping up to the contemporary ice margin, as many parts of the now exposed upper valleys were covered by ice in 2003.

Bofedales wetlands were derived from a national inventory derived from remote sensing using dry-season NDVI (INAIGEM, 2023a). This was based on supervised classification using the machine learning algorithm Random Forest, with a wide set of spectral topographic and vegetation indices with some ground-truth validation (INAIGEM, 2023a). However, we note that this inventory was conducted with limited ground-truthing and may over-estimate *bofedal* area, particularly in artificial channels and whole irrigation systems. The shapefile was manually inspected, compared with the satellite imagery datasets listed above, and edited to improve representation of *bofedales* wetlands across the area. This removed obvious misclassifications (e.g., *bofedales* on glacier ice surfaces and lakes).

Published cosmogenic ages (Kelly et al., 2015; Sagredo et al., 2016; Stroup et al., 2014; Stroup et al., 2015) were collated using the ICE-D database and the literature, and are recalculated using the Version 3 CRONUS-Earth online exposure age calculator. Morphostratigraphic chronologies for undated moraines are presented in Davies et al. (2026). We present samples on maps with the LSDn scaling scheme (Borchers et al., 2016; Lifton, Sato, & Dunai, 2014) and the global production rate (Borchers et al., 2016). Radiocarbon ages were collated from the literature and recalibrated using Calib version 8.20 ^{14}C (Stuiver & Reimer, 1993), using the IntCal20 dataset (Reimer et al., 2020) and are presented as calibrated ages (cal. ka BP) on figures and maps.

3.2 | Glacial landsystem development

The 'landsystems' approach recognises a landsystem as an area with common terrain attributes, reflecting underlying geology, glacial thermal regime, ice-flow history, climate, previous erosional and depositional processes (Benn & Evans, 2010; Knight, Mitchell, & Rose, 2011). It classifies landscapes by considering them as integrated systems rather than analysing isolated landforms and sediments, which can be ambiguous or suffer from equifinality issues (Chandler et al., 2018; Evans, 2003b; Evans & Twigg, 2002). The landsystems approach groups together recurring patterns of landforms, sediments and processes into sediment-landform assemblages, which occur in association with one another under particular environmental conditions. These suites of sediment-landform assemblages can therefore be related to the processes involved in their development, sediment-transfer pathways and glaciological regimes (cf. Benn & Evans, 2010; Evans, 2003b; Hambrey & Glasser, 2012). Here, we therefore classify landforms according to the criteria in Table 1, and then group them into suites, or 'assemblages', of glacial (described in more detail in Davies et al., 2026), fluvial, lacustrine and paraglacial landforms, before examining and classifying the *bofedales* wetlands in the study region.

The landsystems approach emphasises that landscapes evolve as dynamic systems, shaped by the interaction of geology and topography, processes by geomorphic agents such as water, wind and ice, and time, and emphasises the relationships and processes that link landforms. It is an interpretative conceptual tool that allows an integrative perspective on the feedbacks, interactions and linkages between different landscape elements. The landsystems approach has been used widely to characterise the sediment-landform assemblages and gain insights into glaciological processes and styles of glaciation

TABLE 1 Mapping criteria for landforms in Cordillera Vilcanota.

Feature	Visual appearance on satellite imagery	Sedimentary characteristics	Significance
Fluvial assemblage			
Rivers and streams	Linear, sinuous water courses, may be surrounded by glaciofluvial sediments		Indicates the lowest elevation within a valley.
Gravel braided river	Valley-floor accumulations of sediment, light-grey colour, smooth surface, dissected by braided rivers and streams	Meltwater channels composed of gravel and boulders, outwash plains, subangular to subrounded clasts.	Glaciofluvial sediments, indicates a high sediment load
River terrace	Terraces running extensively along the valley side, sloping gently down-valley.	Uniformly textured, vegetated surface, terraces running along valley side above valley floor.	Indicate former floodplain and subsequent down-cutting.
Palaeosandar	Flat, well-drained area, may have meltwater channels developed on surface.	Gravel, may have subtle meltwater channels, subangular to rounded clasts	Indicates former drainage regime of a glacier
Lacustrine assemblage			
Lake	Lake disconnected from ice margin and not within damming moraines. Smooth surface, dark blue to light grey colour. Found within overdeepenings and depressions.	Water is present	Ponding of water disconnected from the ice margin, often forming in overdeepened valleys. Infilling results in <i>bofedal</i> formation.
Moraine-dammed lake	Lake dammed within an over-deepening, inside large moraines. May be infilling with vegetation and peat.		May be hazardous if susceptible to ice or rock avalanches into the lake.
Kettle lake	Rounded or ovate depression in area of morainic or glaciofluvial material, often filled with water, can be dried		Indicates previously glaciated area. May indicate ice stagnation.
Proglacial lake	Ice-contact lake ponding at the glacier snout.		Ponding of meltwater in a forefield depression
<i>Bofedales</i> wetlands (INAIGEM, 2023a)	Dark to light green in colour, developed in flat areas, around ponds, along streams and springs, year-round green colour.	Typical vegetation found in valley floor. Typical vegetation includes the firm, round cushions of <i>Distichia</i> peatland, and the <i>Asteraceae</i> and <i>Apiaceae</i> families. Diverse vegetation. Maldonado-Fonkén (2014)	Occupies swampy areas above 3500 m asl. An important water resource that interacts with other geomorphic features.
Palaeolake	Associated with kame terraces, meltwater channels, moraine spillways, indicating the presence of a former moraine-dammed lake	In the field, cores may show presence of well-sorted lacustrine clays.	Indicates the presence of a former moraine-dammed lake, now drained.
Spillway/col	Spillway drainage point from a moraine-dammed lake. Found on moraines, with abandoned meltwater channels on the ice-distal side. Is located at a low point on the moraine. Breach in moraine shows a sharp down-cutting and formation of a new drainage. May be a brighter colour due to exposure of fresh sediments.	May be a gentle gradient and associated with obvious meltwater channels. Breach may be currently occupied by a stream.	Indicates the past and current drainage point from a moraine-dammed lake.
Boulder bar	Elongated, positive relief, valley-floor feature with tapered ends.	Boulders present on the surface.	Often indicative of a large hydrological erosion and sediment-transport event, such as a flood; may form as a result of a glacial lake outburst flood.
Paraglacial assemblage			
Talus cones	Steeply sloping fan or cone of sediment at the valley side, accumulating and sloping to valley floor. Smooth texture, light to dark grey in colour, largely unvegetated.	Visible from valley floor, unconsolidated materials. Angular clasts.	Paraglacial processes active
Alluvial fan	Sub-horizontal or sloping fans from valley sides fed by a river or stream. Smooth surface, splaying out in a fan shape from valley side to valley floor. Sharp boundary with surrounding topography and vegetation.	Cobble-gravel texture	Reworking of unconsolidated material by meltwater channels and streams.
Mass movement	Slumped and hummocky appearance, scar may be visible on mountain side, arcuate foot	Slumped appearance against valley walls	Indicates large-scale rock slope failure following deglaciation of the valley.

(e.g., Bickerdike et al., 2018; Chandler et al., 2020; Darvill et al., 2017; Evans, 2003a; Evans & Rea, 2003; Małeckı et al., 2018; McCerery et al., 2025; Narro Pérez et al., 2023). Here, following systematic mapping of glaciers, fluvial and lacustrine landforms, and *bofedales* wetlands, and building on the glacial geomorphological mapping presented in Davies et al. (2026), we apply the landsystems approach to determine the process linkages, feedbacks and interrelationships between sediment-landform assemblages, and how these relationships have changed through time.

4 | GLACIERS AND THE FLUVIAL, LACUSTRINE AND PARAGLACIAL LANDFORMS OF CORDILLERA VILCANOTA

4.1 | Glacier change

The Randolph Glacier Inventory v.6.0 identified 233 glaciers in this study area, mapped from imagery acquired in 2003. Editing of the glacier outlines in line with 2022 Sentinel-2A satellite imagery yielded a total of 237 glaciers within the domain (Table 3), indicating a total glacier shrinkage of 133.00 km² (34.97% area loss) over the 19 years between the two inventories. The 2020 INAIGEM inventory in comparison found a loss of 12.22 km² from 2016 to 2020 (INAIGEM, 2023b). The increase in number of glaciers indicates that fragmentation of the ice has occurred alongside glacier recession. This equates to a total rate of shrinkage of 7.00 km² a⁻¹ from 2003 to 2022 (1.85% a⁻¹) (Table 3). This is an acceleration of the regional retreat observed from 1985 to 2009 (0.95% a⁻¹) (Salzmann et al., 2013) but similar to that observed regionally from 1989 to 2016 (1.8% a⁻¹) (INAIGEM, 2018) and 2016–2020 (1.26% a⁻¹) (INAIGEM, 2023b). Over this time, glacier termini have retreated uphill, with the lowest glacier termini raising from 4565 m to 4686.9 m asl; mean z-min (lowest elevation in the glacier) has risen from 4954 m to 5085 m asl (Table 3). Occurring alongside the observed shrinkage and thinning (Hugonnet et al., 2021) are clear signs of fragmentation, with bedrock now often visible within the glacier body itself.

Quelccaya Ice Cap (Figures 4 and 6a–c) covered 39.46 km² in 2022, divided between 15 outlet glaciers that drained the main ice cap (Figure 4 and Table 3). The largest is Morajani Glacier (11.66 km²). While Qori Kalis Glacier terminated in a proglacial lake, which drove accelerated terminus recession from 1963 to 2005 (Salzmann et al., 2013), this outlet glacier has now receded up-valley and has no contact with the lake water (Figures 4 and 6c). All glaciers draining the ice cap are now land-terminating and terminate variously on the plateau itself or descend into valleys headed by steep-walled cirques. The outlet glaciers are intensely crevassed at the break in slope, with arcuate crevasses and ice falls denoting the longitudinal extension over the steeper slopes.

The remainder of the glaciers are steep mountain glaciers, often with elevational ranges of over 1000 m in altitude over just a few kilometres of horizontal distance (e.g., Figure 6d,e). These glaciers often have steep cirque backwalls and the longest glacier tongues still reach the valley. Three of these glaciers terminate in proglacial lakes and the remainder are land-terminating. Only one mountain glacier in the study area calves icebergs into a proglacial lake. The largest

glacier, draining from the Chumpi massif (Figure 6e), covers 8.60 km², up to 180 m thick (Millan et al., 2022) and is 1000 m long from ice divide to terminus, with an elevational range of 1800 m. However, the longest glaciers reach >4000 m in length.

4.2 | Glacial geomorphology

The mapped area (domain in Figures 1c and 3) can be divided into four distinctive regions: north of the Cordillera Vilcanota; the main Sibinacocha Plateau within the arc of the Cordillera Vilcanota range; lower-elevation areas dominated by fluvial, rather than glacial, geomorphology away from the ice masses; and fresh geomorphic features in close proximity to present-day glacier ice. We focus on mapping and presenting the fluvial, lacustrine and paraglacial sediment-landform assemblages of the Sibinacocha Plateau and its environs (Figure 3 and Table 2). The glacial geomorphology is covered in detail in Davies et al. (2026) and is summarised briefly here.

The glacierised peaks surrounding the Sibinacocha Plateau comprise steep mountain glaciers, especially around the Ausangate, Chumpi and Huila Aje massifs (Figure 3). Quelccaya Ice Cap comprises 14 low-slope glaciers on an ignimbrite plateau (Figure 4). Between the glacierised mountain peaks lie over-deepened parabolic valleys. These often have lakes along their valley floor and comprise a heavily dissected glacial landscape. Geological intrusions interrupt the landscape, with bedrock ridges prominent in the landscape. Ignimbrite and basalt plateaux rise above the lower Sibinacocha Plateau, bearing present-day ice caps (Quelccaya Ice Cap) and geomorphic evidence of former ice caps (Figure 3).

Across the Sibinacocha Plateau is evidence of palaeoglacier advance, including moraines, drumlins, and flutings (Davies et al., 2026) (Figure 3). Ice-scoured bedrock is widely observed both within the boundaries of Late Holocene and mid-valley moraines (Figure 3). Outside the major moraines, flat, well-drained areas, occasionally with some palaeochannels, indicate the former presence of sandar, now disconnected from the glacial meltwater supply.

Moraines across the study domain are largely limited to above 4200 m, with a mean altitude of 4864 m asl. They are widespread across the Sibinacocha Plateau (Figure 3), which supported large palaeoglacier fluctuations during previous glacials (Davies et al., 2026; Mercer & Palacios, 1977). The most recent moraines occur near the ice margin. These moraines are dated to the Late Holocene, during the ‘Little Ice Age’ chronozone (Carrivick et al., 2024; Sagredo et al., 2016; Stroup et al., 2014), and they frequently enclose a moraine-dammed lake (Figures 3 and 4). Down-valley of these Late-Holocene moraines are moraine sequences, likely deposited during the Late Glacial; moraines dated to the Younger Dryas chronozone are present nearby in the Challpachocha and Huancané valleys (Kelly et al., 2015; Mercer & Palacios, 1977; Stroup et al., 2014; Stroup et al., 2015) (Figure 4).

Further down-valley are older moraines, such as the Quisoquipina III moraines and the Qori Kalis III moraines (Davies et al., 2026), which likely date to earlier in the Late Glacial Period. The glaciated valleys associated with these moraines are characterised by streamlined landforms including drumlins and ice-scoured bedrock (Figures 3 and 5h). Finally, a major advance of the glaciers, potentially relating to the local Last Glacial Maximum (LLGM), is documented by a series of moraines

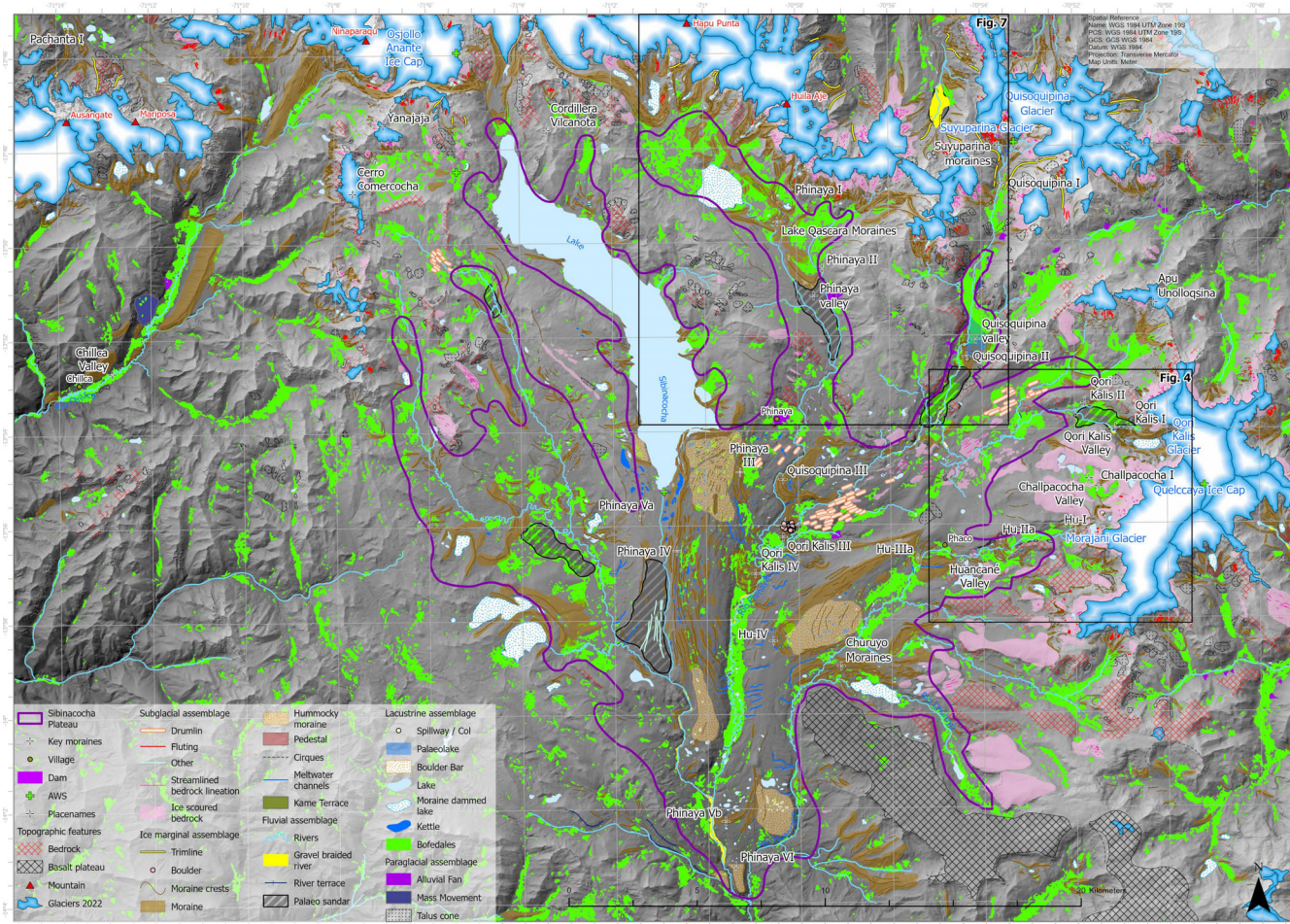


FIGURE 3 Geomorphology of the Sibinacocha plateau, with moraine names mentioned in text. *Bofedales* wetlands shapefile from INAIGEM (2023a). Glaciers, ice marginal and subglacial features are presented in detail in Davies et al. (2026). Landform inventory for original mapping in this publication in Table 2.

reaching the southern limit of the Sibinacocha Plateau. These include the Phinaya IV, V and VI moraines (Figures 3 and 5f).

4.3 | Fluvial landforms

Most valleys have a small river at their base, flowing into and out of *bofedales* wetlands, often with a source associated with glaciers and ice at the valley headwall (Figure 3). These rivers sometimes occur as gravel-bed braided rivers with typical gravel point bars, but the widths are rather narrow with low-volume flows, compared with more temperate proximal glaciofluvial settings (Figure 5h). Most of the glaciofluvial rivers bear a suspended sediment load typical of glacially sourced rivers and flow into, around or adjacent to the *bofedales*. These rivers have infilled valley floors with alluvial deposits, resulting in wide, flat valleys. Peat is now often forming on top of this valley fill. However, larger palaeosanders are mapped beyond some of the significant mid-valley terminal moraines from enlarged palaeoglaciers (Figure 3).

There is some fluvial incision, especially associated with rivers cutting through older moraines such as the Phinaya VI, V and VI moraines or the Chumpi IV moraines north-west of Ausangate. The incision of these older moraines suggests uplift has occurred since their deposition, likely isostatic uplift related to the removal of large

ice masses since the end of the Late Glacial and Last Glacial Maximum advances. This results in clear river terraces forming alongside the main channel.

4.4 | Lacustrine landforms

Lakes are common in the landscape, often infilling bedrock-dammed overdeepenings, such as Lake Sibinacocha (28.97 km²), forming behind moraine dams, such as Lake Qascara (Figures 3 and 7), and as small kettle lakes between moraine ridge crests (for example, between the Vilcanota Moraines I). Beyond the glaciated region, and outside the plateau, lakes are sparse, showing the importance of glacial erosion in providing accommodation space for lake development. The smallest lakes (<0.02 km²) are likely rain-fed, and their size oscillates with precipitation and evaporation variability, leading to seasonal drying (Drenkhan et al., 2018).

Within the study area there are 59 moraine-dammed lakes (Table 2), which mostly occur within the overdeepenings in the glacier forefield, impounded by the Late Holocene moraines. This suggests that many of the mountain glaciers formerly terminated in proglacial lakes. The glacier termini have almost entirely receded away from these lakes, and only three of the moraine-dammed lakes are currently still in contact with the ice margin. Only one pro-glacier lake, which

TABLE 2 Landform inventory for cordillera Vilcanota, within the 3000-km² study domain focused on the Sibinacocha Plateau.

Feature	Number of observations	Total area, km ²	Mean area, km ² (SD)*	Mean altitude, m asl (SD)*	Description and comments
<i>Fluvial assemblage</i>					
Rivers and streams	206				These rivers sometimes occur as gravel-bed braided rivers with typical gravel point bars, but the widths are rather superficial. Those fed by glacial meltwater typically bear a high suspended sediment load.
Palaeosandar	8	13.7	1.7 (1.5)	4897.5 (67.8)	
River terrace	22				Observed incision and terrace formation in association with the stratigraphically oldest moraines
<i>Lacustrine assemblage</i>					
Spillway (Point at which the palaeolake drained across the Quisoquipina Moraines I)	1			4838.4	Palaeospillway across the Quisoquipina Moraines I, indicating the drainage point for a former moraine-dammed palaeolake.
Moraine breach through moraine, formed during flood	2			4823.8 (Quisoquipina Moraines I) and 4702.1	E.g., Incision through moraine crest at Quisoquipina Moraines I (4823.8 m)
Palaeolake	1	1.0		4838.4	Dammed by the Quisoquipina Moraines I and aligned with spillway and abandoned palaeochannels on the moraine crest.
Boulder bar	1	0.03		4797.7	Formed 7 km down-valley of Qori Kalis glacier.
Lake	975	56.0	0.06 (0.9)	4826.3 (174.3)	
of which are ice-contact proglacial lakes	3	0.8	0.3 (0.1)	4810.7 (193.2)	Three moraine-dammed lakes are still in contact with the glaciers. Only one glacier, which drains westwards from the Ausangate massif, has icebergs within it, indicating that calving is a significant component of mass loss.
of which formed since the RGI v.6.0 (2003)	5	0.08	0.02 (0.007)	5022.5 (147.7)	Formed between the ice limits mapped in 2003 (RGI) and 2022 (this study)
of which are Moraine-dammed lakes	59	15.6	0.3 (0.5)	4883.7 (159.4)	Widespread within boundaries of the Little Ice Age moraines.
of which are Kettle lakes	479	1.9	0.004 (0.01)	4812.1 (134.9)	For example, small lakes widespread between both Late Holocene (e.g. Huile Aje Moraines) and older moraines (e.g., Vilcanota Moraines I).
<i>Bofedal wetlands</i> (INAIGEM, 2023a)	9244	249.7	0.03 (0.1)	4673.4 (281.9)	Evolve by infilling former lakes, forming most frequently behind bedrock dams, moraine dams, and along water courses and on floodplains.
<i>Paraglacial assemblage</i>					
Talus cone	581	27.9	0.05 (0.06)	4961.4 (266.6)	Mantle many steep-sided valley walls, often below bedrock cliffs. These are geographically variable, reflecting the important role of geology in controlling the type, and development, of the talus cones. For example, around the Quelccaya plateau, the ignimbrite bedrock easily weathers to a sandy material that mantles the slopes. Below intrusive dykes, talus cones comprise coarser material. In the Huanané Valley, talus cones mantle the slopes above the moraines and <i>bofedales</i> wetlands occupying the valley floor (Figure 4). In the Quisoquipina valley, abundant talus cones and alluvial fans mantle the slopes, also reaching the <i>bofedales</i> on the valley floor. These talus cones connect with the Quisoquipina Moraines I, with substantial angular, supraglacially derived material in the moraines close to the rock walls. In contrast, in the more resistant granitic bedrock that forms the mountains of Huile Aje, talus cones are less common, with more streamlined bedrock (Figures 4 and 3).

(Continues)

TABLE 2 (Continued)

Feature	Number of observations	Total area, km ²	Mean area, km ² (SD)*	Mean altitude, m asl (SD)*	Description and comments
Alluvial fan	67	4.7	0.07 (0.09)	4730.7 (260.6)	The alluvial fan forms on the valley floor at the base of a gully, often connecting with <i>bofedales</i> wetlands developed on the valley floor.
Mass movement	4	1.6	0.4 (0.4)	4580.1 (240.6)	Examples occur in the Quisoquipina and Chillca valleys.

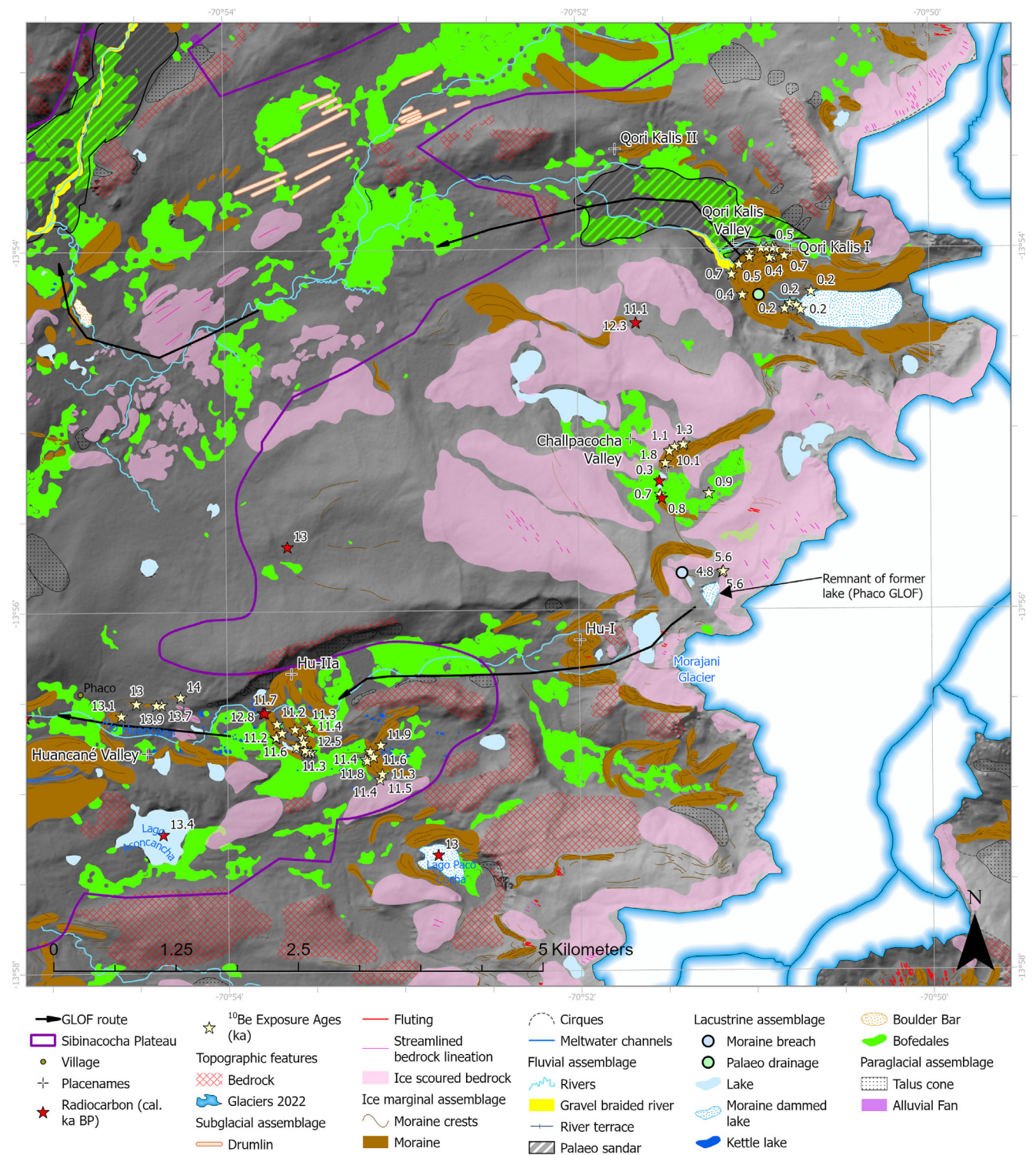


FIGURE 4 Glacial geomorphology, glaciers, lakes and *bofedales* in the Qori Kalis, Challapacocha and Huancané valleys west of Quelccaya Ice Cap, along with published moraine chronostratigraphy (Kelly et al., 2015; Mark et al., 2002; Mercer & Palacios, 1977; Stroup et al., 2014; Stroup et al., 2015). Glacial geomorphology from Davies et al. (2026). *Bofedales* wetlands shapefile from INAIGEM (2023a).

FIGURE 5 Landsystem elements of cordillera Vilcanota. (a) Suyuparina Glacier terminus. (b) Flutes in front of Suyuparina Glacier. (c) Recent moraines and flutes in front of Suyuparina Glacier. (d) Late Holocene Phinaya I moraines above Lake Qascara (Carrivick et al., 2024). (e) Well-drained Quisoquipina II Moraines, likely Late Glacial in age (Davies et al., 2026). (f) Well-drained local Last Glacial Maximum Phinaya IV moraines. (g) Talus cones, mass movements and *bofedales* in Quisoquipina valley. (h) Gravel braided river and rock outcrops down-valley of Quelccaya Ice Cap.



drains westwards from the Ausangate massif, still has icebergs within it, indicating that calving remains a significant component of mass loss for only one glacier. In contrast, at least 10 glaciers terminated directly in glacial lakes at the time of the RGI inventory in 2003, and at least five lakes have formed in the proglacial overdeepenings exposed as glaciers retreated between the two inventories (Table 2). While calving may have formerly formed a significant part of the mass loss of some glaciers such as Qori Kalis Glacier (Salzmann et al., 2013), it is now a very limited component of ablation in the study region (Table 2). Qori Kalis Glacier has, for example, receded out of its lake (Figure 6c). However, many of these lakes are still directly influenced by proximal glaciers, with influx of turbid, cold and sediment-laden water (Michelutti et al., 2019) (Figure 6c).

There are records of contemporary glacial lake outburst floods (GLOFs) from pro-glacial lakes associated with glaciers draining Quelccaya Ice Cap (Thompson et al., 2011; Thompson et al., 2021) in 2006 and 2007 (see mapped GLOF routes in Figure 4). There is also

some geomorphic evidence of palaeo-GLOFs. For example, a moraine-dammed lake is reconstructed within the Quisoquipina II moraines, aligned with a spillway col on the moraine crest and flat terraces within the moraine boundaries (Table 2 and Figure 7). A flat-topped kame terrace on the eastern bank is aligned with a spillway (4838.4 m) and abandoned meltwater channels on the low-gradient moraines on the ice-distal side (Figure 7). The river now exists through a lower moraine breach (4823 m) (Figure 12b). We mapped a boulder bar 7 km downstream of Qori Kalis glacier (Figure 4), which may have formed during the 2006 or an earlier GLOF.

While these glacial lakes grew substantially over the 1990s and 2000s (Drenkhan et al., 2019; Hanshaw & Bookhagen, 2014), substantial further lake growth is unlikely and the majority of moraine-dammed lakes are likely already formed, as noted in other parts of Peru (Emmer et al., 2020). Numerical simulations predicting future glacier lake growth by Drenkhan et al. (2018) in the Vilcanota–Urubamba basin suggest that some lakes will form in the overdeepenings under



FIGURE 6 Example photographs of glaciers in the study region. (a,b) The low-slope Quelccaya Ice Cap. Streamlined bedrock with P-forms (b) in the foreground. (c) Qori Kalis Glacier, draining Quelccaya Ice Cap. (d) Steep mountain glaciers on the flanks of Huila Aje. Lake Qasquara in the foreground. (e) The steep mountain glaciers of Cordillera Vilcanota, and the head of Lake Sibinacocha.

the currently larger glacier tongues, with 14–16 smaller lakes predicted to form under the RCP 2.6 and RCP 8.5 scenarios, respectively, with a total area of 1.57 km². We note that this is a minimum figure; it will be larger for the whole study domain since this forward modelling had a clearly defined spatial scope, restricted to the Vilcanota catchment (Figure 8) and not the entire study area, and therefore did not include glaciers north of the ice divide. Once glaciers recede to the steeper mountain sides, which is likely by 2050 under all climate scenarios (Drenkhan et al., 2018), there are few flat areas for new lakes to form; any further lake growth in subglacial over-deepening is likely to be insubstantial (cf. Colonia et al., 2017).

4.5 | Paraglacial landforms

Slope deposits are an important part of the Cordillera Vilcanota landscape. Talus cones mantle the slopes of many of the steep-sided valley walls, often forming below steep bedrock cliffs, but also on

lower-sloped hillsides derived from weaker sedimentary substrate. The talus cones often terminate on the broader valley floor, connecting with *bofedales* wetlands and glacial moraines (e.g., Figures 4, 5g, 7 and 12d and Table 2). Alluvial fans are also a common hillslope feature within this catchment, often forming where small streams from adjacent valleys meet a larger valley. Finally, a small number of large-scale mass movements were mapped. These mass movements occur for example in the Quisoquipina and Chillca valleys, because of large-scale rock-slope failure (Figure 3). Rock glaciers are rare within the study area (INAIGEM, 2023b) but may contribute to hillslope hydrology where present.

Talus cones and alluvial fans are common in periglacial and paraglacial environments, where non-glacial processes conditioned by (de) glaciation occur (Slaymaker, 2009). Recession of the glaciers of Cordillera Vilcanota has exposed steep rock slopes, which can render them susceptible to large-scale rock slope failure, as well as to rapid adjustment of rock faces by discrete rockfall events, leading to the accumulation of talus cones at the foot of the slope (Ballantyne, 2002). The

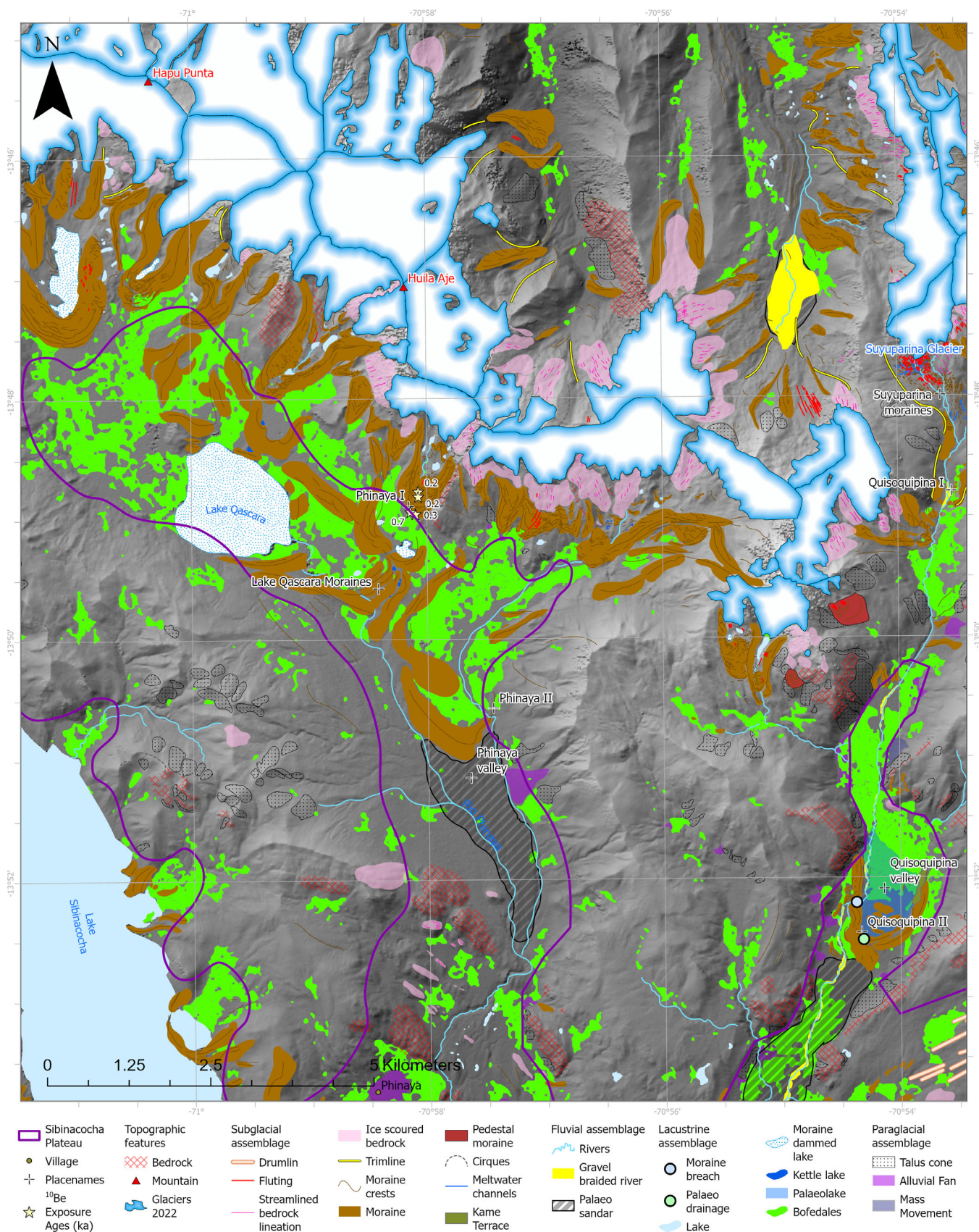


FIGURE 7 Glaciers, moraines, and slope, fluvial and lacustrine landforms around Mt. Huila Aje, Cordillera Vilcanota, with published chronostratigraphy (Sagredo et al., 2016). Glacial geomorphology from Davies et al. (2026). Bofedales shapefile from INAIGEM (2023a).

abundant sediment supply from the valley sides also likely supported the development of the substantial mid-valley and large-scale outer moraines (up to 30 m high, ridge crests up to 10–15 m wide) seen in Cordillera Vilcanota (see Davies et al., 2026).

Glacial advance over these large valley-side talus deposits results in the formation of pedestal moraines (Iturrizaga, 2018). Pedestal moraines form where the input of rockfall is so high that small mountain glaciers forming here are raised on pedestals of loose rock above

the valley floor. These pedestal moraines, where the glacier was situated on top of thick debris accumulations raised above the valley floor, significantly exceed the thickness and width of the glacier. They have been observed in Cordillera Blanca (Iturrizaga, 2018) as well as in Asian subtropical high-altitude mountains. In Cordillera Blanca, these moraines are sparser than in the Cordillera Vilcanota, due to the wider valleys and comparatively lower debris input of the latter.

Research in the Cordillera Blanca has shown that slope deposits such as these allow for groundwater recharge and transmittance (Baraer et al., 2015; Glas et al., 2018). These slope deposits can be a conduit for precipitation and meltwater to reach subsurface pathways (Caballero et al., 2002; Glas et al., 2018), facilitating groundwater-surface water interactions further down-valley. Slope deposits are also important in the early formation of *bofedales* wetlands in glacier forefields. When lakes form following glacial recession, they cover over the lower part of slope deposits. These then become buried under organic material when the lake infills. These finer grained deposits store groundwater, delaying discharge to streams and tributaries (Glas et al., 2018).

4.6 | *Bofedales* wetlands development

There is widespread *bofedal* wetland vegetation coverage across the Sibinacocha Plateau and beyond into the steeper terrain dominated by fluvial action (Figures 2, 3, 4 and 7 and Table 2). In total, 9244

mapped *bofedales* wetlands cover a total of 249.7 km² and form at elevations of 3896 to 5327 m asl (mean elevation 4673 m asl; Table 4). They form both in the northern part of the study domain, which has been extensively glaciated, but also in the southern part, which had few palaeoglaciers. Many *bofedales* are developed by infilling former lakes (cf. Emmer, 2024; Glas et al., 2018), and so form in similar places as lakes. These lakes infill first with lacustrine fine-grained material with low permeability (lake paludification), and are then colonised by vegetation, with organic peat formation (Glas et al., 2018).

Bofedales wetlands form widely in both valleys with direct glacial meltwater supply, as well as in valleys topographically disconnected from current and previous glacial melt influence. We suggest that the *bofedales* with no glacial meltwater influence are likely to be more seasonally variable, with changing precipitation influencing seasonal drying of both lakes (Drenkhan et al., 2018) and *bofedales* wetlands (Ross et al., 2023).

Within the glaciated portion of the study domain, valleys are relatively wide and flat, with multiple bedrock overdeepenings resulting from glacial erosion, glacial lakes, and hummocky topography from moraines that provide poorly drained conditions suitable for *bofedal* wetland development. Outside the glaciated catchment, *bofedales* wetlands are more limited due to the steep, narrow river valleys. Within the study domain, the *bofedales* can therefore be broadly categorised as (1) bedrock-constrained *bofedales*; (2) *bofedales* forming on hillsides; (3) *bofedales* forming in basins behind moraine dams;

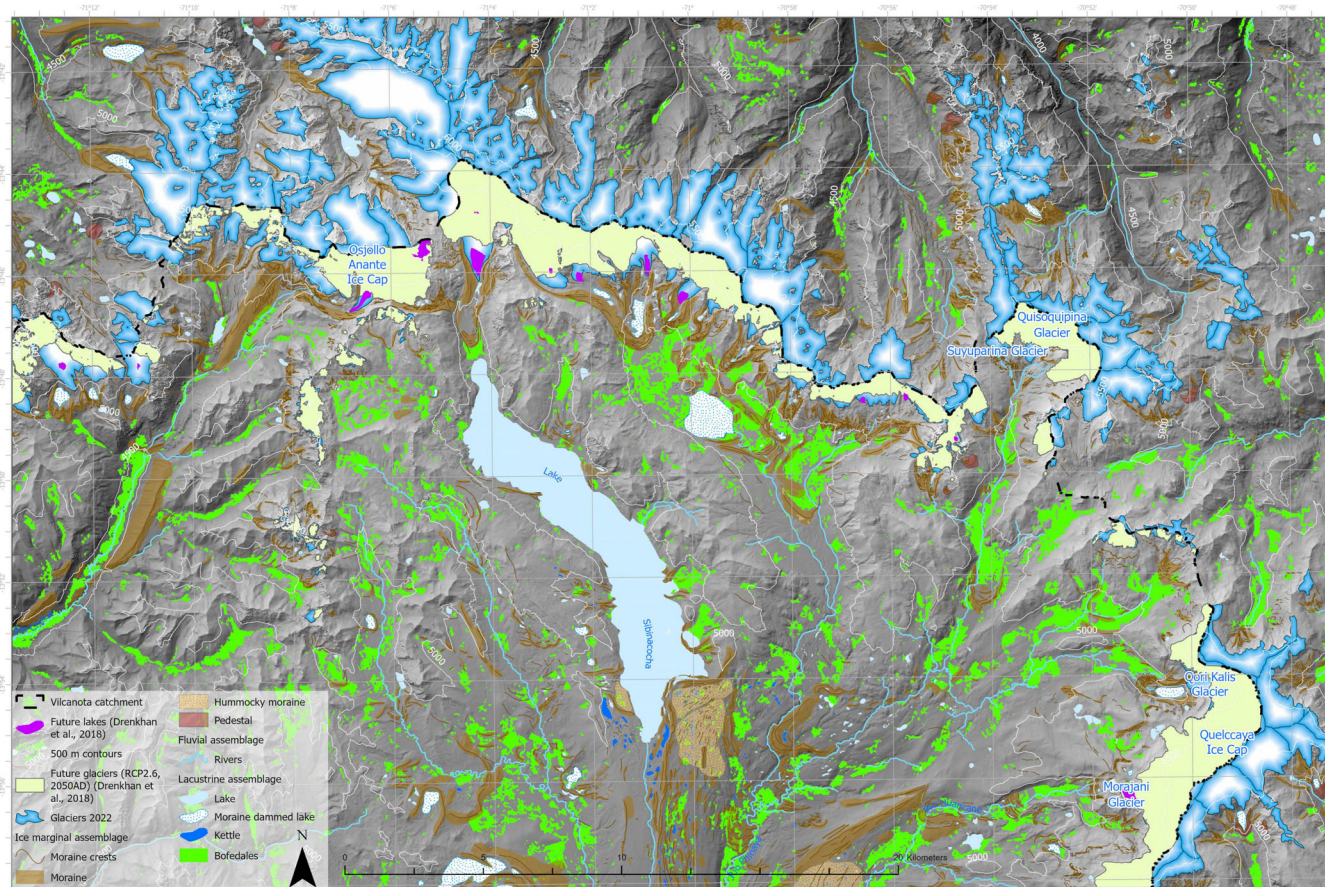


FIGURE 8 The *bofedales* wetlands and current and future glaciers and glacier lakes developed by 2050 CE (RCP 2.6) for Cordillera Vilcanota. Future glaciers and lakes from Drenkhan et al. (2018). Glacial geomorphology (moraines) from Davies et al. (2026). *Bofedales* shapefile from INAIGEM (2023a).

(4) *bofedales* infilling small kettle lakes and meltwater channels within and between moraines; (5) floodplain and river valley *bofedales* along water courses and over sandar; and (6) alongside large lake margins (Figures 9 and 10 and Table 4). The latter of these are the most widespread and extensive. A visual inspection and manual classification of surface meltwater pathways shows that 27% of the *bofedales* across the whole study domain occur in close association with glacier-fed meltwater streams in glacierised catchments (Figure 9b and Table 4), mostly occurring closer to the glacierised region.

4.6.1 | Bedrock-constrained *bofedales* wetlands

Bedrock-constrained *bofedales* wetlands infill smaller-scale lakes or bedrock hollows or overdeepenings, without being associated with moraines (e.g., Figures 11a,b and 12a). In some places these overdeepenings are still partly occupied by a lake, yet to be infilled and colonised by *bofedal* vegetation. These *bofedales* occur commonly in tarns in deglaciated cirque basins, and between areas of ice-scoured bedrock with *roche moutonnée* within the plateau. Another example is the *bofedal* wetland forming in the Quisoquipina tributary valleys at the point where the hanging valley enters the more deeply incised main valley (Figure 12a) and in the Qasquara valley, where the *bofedal* vegetation is encroaching on the lake in the overdeepening behind the moraine dam (Figure 12a). Within the study area, bedrock-constrained *bofedales* cover 37.74 km² and form at a mean elevation of 4768 m asl (Figure 10 and Table 4). Around 9.5% of these *bofedales* occur in glacierised catchments (Figure 9b).

4.6.2 | Hillside *bofedales* wetlands

Small *bofedales* wetlands are developed on hillsides, away from floodplains and rivers. These *bofedales* are likely sustained by groundwater flow through hillside deposits such as talus cones, moraines or rock glaciers (a minor component in this study domain), and form where surface and groundwater flow are impeded by topography. They form only a small part of the *bofedales* within the study area (Figure 10), and based on topography, most cannot be supplied directly by glacial meltwater (Figure 9b and Table 4).

4.6.3 | Moraine-dammed *bofedales* wetlands

Within the Sibinacocha Plateau and within the limits of the Late Glacial and, to a lesser extent, Late Holocene ice limits, *bofedales* wetlands are commonly formed behind and between moraines. These *bofedales* infill the larger glacial overdeepenings with moraines at their terminus. For many of these, both glacial and non-glacial groundwater sources likely provide the principal water sources. Close to the glaciers, these moraine-dammed *bofedales* cover the majority of the *bofedal* area and comprise a significant proportion of the total area (25% or 62.7 km²) (Figure 10). These *bofedales* are commonly found in currently glacierised catchments, with 49.3% occurring close to glacier-fed meltwater streams (Figure 9b and Table 4).

For example, in Figure 12b, the Quisoquipina II moraine acts as a topographic barrier between the hillslope springs (with no up-gradient

glacial connection) and the floodplain to maintain an elevated water table sufficient for peat-forming plant colonisation (Figures 11e and 12b). Here, the drainage of the larger lake following moraine breach provided accommodation space for the *bofedal* vegetation, with the overdeepening behind the moraines and the moraines themselves retaining the poor drainage conditions needed for *bofedal* development. Because the palaeolake drained via the moraine breach, the water table has stabilised at a lower level than previously, meaning that the resulting *bofedal* is smaller than the palaeolake. The drop in the water table is too large to allow *bofedal* formation in the area immediately behind the moraine, with the present-day *bofedal* extent as defined by INAIGEM (2023a) forming a few hundred metres distant from the terminal moraine crest (Figure 12c). Here, at lower elevations, the water table is closer to the ground surface and therefore presently able to sustain *bofedal* vegetation.

4.6.4 | *Bofedales* wetlands in kettle lakes and meltwater channels

Small *bofedales* wetlands are also frequently found in inter-moraine depressions such as former meltwater channels, where groundwater exfiltration is likely occurring in focussed areas at the foot of the moraines (Figure 12c, background *bofedal*). In the most freshly exposed ice-proximal moraines, the connection to meltwater supply may be a critical control on sustaining *bofedal* vegetation between moraines due to the small upslope contributing areas in the absence of glaciers. The colonisation of the Late Holocene Phinaya I moraines near Lake Qasqara (Figures 7a and 12e) with peat-forming *Distichia muscoides* *bofedal* vegetation is much more extensive than at Qori Kalis. The Phinaya I moraines remain topographically connected to the melt source from the mountain glacier above, with melt water channels running between moraines (Figure 12e). In contrast, the melt supply bypasses the Late Holocene Qori Kalis moraines, leaving them with no upslope contributing sources beyond incident rainfall on the moraines themselves. The sandier matrix of the moraines here is also likely to be highly permeable, reducing water retention. Glaciofluvial downcutting here has also likely lowered the water table, disconnecting the inter-moraine regions from water sources.

Small-scale *bofedales* wetlands are also developed in former kettle lakes, within and between moraine ridges, as the fines-rich texture of the moraines contributes to water retention. In the older lateral Phinaya IV moraines, small kettle lakes between moraine crests emphasise the poor drainage, and these kettle holes are gradually infilled and replaced by *bofedal* (e.g., Figure 11f). These *bofedales* are disconnected from the directly glacier-fed meltwater streams (Table 4) and therefore are most likely sustained by surface and groundwater flow. In some places, fluvial downcutting through older moraines (such as the Phinaya VI moraines) has acted to disconnect *bofedales* on the moraine surface with the water table and groundwater flow. The hummocky moraine within the Phinaya VI moraines and the Hu-IV moraines may be former, now dried, *bofedales*, with fluvial incision (driven by a combination of isostatic rebound and changing glacial dynamics) lowering the local water table and disconnecting the *bofedales* from water supply. A thin layer of peat remains above the glacial sediments forming the moraines, visible in river and road sections (Figure 12f).

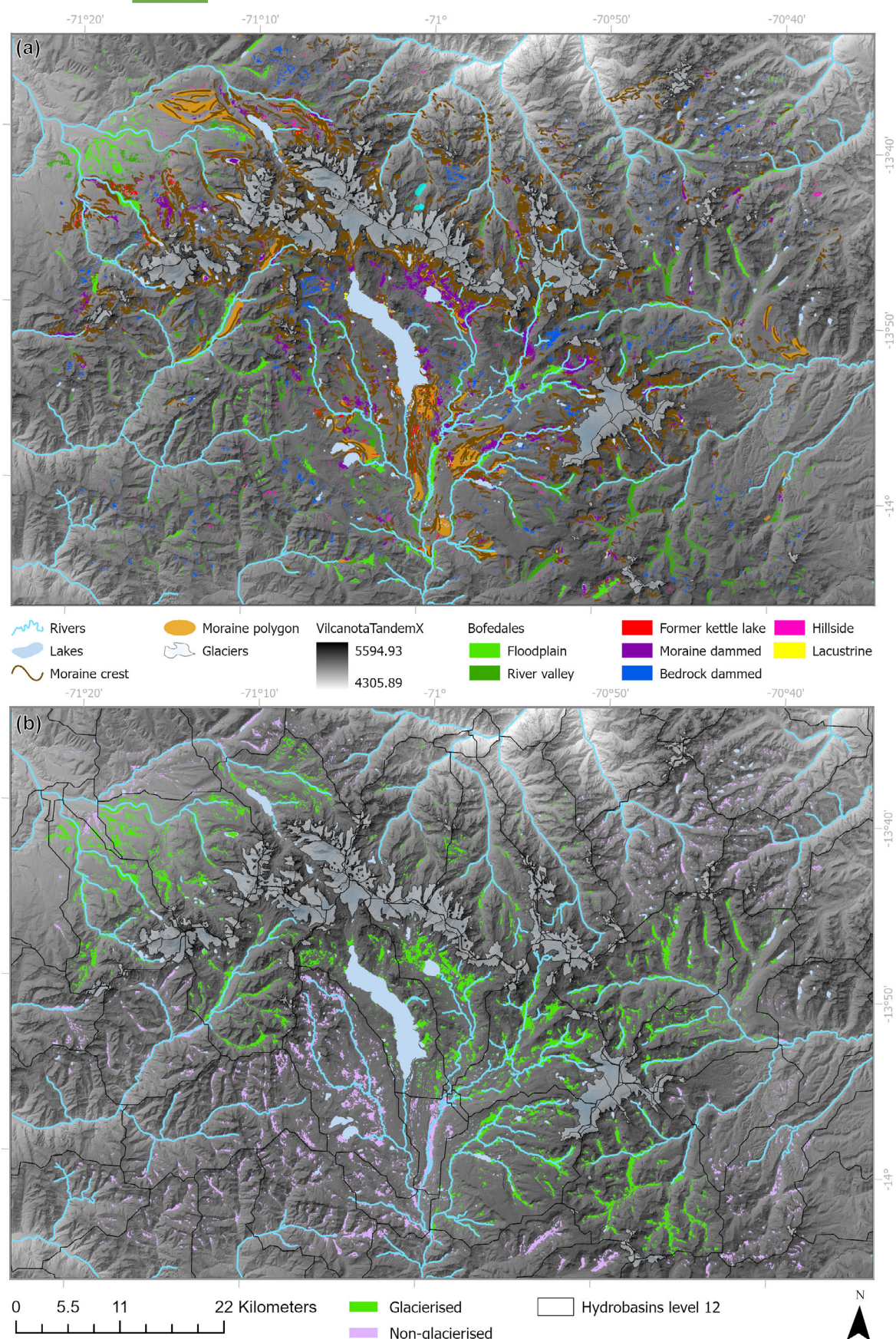
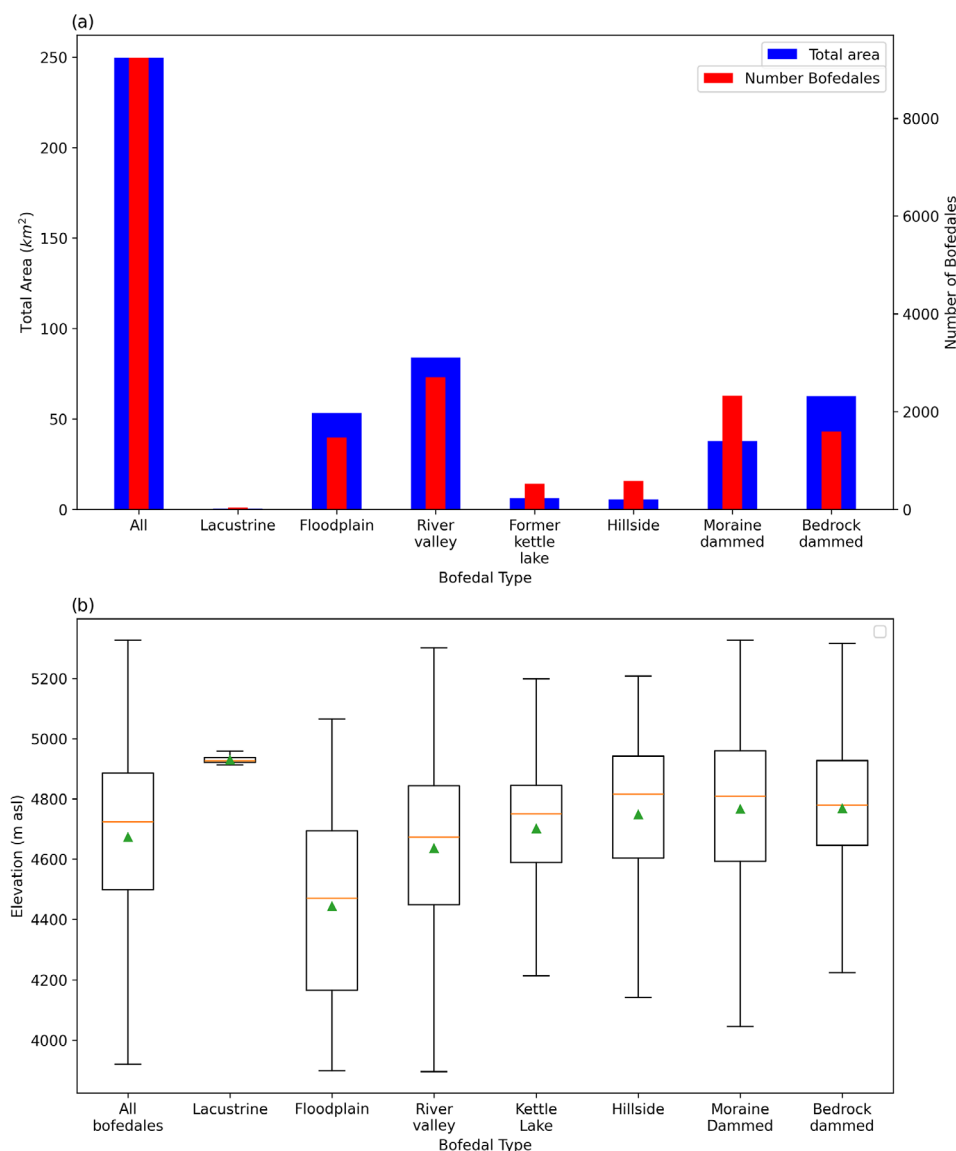


FIGURE 9 (a) Manual classification of *bofedales* across the study region. Glacial geomorphology from Davies et al. (2026). *Bofedales* shapefile edited from INAIGEM (2023a). (b) *Bofedales* manually classified according to the whether they occur along glacier-fed surface meltwater pathways. For details see Table 4.

FIGURE 10 (a) Area and count of *bofedales* wetlands formed in different settings. (b) Box plots showing elevation distribution of *bofedales* in different settings. Triangles are mean, orange bars are median.



4.6.5 | Floodplain and river valley *bofedales* wetlands

Bofedales wetlands frequently form along water courses and lakes, and over palaeo sandar. Wetlands are extensive along floodplains inside Sibilacocha Plateau, and along the floor of steep-sided narrow river valleys beyond the glaciated limits, covering a combined total of 137.3 km² (55.0% of *bofedal* area; Table 4 and Figure 10). Many are well developed for example along the Rio Vilcanota, and other glacier-fed rivers within the domain; some 31% of floodplain *bofedales* occur along glacier-fed rivers. Outside the glaciated area, *bofedales* along water courses in valley floors comprise the majority of wetland area, and are mostly disconnected entirely from glacier influence. Within the glaciated Sibilacocha Plateau, an example of a floodplain wetland is shown in the foreground of Figure 12d, supported by groundwater spring supply from active talus and an alluvial fan. Such *bofedales* may have a strong connection with the underlying glaciofluvial aquifer (sandar) as well as the river itself via exchanges through these superficial units (Ó Dochartaigh et al., 2019). Slope deposits such as talus and alluvial fans are also likely to be important sources of water supply to these *bofedales*, especially at greater distances from the

glaciers and in smaller valleys. Finally, a small number of smaller *bofedales* are formed around the edge of the larger lakes such as Lake Sibilacocha, likely fed by abstraction from the lake or groundwater seepage.

5 | DISCUSSION

5.1 | Glacier change

The present and the future changes of glaciers in this catchment are important, because they have implications for the future viability of the wetlands. The extent to which wetlands are dependent upon glaciers versus resilient to their loss, and the impact of large-scale glacier loss on water security and evolution of glacier hazards, is a critical question covered in this Discussion. Glaciers in this region are currently receding substantially, with Quelccaya Ice Cap receding by 11.07 km² (–21.9%) between 2003 and 2022 (Table 3).

This retreat is likely to continue, with significant mass loss of tropical glaciers anticipated. Climate Action Tracker predicts global temperatures of +2.7°C above pre-industrial by 2100 CE, based on

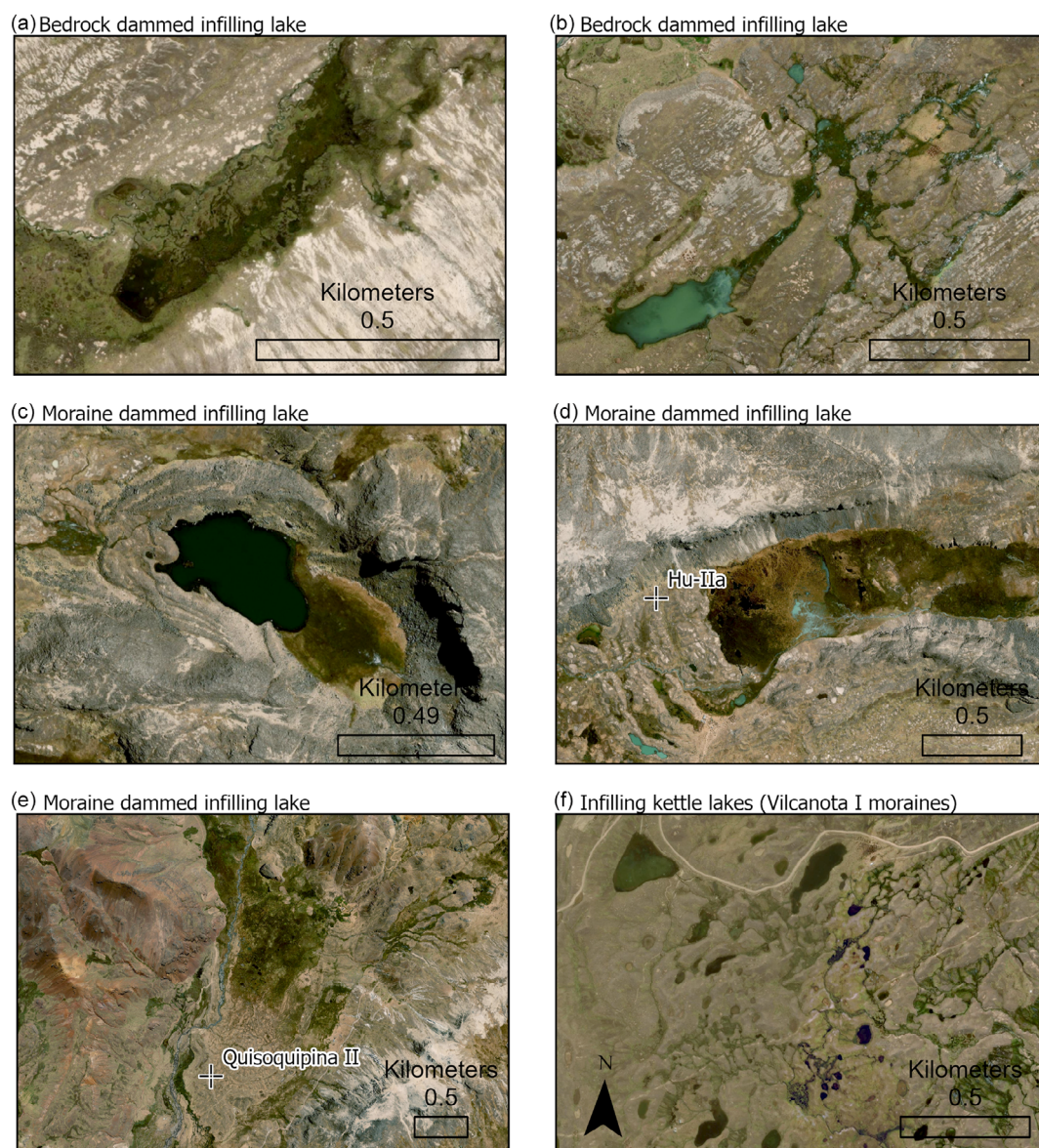


FIGURE 11 Examples of infilling lakes from bedrock (a, b) and moraine-dammed (c–e) lakes, and infilling kettle lakes in the Vilcanota Moraines I (f). Shown on 1.5-m resolution SPOT-6.

current policies (Climate Action Tracker, 2024). Under the similar RCP 4.5 scenario (Lee et al., 2023), global-scale numerical glacier modelling indicates that the Low Latitudes (which includes the tropical Andes) are projected to lose $88\% \pm 11\%$ of the glacier area in 2100 CE relative to 2015 CE (Rounce et al., 2023). In the Cordillera Vilcanota specifically, future glacier estimates based on more simplistic freezing level heights suggests that glacier loss by 2100 CE under RCP 4.5 could be as much as 92.7%, with the remaining ice concentrated at altitudes above 6000 m asl (Drenkhan et al., 2018).

The Cordillera Vilcanota today encompasses a range of glacier types, with different sensitivities and likely to be affected by different feedback processes, which could further accelerate glacier mass loss. Recession and fragmentation of the steep mountain glaciers is exposing substantially more areas of dark-coloured bedrock, which is likely to decrease the regional mountain albedo. Declining snow and ice cover and a lower albedo are associated with an increase in net short-wave radiation, impacting the energy balance and likely to increase snow and ice melt (Fyffe et al., 2021; Johnson & Rupper, 2020). Fragmentation of glaciers and bare rock appearing within glacier

boundaries is likely to have a significant impact on local energy balance due to an increase in radiative forcing (Davies et al., 2022; Davies et al., 2024; Rippin et al., 2020).

Quelccaya Ice Cap and the lower-slope mountain glaciers like Suyuparina and Quisoquipina glacier are likely to be impacted by an elevation-mass balance feedback as surface lowering accelerates during recession (Bolibar et al., 2022; Sass et al., 2017; Zekollari et al., 2017). Warming is already causing increased surface melt and lowering the regional albedo (Fyffe et al., 2021). Continued thinning may drive further melt-amplifying feedbacks, such as a surface mass balance-elevation feedback as the ice surface lowers into warmer air, as seen at other plateau icefields and ice caps globally (Davies et al., 2024; Sass et al., 2017). Increasing surface melt across Quelccaya Ice Cap may render it susceptible to a firn air content feedback, whereby meltwater retention capacity decreases due to firn densification and reduction in meltwater refreezing (Marshall, 2021; Noël et al., 2017; Van Pelt & Kohler, 2015). On low-slope ice caps like Quelccaya, warming firn can drive large areal transitions to areas of increased ablation rapidly (Marshall, 2021; Noël et al., 2020).

FIGURE 12 Examples of landform assemblages associated with *bofedal* formation. (a) Example *bofedal* found behind a bedrock control in a tributary valley adjoining the main Quisoquipina valley. (b) Example *bofedal* found between hillslope and large Quisoquipina II moraine (see Figure 3). (c) Example *bofedal* forming behind terminal moraine (foreground), and in inter-moraine area (background). Note the area of current *bofedal* extent has retreated upstream from the former position of the paleo-lake. (d) Example of *bofedal* forming on floodplain with groundwater spring supply from active talus and alluvial fan, ~1.75 km up valley from Quisoquipina II moraines. (e) *Bofedales* forming along meltwater channels connected with glacial meltwater supply, Phinaya I moraines. (f) Road cutting in the terminal Phinaya VI moraines, showing peat and desiccated *bofedal* on top of glacial till.

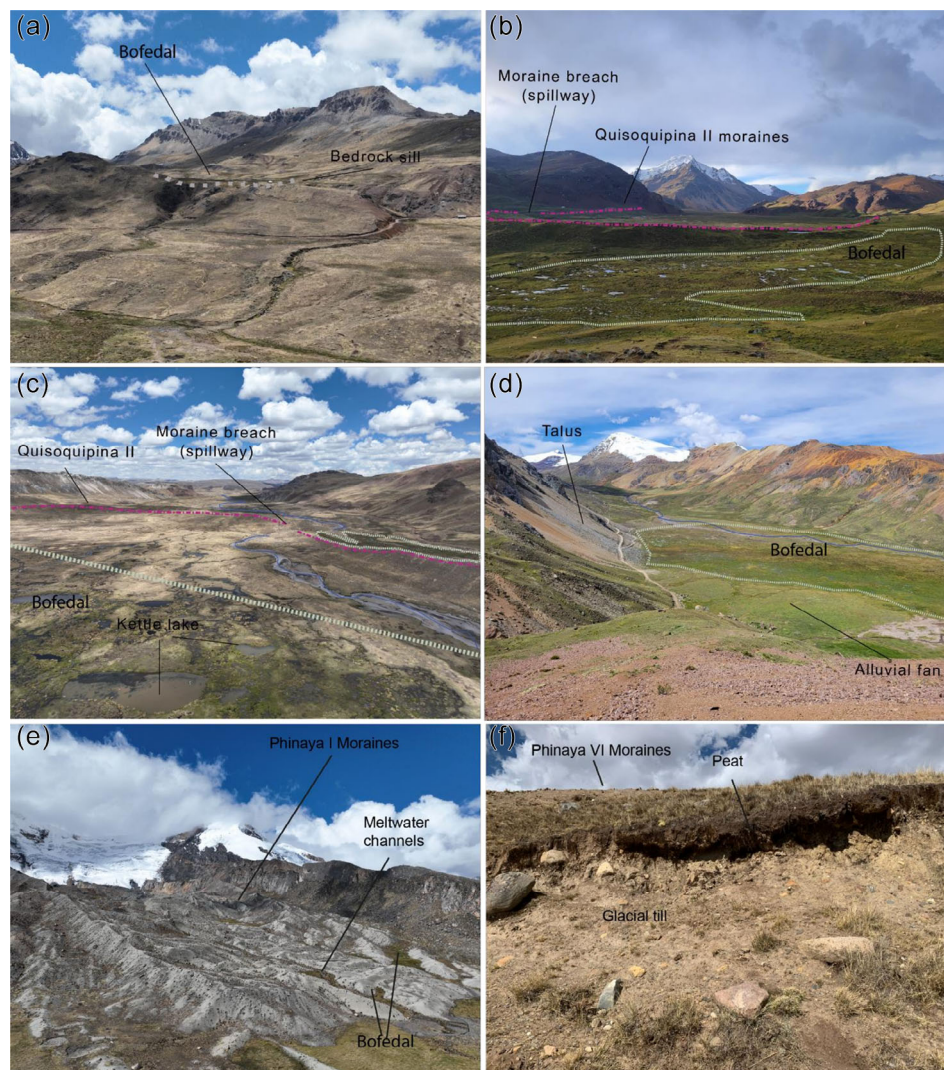


TABLE 3 Details of glaciers mapped in the study region (Figure 2). Z-min = minimum elevation. Z-max = maximum elevation. SD = standard deviation.

	Glaciers 2022				RGI V.6.0 (2003)			
	All glaciers and ice caps	Quelccaya Ice Cap	Osjolla Anante Ice Cap	Ausangate massif	All glaciers and ice caps	Quelccaya Ice Cap	Osjolla Anante Ice Cap	Ausangate massif
Number	237	15	4	15	233	14	3	11
Area (total) (km ²)	245.11	39.46	15.47	23.78	378.11	50.53	23.82	36.60
Mean area (km ²) (SD)	1.04 (1.60)	2.63 (2.93)	3.87 (1.91)	1.59 (1.85)	1.62 (2.43)	3.61 (3.65)	7.94 (3.48)	3.33 (2.77)
Min size (km ²)	0.0001	0.042	1.83	0.05	0.011	0.12	4.45	0.14
Max size (km ²)	11.66	11.66	6.34	6.37	14.54	14.54	11.42	8.47
Mean Z-min (m asl)	5085	5177	5180	4935	4952	5039	5062	4795
Z-Max (m asl)	6306	5708	5936	6306	6306	5659	6072	6306
Area change, 2003–2022 (km ²)	–133.00	–11.07	–8.35	–12.82	Area change, Cordillera Vilcanota, 2016–2020 (km ²) (INAIGEM, 2023b)		–12.22	
km ² a ^{–1}	–7.00	–0.58	–0.44	–0.67	km ² a ^{–1}		–3.06	
% change	–35.17	–21.91	–35.05	–35.03	% change		–5.02	
% a ^{–1}	–1.85	–1.15	–1.84	–1.84	% a ^{–1}		–1.26	

Together, climate warming and mass loss amplifiers and feedbacks could result in faster than expected glacier loss in the Tropical Andes. Adapting to the loss of this volume of glacier ice will be especially

challenging for the local and often highly vulnerable communities, who depend on melt supply to enhance supply to *bofedales* wetlands for grazing during the dry season.

5.2 | Lake change and GLOF risk

Our results indicate that most glaciers are now receding away from their valley floor proglacial lakes, with only three moraine-dammed lakes still in contact with the glacier termini. Continued glacier recession will likely diminish glacier influence on these lakes. Substantial new lake growth is unlikely, with limited new bedrock-dammed lakes likely to form in subglacial areas currently beneath the glaciers and their tongues (cf. Colonia et al., 2017; Drenkhan et al., 2018; Drenkhan et al., 2019). The limited potential for the growth of new lakes means that the water storage and buffering capacity offered by glaciers is unlikely to be replaced by equivalent growth of glacial lakes as the glaciers recede; across Peru, new lakes are likely to be equivalent to only 0.5%–1% of current glacier volume (Colonia et al., 2017). In the Vilcanota-Urubamba basin, the projected lake volume increase is only 3.72% of the estimated water equivalent of glacier volume loss (Drenkhan et al., 2019). Future loss of glacier ice below 5500 m asl would therefore result in a considerable loss of permanently stored water (cf. Drenkhan et al., 2019), with steep glacier slopes above this altitude limiting water storage now and in the future.

These new lakes could be susceptible to GLOFs triggered by slope instabilities (Haeberli & Drenkhan, 2022), though the low lake volume and low population density result in a relatively low risk. Secondly, as these new lakes are likely to be formed in bedrock-dammed overdeepenings, the risk of moraine dam failure causing GLOFs from these new lakes is limited (cf. Emmer et al., 2020). Alternatively, over-steepened ice and rock walls and slope instabilities associated with permafrost degradation could trigger new bedrock-dammed lakes to overtop (Emmer et al., 2020; Haeberli & Drenkhan, 2022).

Significant and dangerous GLOFs have occurred in the Cordillera Vilcabamba and in the north-western part of the Urubamba catchment, causing the loss of human lives and infrastructure (Drenkhan et al., 2019). Across Peru, GLOFs present a significant risk (Taylor et al., 2023). While the probability of GLOF occurrence is likely to remain high across the Vilcanota catchment (Drenkhan et al., 2019), the risk is relatively low compared with other parts of Peru due to low population densities limiting exposure, low lake volumes, low valley trajectory slopes and short runout distances (Drenkhan et al., 2019; Taylor et al., 2023). While moraine-dammed and proglacial lakes grew substantially over the 1990s and 2000s (Drenkhan et al., 2019; Hanshaw & Bookhagen, 2014), significant further growth is unlikely and the majority of moraine-dammed lakes are likely already formed, as noted in other parts of Peru (Emmer et al., 2020). GLOF risk from moraine-dammed lakes is therefore unlikely to significantly increase as glaciers recede.

5.3 | The high Andean tropical glacier, lake and *bofedal* wetland landscape

Glaciated landscapes provide ample opportunities for *bofedal* wetland formation and sustenance. Here, we present a conceptual integrative landscape model showing the stages of *bofedal* development and interaction with glacial and slope deposits (Figure 13). This conceptual model emphasises the interactions, feedbacks and linkages between different suites of landforms mapped in the Cordillera Vilcanota and

derives new process understanding. This landscape model is likely applicable in numerous high mountain environments which bear wetlands, which occur commonly worldwide (Becker et al., 2026), as it specifically links glacial dynamics and *bofedales* wetland development. During glacial maxima, temperate glaciers advanced, actively eroding bedrock and depositing glacial moraines at their termini (Figure 3; Davies et al., 2026). These glaciers excavated overdeepenings under their tongues, and sandar developed in the glacier forefield (Figures 3 and 13a). Following climatic amelioration and glacier recession, lakes were common in the landscape, occupying overdeepenings and as kettle lakes and moraine-dammed lakes (Figure 13b). These lakes started to accumulate fine-grained glaciolacustrine clays in their basins, which form an impermeable layer (Emmer, 2024; Glas et al., 2018). Over time, vegetation and peat start to encroach upon these lakes, permitting the evolution of *bofedales* wetlands (Figure 13c). The narrower Huanané, Quascara and Quisoquipina valleys are good examples of this process (Figures 4, 7, 11d and 13), and similar to the processes observed in Cordillera Blanca (Emmer, 2024; Glas et al., 2018). At the Hu-Ila moraines, the infilled former lake is still partly visible (Table 4 and Figures 4 and 11d). The *bofedales* formed in this manner account for some 25% of the total *bofedal* coverage across the study domain (Figure 10). The remainder largely form along river valleys and floodplains. Some such *bofedales* form over sandar, and based on analogue settings (Ó Dochartaigh et al., 2019), may be associated with the emergence of perennial springs and seeps from the highly permeable aquifer below.

The current glaciers likely provide a meltwater source for some of these *bofedales* wetlands, particularly during the dry season, but the extent to which glacial meltwater contributes to and sustains *bofedales* is variable. In the immediate glacier forefield and moraines, streamflow is strongly supported by glacial meltwater (Buytaert et al., 2017), and a direct meltwater contribution is essential to sustain the *bofedales*, and the 25% of *bofedales* forming behind moraine dams (Figure 9; Figure 10) likely receive a high proportion of water from glacial meltwater contributions. Within the Sibinacocha plateau, *bofedales* in valleys with streams draining glaciers likely all depend on meltwater, particularly in dry seasons and droughts.

However, across much of the plateau, substantial *bofedales* wetlands form in valleys and regions with no surface water connection to glaciers, such as behind moraines adjacent to the eastern shore of Lake Sibinacocha (Figure 3), in kettle lakes within the Phinaya IV moraines (Figures 3 and 11f), and along river valleys without glaciers at their headwaters. In valleys more distant from the glaciers, glacial meltwater is subsidiary to groundwater flow (Gribbin et al., 2024; Ross et al., 2023). River-sustained *bofedales* along river valleys are particularly prominent beyond the glaciated limits of the Sibinacocha Plateau. *Bofedales* across the Sibinacocha Plateau therefore receive water from both glacial meltwater streams, especially in the headlands of the valley and proximal to the glacial ice, but are also recharged by direct precipitation and groundwater flow from precipitation and glacial melt (Figure 13d).

The significance of hillslope groundwater flow is supported by groundwater monitoring around the village of Phinaya (Cooper et al., 2019). The groundwater interacts with surface water and is recharged through coarse-grained deposits such as talus cones, alluvial fans, glaciofluvial sandar and lateral and terminal moraines (Figure 13d) (Cooper et al., 2019; Glas et al., 2018). Water is then

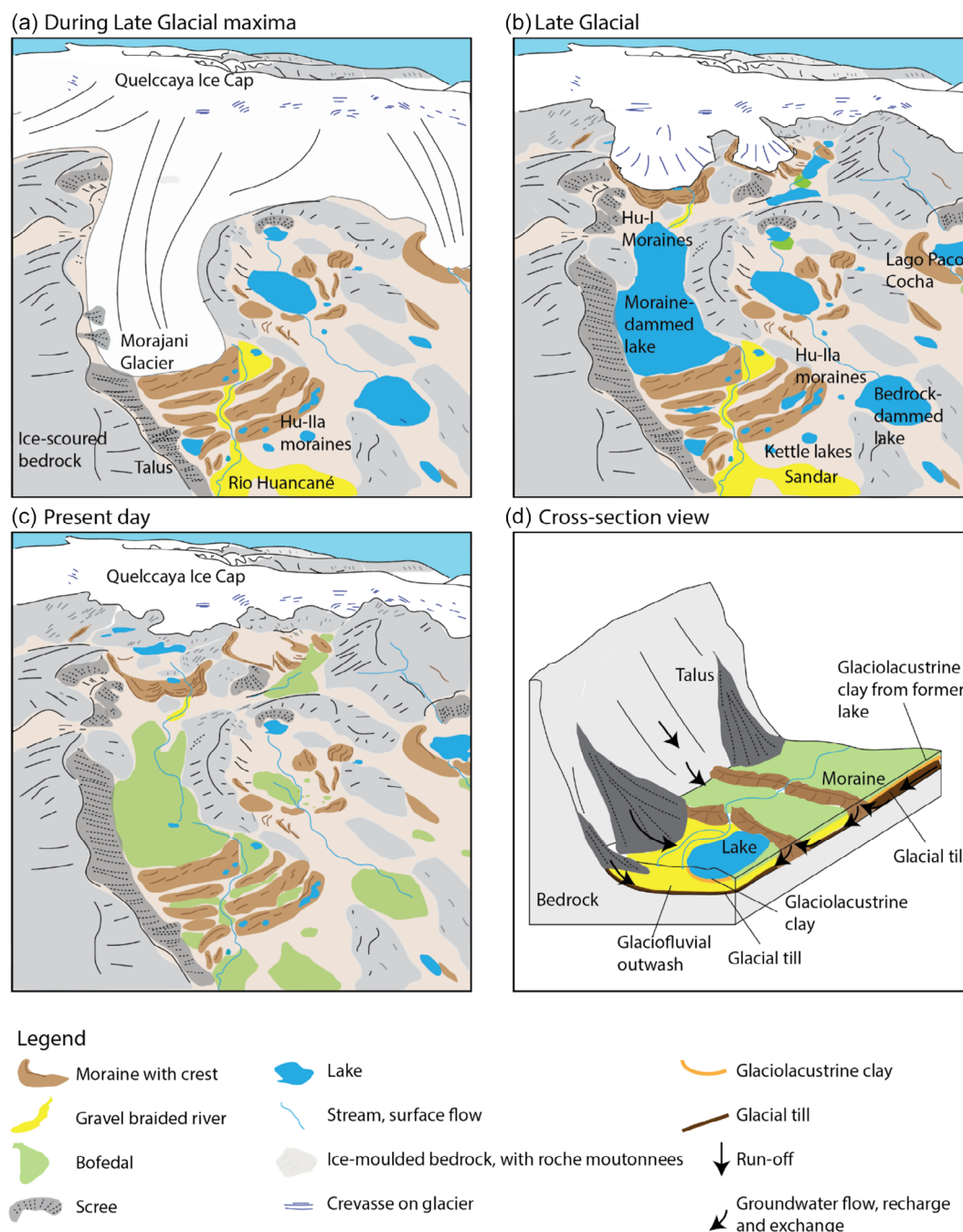


FIGURE 13 Landsystem based on the Huanacán Valley, western Quelccaya Ice Cap. (a) Moraines deposited by an enlarged Morajani Glacier, well-dated to during the Younger Dryas glacial maxima (Kelly et al., 2015). The temperate glacier actively erodes bedrock, forming ice-scoured bedrock, roche moutonnée and occasionally flutes. (b) Following glacial retreat during climatic amelioration, lakes form as moraine-dammed lakes and kettle lakes behind and between moraine crests. Sandar develops in the glacial forefield. (c) After a period of time the main moraine-dammed lake is completely evolved into a *bofedal* wetland. (d) Idealised cross-section of the same valley, showing groundwater flows through the system, with moraines and slope deposits forming opportunities for groundwater recharge, flow and exchange. Figure 11d shows the current development of this *bofedal* wetland.

stored and released slowly from the fine-grained peat forming within the *bofedales* (cf. Glas et al., 2018). The significance of groundwater in sustaining these *bofedales* likely increases downstream and with distance from glaciers. We argue therefore that the majority of *bofedales*, especially the 33% in the river valleys and those beyond the glaciated Sibinacocha Plateau (Table 4), would be relatively stable even in the event of glacier decline or total loss. However, they would be particularly vulnerable to changing precipitation patterns and climatic and seasonal drying in the absence of glacial meltwater.

5.4 | Timeframe for *bofedal* wetland development

The existing published chronology (Carrivick et al., 2024; Goodman et al., 2001; Kelly et al., 2015; Mark et al., 2002; Mercer & Palacios, 1977; Rodbell, Smith, & Mark, 2009; Sagredo et al., 2016; Stroup et al., 2014; Stroup et al., 2015) together with morphostratigraphic correlations is summarised in Davies et al. (2026). This framework provides a timeframe for *bofedal* wetland development. The oldest moraines, likely dating to the Last Glacial Maximum (~27 ka) or

TABLE 4 Area and elevation of *bofedales* wetlands formed in different environments within the study area.

	Count	Elevation (m asl)			Area (km ²)				% total <i>bofedales</i> area	Area (km ²) <i>bofedales</i> with headwaters in glacierised catchment	% <i>bofedales</i> with headwaters in glacierised catchment	Mean elevation (m asl) for <i>bofedales</i> with headwaters in glacierised catchment
		Mean	Max	Min	Mean	Sum	Max	Min				
All	9244	4673	5327	3895	0.027	249.85	3.54	0.0009		67.88	27.16	4709
Lacustrine	35	4930	4959	4913	0.011	0.4	0.13	0.001	0.2	0.006	1.34	4921
Floodplain	1470	4444	5066	3899	0.036	53.35	2.46	0.0009	21.4	16.39	30.73	4596
River valley	2704	4637	5301	3895	0.031	83.99	3.179	0.0009	33.6	15.80	18.82	4574
Former kettle lake	528	4702	5270	4122	0.012	6.15	0.37	0.0009	2.5	0.85	13.86	4725
Hillside	587	4749	5208	3901	0.009	5.53	0.24	0.0009	2.2	0.34	6.09	4737
Bedrock dammed	2326	4768	5317	3904	0.016	37.74	1.68	0.0009	15.1	3.58	9.45	4770
Moraine dammed	1594	4767	5327	3943	0.039	62.7	3.54	0.0009	25.1	30.91	49.30	4806

older (Davies et al., 2026), are no longer associated with *bofedales* due to river incision and subsequent lowering of the floodplain water table to the extent that hydrophytic *bofedal* vegetation is no longer sufficiently saturated. This leaves palaeo-*bofedales*, for example, near the Phinaya VI moraines. These moraines are now raised above the contemporary stream and the water table and consequently have little groundwater recharge. Typical *bofedal* vegetation is absent. They leave mostly only buried peat and a dried, hummocky terrain, with sections exposed in road cuttings showing only a thin dried peat layer above glacial tills. These landscape-scale changes suggest that on longer time scales, moraine-dammed *bofedales* may not be permanent sources of carbon sequestration. This also highlights how landscape processes can influence *bofedales* over longer timescales.

Extensive *bofedales* wetlands are formed behind moraine dams dated securely to the Late Glacial and Younger Dryas. For example, the Hu-Ila moraines (dated by Kelly et al., 2015 to a mean age of 11.6 ka) extend over 1.3 km and occupy the full valley width of >400 m (Figure 4). This suggests that these extensive *bofedales* developed since the Early Holocene and have ages of ~2000–10 000 years, similar to the ages noted in *bofedales* in north-western Bolivia (Hribljan et al., 2015). Smaller *bofedales* in kettle lakes (<10 m wide) associated with the Late Holocene moraines are as young as a few hundred years old (Carrivick et al., 2024; Sagredo et al., 2016). Notably, the large lakes impounded behind Late Holocene moraines, such as the Phinaya I moraines at Huila Aje, are not yet infilled despite encroachment from the lake sides, likely because of lake depth and size. This suggests that over future millennia we would expect the moraine-dammed lakes prevalent behind Late Holocene moraines to infill and become a *bofedal*, particularly as glaciers recede and direct glacial influence on the lakes reduces, and lakes start to infill with fine-grained glaciolacustrine materials, and then vegetation and peat (Glas et al., 2018).

5.5 | Future resilience of *bofedales* wetlands for future drought-buffering capacity and ecosystems services provision

There is some opportunity for further *bofedal* wetland growth, resulting in further ecosystem service provision through carbon

sequestration and buffering of water release within the high Andes, as glaciers recede, exposing new lakes, and the younger moraine-dammed lakes become infilled. However, the ability of this to compensate for the projected glacier mass loss (Zekollari et al., 2025) is likely to be small. Opportunities for further large lakes suitable for new *bofedal* formation in the future are limited as glaciers recede into steep terrain, with lakes largely limited to small-scale bedrock depressions (Colonia et al., 2017) (Figure 8). In addition, the extensive *bofedales* within moraine dams and in the floodplain of strongly glacier-fed rivers are likely more susceptible to decreases in streamflow as glaciers shrink, especially in the dry season; we note that 27% of all *bofedales* occur along rivers with glaciers in their headwaters, rising to 31% for floodplain *bofedales* and 49% for moraine-dammed *bofedales* (Table 4), both of which are extensive across the study area. Loss of glacier ice will therefore likely result in a drying of these *bofedales*, especially in the dry season, loss of wetland vegetation, and a permanent decrease in dry season drought-buffering capacity.

We suggest that the geomorphological independence of the remaining 73% of the *bofedal* area from direct sources of glacial meltwater (cf. Table 4 and 9b), especially the river-valley *bofedales* outside the glaciated domain and particularly the Sibinacocha plateau, indicates that they are likely relatively invulnerable to glacial decline. These *bofedales* are sustained by a range of water sources, including surface water, direct precipitation and groundwater, rather than principally surface glacial meltwater. We note that within the glaciated domain, *bofedales* that do not receive glacial melt from direct surface water streamflow may be sustained by groundwater that receives input from glaciers. However, this glacier influence likely decreases with distance from the glaciated domain and outside moraine limits. This is relevant when considering that *bofedales* perform an important function in sustaining local subsistence pastoral communities as the mountain range deglaciates, especially those formed at some distance from the current glaciers (García, Prieto, & Kalazich, 2021).

Bofedal productivity, longevity and security are therefore likely dependent on location and regional geomorphology, as well as climate change and other threats such as small and large-scale mining, rural road infrastructure, extensive peat extraction and overgrazing. Ultimately, glaciers are active in forming a landscape suitable for

extensive *bofedal* development but are not necessarily active in their maintenance, especially where disconnected from surface meltwater streams and where contemporary water supply is dominated by groundwater flow fed by precipitation rather than glacial meltwater.

6 | CONCLUSIONS

The tropical Peruvian Andes act as 'water towers' to downstream communities, supporting both local pastoralist and agrarian communities and larger towns with water for irrigation, pastoralist farming, domestic consumption and hydropower. The glaciers, lakes and *bofedales* wetlands that characterise these high mountain regions are critical to the livelihoods of communities and provide extensive ecosystem services. High altitude wetlands are common in the glacierised mountain regions of the tropical Andes (Becker et al., 2026), and understanding their formation and evolution is critical to successful long term management and sustainable adaptation to climate change.

We found that the glaciers of the Cordillera Vilcanota range are largely drained by small, low-volume meltwater streams, reflecting the low melt throughput and relatively high sublimation. Lakes are common within the landscape, with 59 moraine-dammed lakes and nearly 500 kettle lakes mapped across the domain. However, the majority of glaciers have receded out of their proglacial lakes, and calving is now an insignificant component of ice mass loss. Further growth of lakes is unlikely as the glaciers recede up steep mountain slopes, and as they become more ice-distal, glacier lake outburst flood hazard will decline as the risk of triggering ice avalanches becomes lessened. As these glaciers recede there is limited potential for the formation of substantial new lakes, meaning that the projected loss of glacier ice volume will not be meaningfully offset by the formation of new lakes or *bofedales* wetlands.

We developed a novel and integrative conceptual landsystem model summarising the development of and linkages between glacial landforms and *bofedales* wetlands in the proglacial environment in the Cordillera Vilcanota. High Andean *bofedales* wetlands form in bedrock-constrained and moraine-dammed overdeepenings, where they evolve from infilling former lakes, and along water courses and over sandar. These *bofedales* wetlands are sustained by groundwater recharge through coarse-grained slope and glacial deposits such as talus cones, glaciofluvial deposits and moraines, as well as through surface water recharge from direct precipitation and glacial meltwater. Sustenance from glacial meltwater is important in ice-proximal environments but rapidly diminishes down-valley. Our data show that *bofedales* wetlands are well-developed behind moraines dating to the Late Glacial (from direct dating or from morphostratigraphical correlation). *Bofedales* substantially older than this are more likely to be dried as uplift and subsequent fluvial incision leads to a groundwater base level fall and a lack of water to recharge. *Bofedales* are not yet substantially developed in lakes dammed by Late Holocene moraines, which still have a substantial glacial influence via direct meltwater input.

Our novel landsystems model shows that glaciers are important prerequisites for a landscape suitable for *bofedal* development, providing ample poorly drained conditions and overdeepenings appropriate for colonisation, but may not be essential for their maintenance, with contemporary water supply likely often coming from non-glacial sources, especially with increasing distance from glaciers. In the

future, glacier recession is unlikely to increase *bofedal* development by further increasing accommodation space, though *bofedales* may still develop in the lakes dammed by Late Holocene moraines as glacial influence lessens due to glacier shrinkage. *Bofedales* wetlands are likely resilient to drying due to lessening of glacial meltwater as glaciers recede and could therefore form a critical part of a resilience strategy to glacier loss. Therefore, *bofedales* wetlands should be integrated into long-term adaptation strategies to counteract the risk of mountain water insecurity across the tropical Andes.

AUTHOR CONTRIBUTIONS

B. D., T. G., O. K., T. M., J. E. and N. M. undertook fieldwork, supported by F. D. and J. B. B. D. undertook the remotely sensed geomorphological mapping. Funding acquisition: J. E., B. D., T. M., W. B. and J. C. B. D. wrote the main manuscript. All authors contributed to the manuscript.

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DATA AVAILABILITY STATEMENT

- ESRI Shapefiles are available from the supplementary online information and from Davies et al. (2026).
- *Bofedales* shapefile is available from INAIGEM (2023a) (<https://repositorio.inaigem.gob.pe/items/97832168-469d-4804-9a31-449ff5a19a43>).
- Hydrological basins are available from HydroSHEDS (<https://www.hydrosheds.org>).
- Future glacier and lake extents from Drenkhan et al. (2018).

ORCID

Bethan Davies  <https://orcid.org/0000-0002-8636-1813>

Tom Gribbin  <https://orcid.org/0009-0001-6905-5822>

Owen King  <https://orcid.org/0000-0003-1807-9821>

Tom Matthews  <https://orcid.org/0000-0001-6295-1870>

Jan R. Baiker  <https://orcid.org/0000-0002-2634-0690>

Rike Becker  <https://orcid.org/0000-0002-9040-1355>

Wouter Buytaert  <https://orcid.org/0000-0001-6994-4454>

Jonathan Carrivick  <https://orcid.org/0000-0002-9286-5348>

Fabian Drenkhan  <https://orcid.org/0000-0002-9443-9596>

Juan-Luis García  <https://orcid.org/0000-0002-9028-7572>

Nilton Montoya  <https://orcid.org/0000-0002-4147-2579>

Baker Perry  <https://orcid.org/0000-0003-0598-6393>

Jeremy Ely  <https://orcid.org/0000-0003-4007-1500>

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