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Deriving targeted intervention packages of nature-based solutions for climate change adaptation and disaster risk reduction: A geospatial multi-criteria approach for building resilience in the Puna region, Peru

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ABSTRACT

Emergent complex climate risks challenge conventional approaches for climate adaptation (CCA) and disaster risk reduction (DRR). This situation demands new ways of addressing climate risks with integrated solutions. Nature-based Solutions (NbS) are promising CCA and DRR given their cost-effectiveness, multifunctionality and low-regret condition in addressing a wide range of risks exacerbated by climate change. However, little attention has been paid to exploring methodological approaches for combining NbS to reduce climate risks. Still, selecting the appropriate and effective combination of NbS is a challenging task. This research applies a geospatial multi-criteria approach for developing intervention packages of NbS for CCA and DRR and applies this innovative methodology to a case study area in the Puna region in Peru. The study started with an in-depth literature analysis coupled with a participatory process with local experts to identify and select locally valid NbS for CCA and DRR. Building upon that, the overall multi-criteria approach was developed, which consists of a matrix-based procedure to evaluate the applicability of relevant measures and their feasibility of being combined in intervention packages. Then, the multi-criteria analysis was integrated into a Geographic Information System using a spatial analysis model to map suitable intervention areas. Next to the methodological innovation, the multi-criteria approach was applied to a case study area to generate a place-based intervention package for addressing the risk of reduced water provision considering climate change conditions, with its respective potential intervention sites differentiated by the appropriate measures. This methodological approach is a novel and pragmatic support tool that helps practitioners design more robust and effective interventions for building resilience to climate change. Furthermore, this methodological approach involves shifting the perspective from activities focused on “one-size-fits-all-solution” to "multi-solution" strategic interventions that address climate risks more comprehensively, recognizing the dynamics and complexities of the social-ecological systems. The authors encourage researchers and practitioners to transfer the methodological approach to other contexts and, with that, accelerate the efficient and targeted implementation of NbS for building resilience to climate change.

Introduction

The increasingly disruptive effects of climate change are challenging conventional approaches to climate change adaptation (CCA) and disaster risk reduction (DRR) [1]. Fragmented adaptation responses and risk management measures are hindering effective solutions to mitigate risks, minimize impacts, and prevent cascading disastrous events [2]. Globally, CCA and DRR planning and decision-making processes require

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an urgent shift towards an integrated perspective capable of implementing solution packages that address the causes, drivers, and impacts of disaster risks comprehensively [3]. While frameworks for assessing the complex nature of climate-related risks have begun to emerge [e.g., 4], a notable gap exists in methodologies that recognize the dynamic nature of these risks to address them effectively [5]. This situation demands that resilience-orientated interventions address the challenges from a socio-ecological system perspective [6].

Currently, some of the most prominent societal emerging risks are largely influenced by worldwide environmental degradation due to human activities [7] and climate change effects [8]. From that perspective, interventions that work *for* and *with* nature can help reducing climate-related risks [7–9]. These interventions, aiming to address social, economic and environmental challenges effectively and adaptively by protecting and improving ecosystem health and functioning, are currently referred to as Nature-based Solutions (NbS) [10, 11].

NbS are essential for addressing a wide range of risks exacerbated by climate change, such as flooding, erosion, landslides and drought [12–14]. Ideally, NbS use both traditional and scientific knowledge to identify good practices for managing natural resources that increase ecosystems' resilience while reducing the vulnerability of local communities to climate change [15–17]. Accordingly, NbS are promising for CCA and DRR given their cost-effectiveness [15,16,18], their ability to deliver multiple socio-economic benefits to communities [9,17], and their potential to accelerate progress to various SDGs [9,19,20]. NbS, such as Ecosystem-based Adaptation (EbA) and Ecosystem-based Disaster Risk Reduction (Eco-DRR), are widely described as "win-win" [7,21], "multifunctional" [22], and "low regret" measures [22,23], which explain why working with nature have recently gained momentum in the scientific debate and on the international climate agenda [9,22].

However, as with any other sort of CCA and DRR measures (i.e., informational, behavioural, technical, structural, regulatory, financial, institutional), NbS are also limited in addressing the complexity of climate change impacts. Even when they are well designed and implemented, NbS can demand several years before fully delivering adaptation and risk reduction benefits [24]. Likewise, since ecosystems are also sensitive to climate variability, NbS performance may decline with climate change [8,25], which may make them less effective in future climate scenarios [8,24,26] or even have unintended consequences [22] if this is not considered during the planning process. Therefore, NbS are not silver bullets [7], and single interventions cannot fully protect communities from all climate hazards and their related impacts [21].

Aware of these limitations, adaptation and risk reduction planners and decision-makers are looking for integrated solutions [9,16,22,27, 28] that maximize overall benefits by balancing the weakness of the individual measures [29,30]. In that context, a combination of differentiated measures can address various vulnerability drivers, interrupting cascading climate effects and better cope with distinct climate impacts [9,25,31], thereby building resilience to climate change effectively.

Although several procedures have been proposed for selecting appropriate measures (e.g., 30,32–37), little attention has been paid to exploring methodological approaches for assembling intervention packages to reduce the increasingly dynamic and complex climate risks with NbS. For example, widely used methods for prioritizing and selecting measures, such as cost-benefit analysis and cost-effectiveness analysis [38], are limited in assessing the interaction of joint interventions.

However, selecting the appropriate and effective combination of measures is a challenging task considering the complex landscape of multiple hazards (climatic and non-climatic), the cascading effects, and the wide range of options and their interdependency on various environmental and societal factors (i.e., social, political, cultural, economic, technological, and legal) [33,38]. Consequently, to effectively combine NbS options, the identification and selection of measures should focus on finding complementarity, cohesion, compatibility and synergies amongst them [9,17,38]. In this regard, NbS has the potential to combine with other measures [7,24,26] such as grey infrastructure and soft approaches (e.g., capacity building and training, raising awareness, regulations, financing schemes), and due to their 'low-regret' and 'win-win' nature, they are the most favourable options for uncertain future climates [28,39].

In response to the motivation and knowledge gap described above, this publication aims to propose a geospatial multi-criteria methodological approach for developing packages of NbS to reduce climate-related disaster risks.

The application of Geographic Information Systems (GIS) in the climate change field has a vast record in the literature. Overall, it is well-recognized as a cost-effective, increasingly open, powerful decision-support tool [39–44]. Given the regional scale of climate risks, GIS-based approaches that consider, explore, and analyse climate conditions and their impacts at various spatial scales can be valuable for adaptation and risk reduction planning. Multi-Criteria Analysis (MCA) has been coupled with GIS for more than two decades to solve spatial problems [40,45]–such as CCA and DRR. The purpose of combining MCA methods with GIS is to complement the "*what*" question with the "*where*" question [46]. Because of that, GIS can inform adaptation and risk reduction projects meaningfully by producing graphical spatial representations of climate-related conditions, processes, and trends across the regions, such as vulnerability, risks, and impacts on places and people at various temporal, spatial and governance scales [47]. In addition, screening-type GIS analysis can be used to gain initial insights into risk management options and facilitate further quantitative assessments, optimizing limited resources before developing a detailed strategy to respond to climate change effects [41]. In this regard, GIS helps indicate where the adaptation needs are and, thus, supports prioritizing locations where measures must be undertaken [39]. Therefore, these GIS-based MCA approaches are an important initial step in identifying approximations for effective adaptation and DRR measures and their respective intervention sites.

The methodological approach proposed in this publication was developed within the framework of the Resilient Puna project[1,2], which seeks to promote NbS for adapting to the changing climate and reducing climate-related risks in local communities in the high Andean region (>3500 m.a.s.l) of southern Peru (departments of Apurimac, Arequipa, Cusco and Puno). Within the context of this work, the following research objectives were established:

(1) Select locally valid NbS to face the challenges of accelerated change in climate and the loss of ecosystems and their services in the Puna region communities.
(2) Develop a methodology for deriving place-based intervention packages of NbS for CCA and DRR.
(3) Generate intervention packages of NbS for CCA and DRR in areas prone to climate impacts in the Puna region (i.e., climate risk hotspots).

In response to these objectives, this paper provides a catalogue of NbS for CCA and DDR applicable to the study area based on a detailed understanding of the Puna region. While this research focuses on presenting a sound methodological procedure to derive intervention packages for CCA and DRR, its application is also exemplified for the respective case study area in the Peruvian Puna region.

[1] For more information about the project, see the Concept Note.

[2] More information about the advisory service at: https://unu.edu/project/advisory-service-development-climate-analysis-and-justification-resilient-puna-project-peru

Study area

The study area, located in the Southern High Andes of Peru (Fig. 1), encompasses 91 districts spanning across four departments: Cusco, Apurímac, Puno and Arequipa. These departments have been designated as part of the Resilience Puna project. Mountains, hill slopes and upland plains characterize the study region's terrain. Depending on the humidity, temperature, and altitude conditions, the landscape encompasses a wide range of ecosystems, such as grasslands, wetlands, peatlands (also known as *bofedales* in the local context), shrub meadows, scrublands, high Andean Forests, meso-Andean Forests, high Andean Lagoons, and areas of few or null vegetation (bare lands).

The population density in the project region is generally low but includes several urban areas and rural population centres [40]. Traditionally, cultivation of tubers (e.g. potatoes) and pseudocereals (e.g. quinoa) dominate small-holder farming in the high Andes. Also, livestock husbandry of both South American camelids (i.e. *Lama glama* and *Vicugna pacos)* and introduced livestock (cattle and sheep) has been increasing in the past decade [49,50].

The high Andean communities of Peru have developed practices for sustainably managing natural resources and responding to climate variations. More than knowledge to face climate change, these practices reflect the profound world's view of the Andean people and their approach towards life. In this worldview, we are all part of the same "body"; consequently, it is crucial to recover and maintain the harmony between humans and nature [51] – an interpretation aligned with the core of the NbS umbrella concept. Traditional techniques of the Andean population, such as rainwater harvesting *(Qucha ruway)*, springs conservation (*Puquio waqaychay*), revegetation (*Yakupa maman*, and *Yaku qayaq*), and crop diversification [51–53], can reduce vulnerability to climate change impacts of rural communities in the high Andean region [54].

However, anthropogenic drivers and climate change effects are pressuring sensitive ecosystems and their services. On the one hand, overgrazing and unsustainable practices such as intensive agriculture and slash-and-burn are degrading key agriculture-related ecosystem services [55–58]. On the other hand, increasing climate variability consisting of rising mean and maximum temperature, decreasing average precipitation, shifting precipitation patterns, and more frequent heavy rainfall [25,59] influence hazardous processes such as mass movements (mud- and landslides [60]), droughts, and flash floods [61–63].

In the context of the Resilient Puna project mentioned above, some of the most relevant climate signals are increasing temperatures and changes in precipitation regimes, having direct consequences as deglaciation [64], increasing droughts [65], changing water availability [66], and potential adverse effects on ecosystems [67] and livelihoods [68]. The overarching risk identified for the study area is the reduction of the ecosystem services due to temperature changes and extreme weather events, and the disturbance of the rural and downstream livelihoods depending on those ecosystem services. Accordingly, the Core Climate Risk Analysis (CCRA)[2] of the Resilient Puna project [69] identified three specific ongoing and future risks for the local population in the study area:

- Reduced water provision
- Reduced provision of agricultural products
- Reduced fodder provision

The selection and analysis of these risks are further described in the

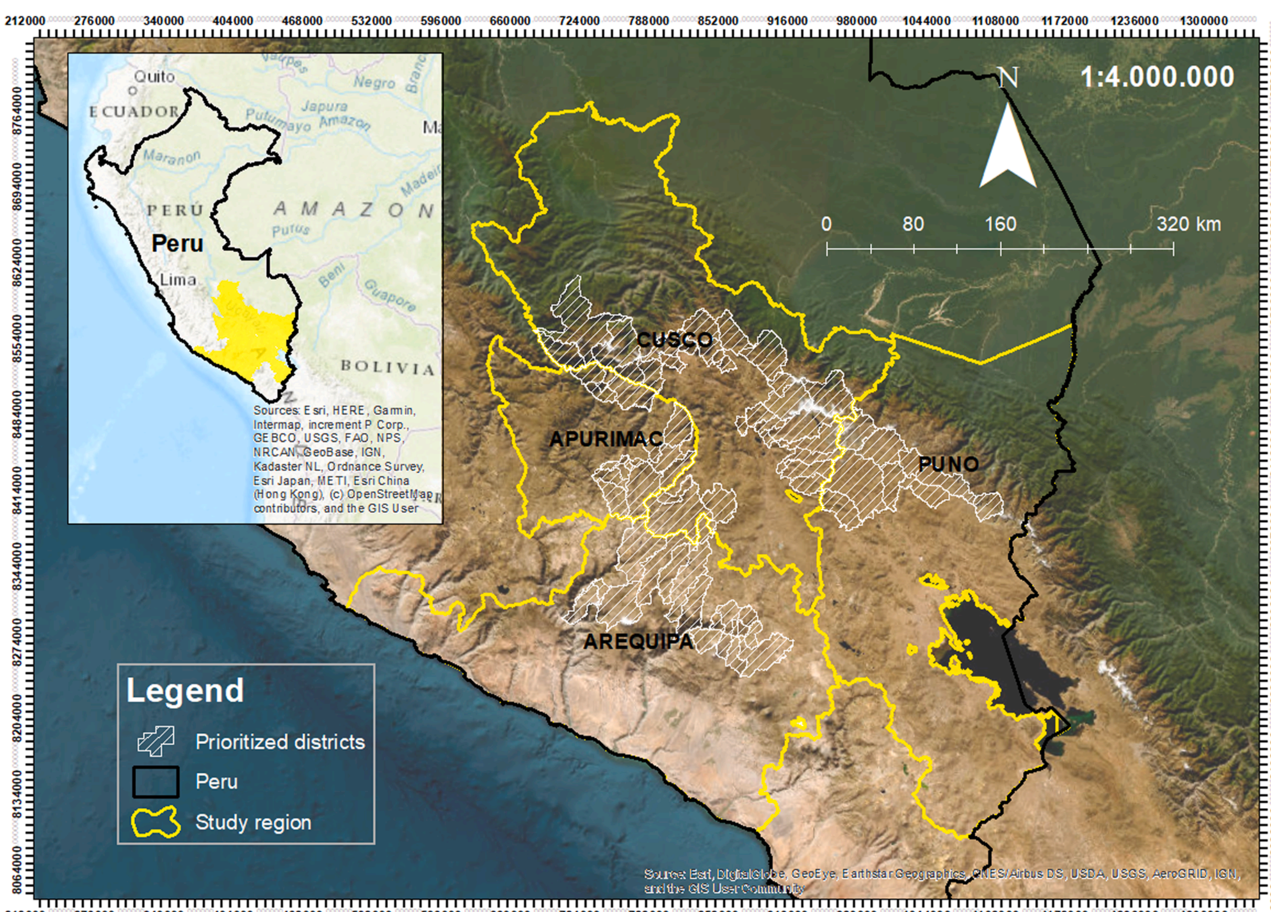

Fig. 1. The study area of the southern Puna region which covers four departments (yellow) and 91 districts (grey) as proposed in the Resilience Puna project context.

CCRA [69] of the Resilient Puna project. This paper builds upon the result of the risk analysis dealing with the water supply by focusing on the risk of reduced water provision. The reduced water provision risk presented in Fig. 2 was characterised by 4 classes ranging from low, moderate, high, and very high. The level of risk is calculated by the combination of hazard, exposure, and vulnerability in each specific area. A very high risk could reflect for example an area with high dependency on water from glaciers, with exposed degrading bofedales and where a population with low income and low livelihood possibilities lives.

Given the high risk of reduced water provision in Challhuahuacho district, located in the department of Apurimac (Fig. 2), an example was developed using the district's characteristics and conditions to derive packages of NbS for CCA and DRR.

Challhuahuacho district has a population over 23,000 people, primarily composed of rural indigenous communities engaged in subsistence agriculture, with a smaller population employed in the mining industry [48,49]. The annual precipitation in Challhuahuaco is relatively low, averaging around 400 mm per year, and with a predominant cold and semi-arid climate [70]. Situated at an average elevation of 3500 m.a.s.l. and characterized by a mountainous landscape as part of the Andean Mountain Range, Challhuahuacho's land cover and land use are primarily dominated by ecosystems such as grasslands (i.e., pajonales), shrublands (i.e., matorrales), and high-Andean forests [67]. However, large-scale mining activities, have impacted the ecosystems causing deforestation, land degradation, water contamination and biodiversity loss [71].

Materials and methods

The research approach is divided into three stages corresponding to the specific research objectives, using five methods: literature review, an online survey, focus group discussion, expert judgement, and spatial analysis (Fig. 3). In addition, the information obtained through each method was triangulated using data from other sources to increase the reliability of the information derived. This section describes how each method was used in the different stages of the overall research approach.

Selection of NbS for CCA and DRR

In this study, NbS for CCA and DRR refer to measures aimed at conserving, sustainably managing, or restoring ecosystems, and are intended to assist communities in adapting to climate change and mitigating associated risks. These NbS include actions, techniques and methods that operate in harmony with nature to strategically address drivers (e.g., deforestation, land degradation, groundwater depletion) and factors (hazard, exposure, vulnerability) of risk. These NbS encompass a diverse array of options, ranging from wider and more intricate interventions like Sustainable Grassland Management, Agroforestry, and Crop diversification, to more targeted and concrete actions such as the rehabilitation of Andean terraces or the construction of micro-reservoirs (Qochas). While some measures contribute to improving, maintaining, or restoring the overall functioning of ecosystems and ecosystem services, others focus on achieving specific outcomes, such as modifying ecological components (e.g., planting native trees), altering biophysical conditions (e.g., changing topography, water direction, and slope drainage), or influencing environmental processes (e.g., soil infiltration capacity, water retention time). By reducing pressures, stressors and disturbances in ecosystems, as well as supporting community livelihoods, NbS not only offer adaptation and resilience benefits but also contribute to additional socio-economic goals (co-

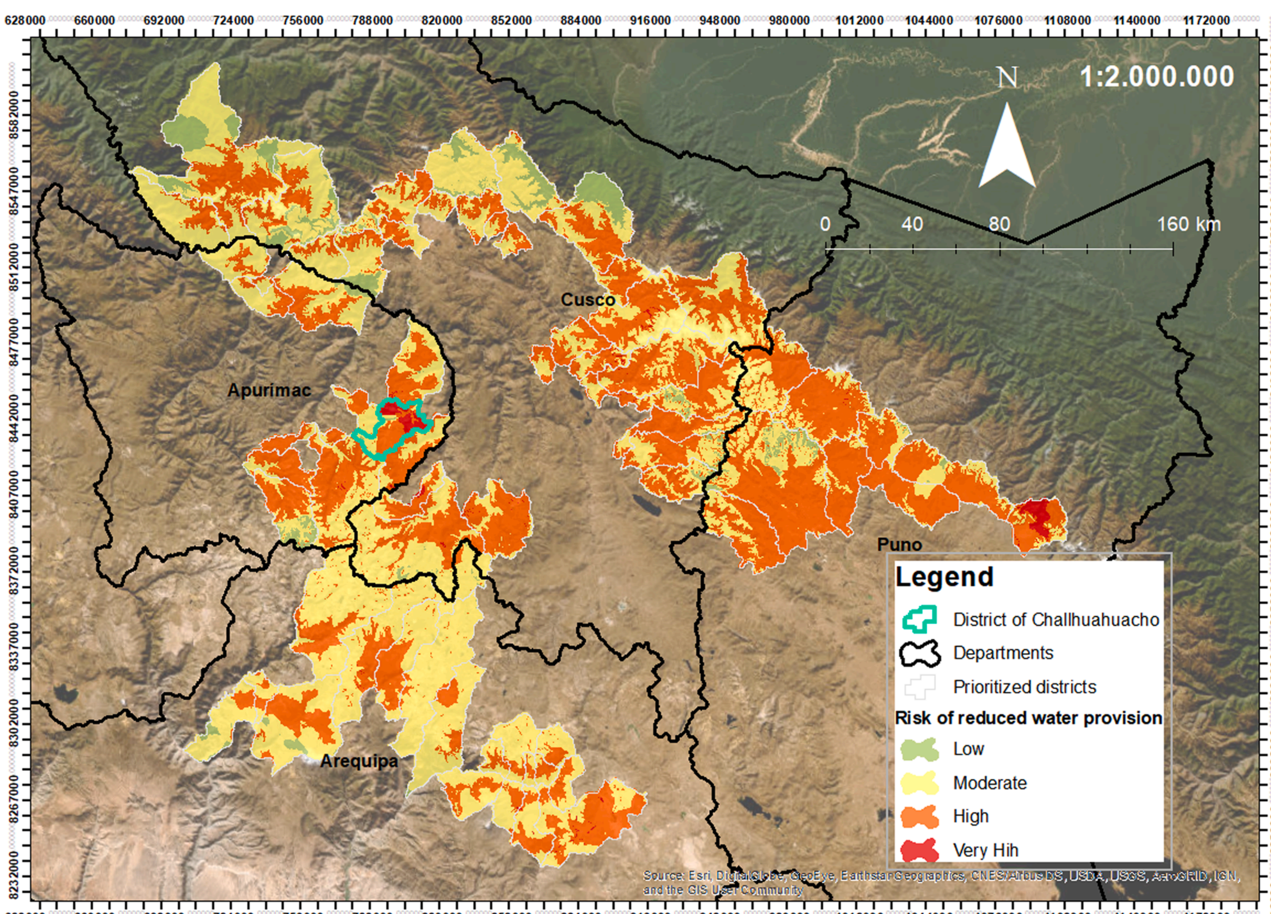

Fig. 2. Map for the climate risk of reduced water provision in the study area [47].

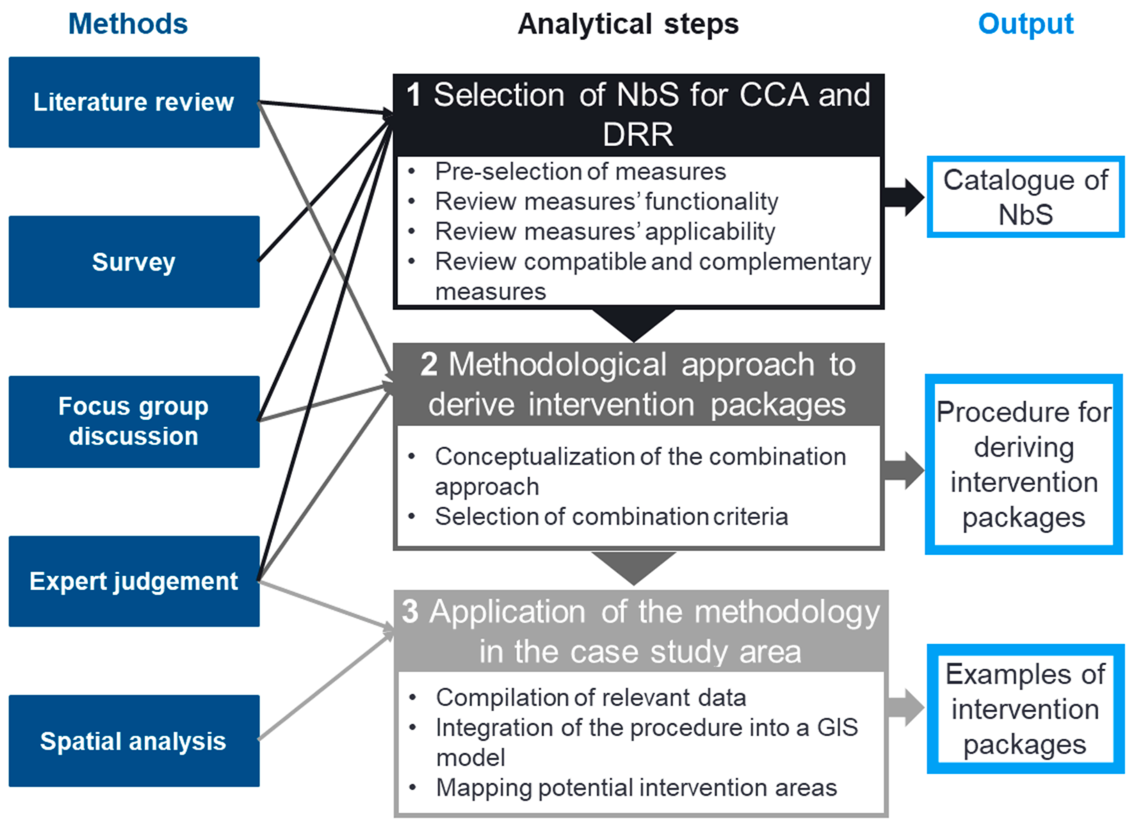

Fig. 3. Research approach: the five methods on the left support the three analytical steps of the research proposed in the centre and lead to three main outputs on the right.

benefits) which can be higher when measures are combined in a harmonized intervention.

The identification and pre-selection of CCA and DRR measures involving nature (hereinafter generically referred to only as "*measures*") for the regional context consisted of two stages: (i) a literature review followed by (ii) a consultation process with local stakeholders. While the literature review served as an initial screening, engaging stakeholders through an online survey and a focus group discussion helped ensure that the short-listed measures aligned with the needs and perspectives of the local community. Integrating the perspectives of different actors involved in the adaptation process increases measures' local acceptance [33,72] and their effectiveness [23] while reducing maladaptation risks [29].

The study started with a general review of existing literature (in English and Spanish) of NbS for CCA and DRR in the high Andean context of Peru, with an emphasis on traditional knowledge and ancestral practices for sustainable natural resource management of Puna region ecosystems. In addition to a scoping search of terms such as "ecosystem-based", "Nature-based Solutions", "Andes ecosystems", "traditional knowledge", "Puna", "ecosystem management", and "natural resources management" in Google Scholar, detailed thematic search was undertaken in GIZ internal thematic and country 'Database Management System' (DMS) and in GIZ supported dedicated knowledge database PANORAMA (https://panorama.solutions/en). A total of 47 publications were selected through a snowballing approach, comprising scientific articles (20), technical reports (13), white papers and technical manuals (9) and book chapters (5). The first screening of publications focused on socio-economic (e.g., livelihoods), environmental (e.g., ecosystems present, climate trends, hydrological dynamics), and institutional (e.g., national regulations, organizational structures) aspects of individual measures.

With an initial list of measures identified from the literature, an online survey was rolled out to local experts, including practitioners, academics, and representatives of locally relevant non-governmental organizations (e.g., Helvetas, Instituto de Montaña) and national governmental institutions (e.g., Geophysicis Institute- IGP, National Institute of Agriculture Innovation- INIA, Hydrological and Meteorological National Service- SENAMHI, Ministry of Environment- MINAM, and Ministry of Irrigation and Agricultural Development- MIDAGRI). This first approach to the stakeholders aimed to scan the participants' level of experience and knowledge on the topic of NbS for CCA and DRR in the high-Andean region of Peru and to levy the participants' perception concerning climate-related risks, their consequences and additional contributing (non-climate) factors. In that sense, the survey focused on the viability of implementing individual measures within the study area, taking into account two aspects: (i) the existence of ecosystems related to the measure (e.g., bofedales to conserve or restore), and (ii) the socio-economic conditions of the department (e.g., economic activities). Additionally, the survey included questions aimed at exploring whether participants had knowledge of other effective measures that may not have been initially identified. Accordingly, the 17 responses from the above-mentioned experts were input on the first validation process of the pre-identified measures.

Pre-selected measures (including those identified after the survey) were further validated through a virtual workshop via Zoom due to COVID19 restrictions, with 35 local stakeholders from governmental bodies, academia, NGOs, and grassroot organizations. Dividing the participants by departments (Apurimac, Arequipa, Cusco and Puno) according to their experience, each group discussed aspects regarding the viability, applicability, effectiveness and limitations of the pre-selected measures. Likewise, stakeholders were asked about measures that can work together based on their experience in the area, as well as other successful actions and practices that had not been identified so far. Responses from these focus groups were used to refine the list of pre-identified measures.

Once the stakeholder consultation process was completed, the list of pre-identified measures was examined using two filtering levels (Fig. 4) to distinguish between NbS and other types of interventions. In line with the Resilient Puna project's framework and scope, the criteria employed in these two filters were centred on the sustainable use of ecosystems (first level) and ensuring local adoption and sustainability of the measures (second level).

The first level uses the five criteria of the Practical Assessment Framework [73] to identify measures that builds resilience to climate-related shocks and risks through ecosystems. To emphasize the direct use of biodiversity and ecosystems service, which allows a clear distinction between green measures from non-green measures, an additional criterion (*B2. Uses ecosystem services, or appropriate species/ varieties*) was included. Accordingly, non-green measures were excluded from the list, and the green measures were further evaluated against the second level of criteria.

The second level in Fig. 4 consisted of selecting locally valid measures for addressing climate-related risks and climate change impacts (e. g., glacier melting, increasing temperature, and increasing variability of rainfall patterns). To that end, information from the literature, local stakeholders, and expert judgement for each measure was evaluated under the following criteria: *local applicability, ecosystem suitability, appropriate scale, climate effectiveness*, and *proven success*. Only measures that met all the second-level criteria were selected for further examination.

The resulting locally valid measures were described in a catalogue of NbS for CCA and DDR in the southern High Andean region of Peru (*see* Supplementary Material- Catalogue). In this catalogue, additional information related to key implementation aspects for each measure is listed, such as ecological settings, biophysical conditions, relationship with local livelihoods, implementation scale, suitability for dealing with climate hazards, capacity to address climate-related impacts and other degradation drivers.

At the same time, the compatibility amongst selected measures was analysed using information about lessons learned from implemented projects, successful experiences in the study area, and other comparable case studies in the high Andean region, collected from focus group discussions and related literature (scientific and empirical). The two following aspects were taken into account during the compatibility analysis:

I **Positive outcomes** between two interacting measures, referring when one measure beneficially influences another [20].

II **Complementary measures**, meaning that they address more risk drivers together than implemented individually [7,74].

For example, integrated livestock management, sustainable grassland management and rehabilitation of ancestral water infrastructure (i. e., *Qochas* and *Amunas)*, and infiltration ditches can accompany reforestation to address landslide risks by closing off grazing on slopes and preventing sediment transport [75]. Based on that understanding, measures were compared pairwise to identify combinations that suggest a more comprehensive intervention in addressing climate risk drivers and generated adaptation benefits.

Conceptualization of the intervention package derivation

The procedure to derive intervention packages follows a GIS-based MCA approach, using ArcGIS software for integrating relevant criteria into a GIS environment. The GIS-based MCA approach has conventionally been used as a decision support tool with numerous empirical

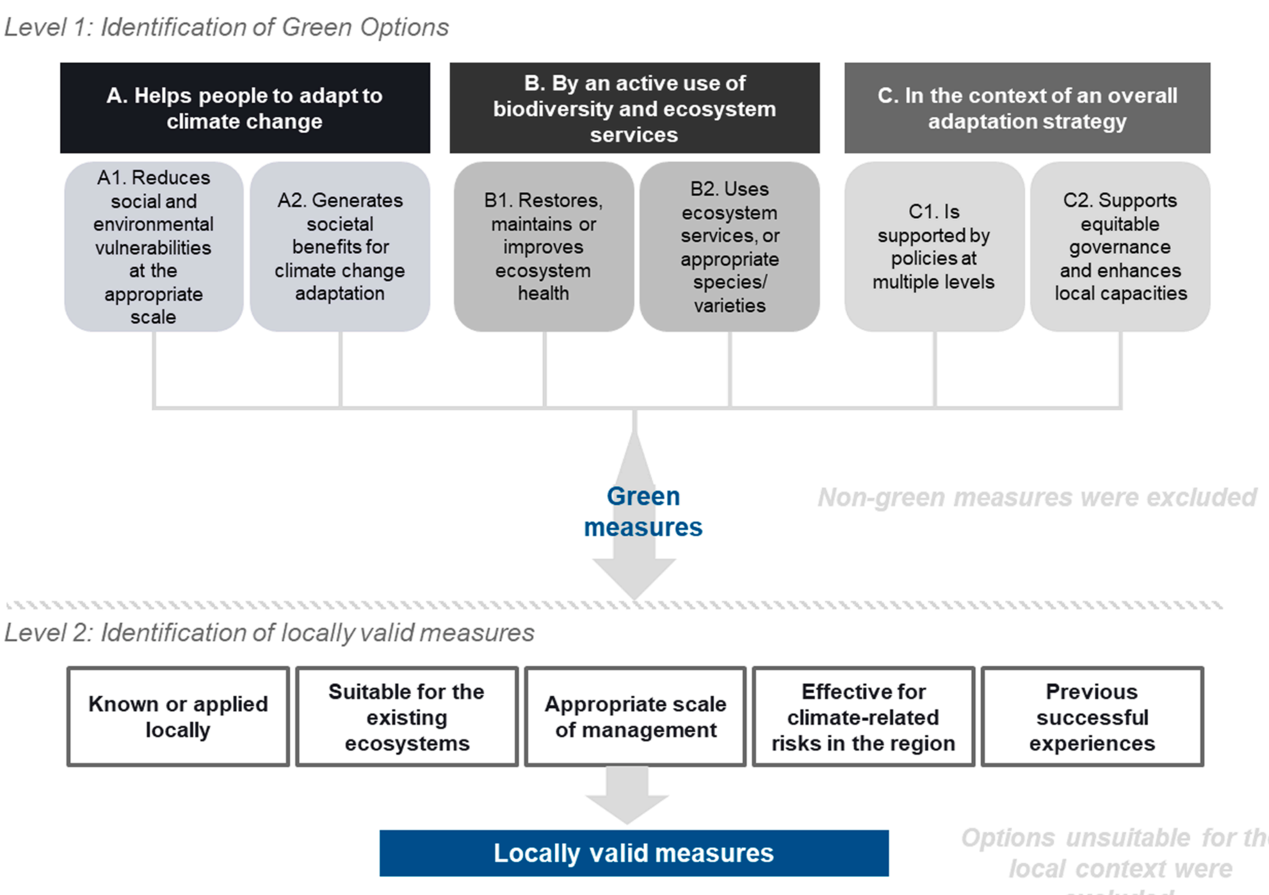

Fig. 4. Criteria for identifying and selecting locally valid measures.

applications in environmental management (e.g., 76), conservation (e.g., 43), restoration planning (e.g., 44), land suitability mapping (e.g., 77), and, more recently, managing climate-related risks [32]. Accordingly, GIS-based MCA is considered an appropriate tool for selecting and prioritizing resilience-building interventions [32] since it allows the aggregation and visualization of multiple criteria to compare different alternatives and suitable locations for their implementation [40].

The procedure to derive intervention packages builds on the decision tree that Greene et al. [40] proposed to select the most convenient GIS-based MCA method. In this study, a single-objective, non-compensatory, conjunctive MCA method was adopted, considering that (1) the aim is to identify intervention packages and their respective intervention sites in response to a climate risk (*single objective)*; (2) every criterion is equally valid and that the criteria do not balance each other out (*non-compensatory*); (3) and all criteria must be met (*conjunctive*) [40] to ensure effective, place-based and locally valid NbS.

Against this background, combination criteria (Table 1) was defined from the information found in the literature and the focus groups' feedback, seeking to identify and combine socially, culturally, economically and environmentally appropriate measures using the particular conditions of the intervention area as filtering parameters. To do so, the criteria were linked to various geographic data (layers) as indicators for each criterion, as shown in Table 1. These layers were selected to spatially represent the conditions in the intervention area and based on the implementation requirements identified for the revised measures listed in the catalogue. For example, to assess "local applicability", several layers of information were incorporated into the analysis. Specifically, an administrative area layer was utilized to differentiate between measures that apply in each department. Additionally, an altitude layer was used to identify areas within the project scope (above 3500 m.a.s.l.). Also, layers representing camelid production areas, water supply basins, and the presence of peasant communities were incorporated to filter measures related to livestock management, water efficiency, and agroecology, respectively. The same was done for the other criteria and their associated indicators. From the combination of different values of these indicators, one can determine which measures are suitable for the intervention area and where each measure can potentially be implemented. In terms of assessing the compatibility of the measures (referred to as the compatibility criterion), a matrix was used to depict which measures can effectively complement each other (see Table 4*)*.

Table 1
Selected combination criteria for deriving intervention packages and related indicators.

Criteria	Indicators (*layers)*
Local applicability: the measure is suitable for the local socio-economic conditions	Administrative areas Altitude Camelid production Water supply basins Peasant communities
Ecological appropriateness: the measure is suitable for the existing ecosystem conditions.	Ecosystem types Glacier influence Ecosystem degradation
Climate relevance: the measure responds to the respective climatic variability—hazards	Extreme precipitation events Maximum Seasonal Temperature Decreasing annual precipitation
Adaptive functionality: the measure addresses climate impacts	Discharge trends (*current flash floods)* Glacier meltwater contribution to river discharge (*future flash floods)* Change in water discharge (*water deficit)* Soil erosion Landslide susceptibility
Territorial coherence: the measure matches the expected land use	Land-use classification Protected areas Areas for conservation and restoration

Based on the combination criteria (and their indicators), a procedure for deriving intervention packages was conceptualized by integrating steps and operational elements from various adaptation-related methodologies [17,26,30,32,33,36,78,79], as well as reorienting them towards the conformation of intervention packages.

Lastly, to identify potential intervention sites, the MCA was translated into a spatial model in a GIS environment (Fig. 5). This model maps all the areas where all the attribute data of a particular measure intersect (*input attributes)*. Hence, it allows spatial allocation of the different measures from an intervention package.

Application of the methodological approach in the case study area

Relevant geodata (Table 2) were compiled and processed to derive intervention packages for mitigating the risk of reduced water provision identified in the project's CCRA [69]. Each compiled dataset corresponds to an indicator of the combination criteria conceptualized in the previous sub-section.

The climate impact chains developed within the CCRA of the Resilient Puna project were also an input for deriving intervention packages in the case study area. An impact chain is an analytical tool that helps conceptualize and visualize cause-effect relationships between risk drivers and factors [17,94–97]. In describing the most relevant factors of the exposure and vulnerability components for a specific climate risk, impact chains provide entry points for identifying options for CCA and DRR (including intervention packages). For instance, EbA and Eco-DRR measures can be derived from vulnerability factors associated with ecological sensitivity [96,97]. Hence, the climate impact chains mainly supported (i) the in-depth understanding of the climate risk at stake and (ii) the analysis of the resilience intervention effects on the respective climate risk.

As a final consideration, the climate risk hotspot map for reduced water provision (Fig. 2) informed the process of prioritizing intervention areas by showing relative risk levels across the project area. The map is the product of the spatial aggregation of indicators associated with the most relevant factors of the main risk components (hazard, exposure and vulnerability). The indicators for the hotspot analysis were selected based on the generated impact chains and considering the spatial and temporal resolution, temporal validity, spatial explicitness, content relevance, and source reliability.

Results

Catalogue of NbS for CCA and DRR

The literature analysis resulted in an initial list of 26 measures potentially applicable to the study area, which was expanded to 31 after the survey and 34 after the focus group session. After the two-level filtering criteria (*see* Section 3.1 - Fig. 4), these 34 pre-identified measures were reduced to a list of 20 locally valid NbS (Table 3).

Each selected measure is described in more detail in the catalogue of NbS for CCA and DRR in the southern high Andean region of Peru (*see* Supplementary Material- Catalogue), which compiles the following information:

- Operating principles
- Key activities
- Benefits
- Requirements
- Enabling conditions
- Scale of implementation
- Constraints
- Trade-offs
- Implementation barriers
- Previous experiences and applicability in the region
- Compatibility with other measures (Table 4)

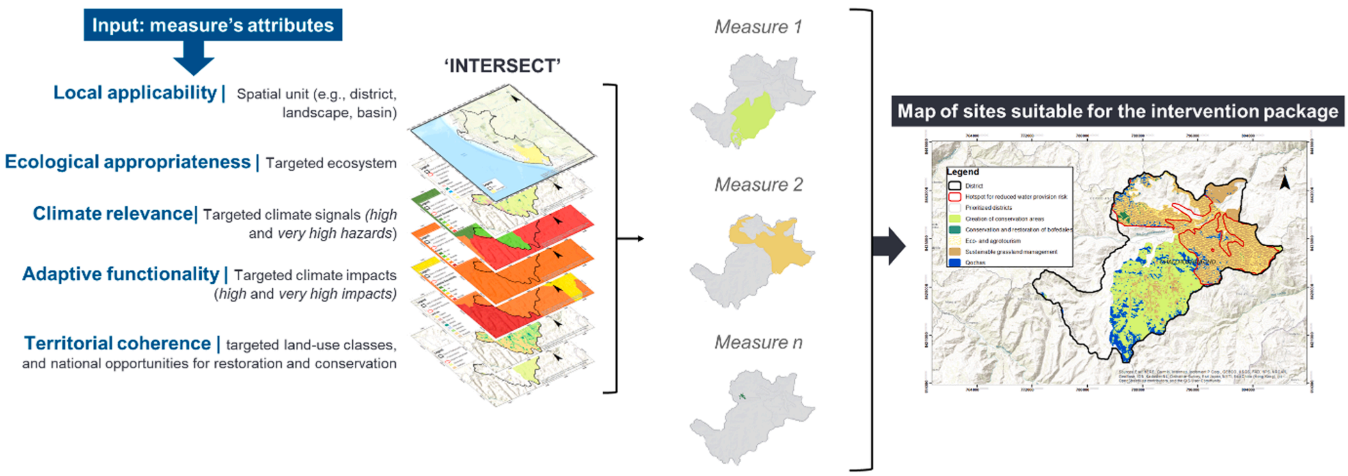

Fig. 5. Spatial Analysis model to determine potential intervention sites for an intervention package.

Table 2
Geodata used for deriving intervention packages in the Puna region.

Geodata	Indicators
Department and district boundaries [80]	Administrative boundaries
Digital Elevation [81]	Altitude
Presence of livestock, poultry, other animals and beehives – Alpaca and Llamas population [82]	Camelid production
Water supply and sanitation EPS basins [83]	Water supply basins
Rural inventory of peasant communities [84]	Peasant communities
National Ecosystem Map [85]	Ecosystem types
National Glacier Inventory [86]	Glacier influence
National map of degraded areas [87]	Ecosystem degradation
Annual trends in heavy precipitation days (R10) at $p < 0.01$ over 2021–2050 using the REMO RCM driven by the Had-CGCM2-ES for RCP8.5 [69]	Heavy rainfall
Projected changes in maximum temperature (°C) towards 2050 under the RCP8.5 scenario for the annual mean using RCA4 RCM driven by the Had-GEM2-ES [69]	Increasing temperature
Annual trends in standardized precipitation index (SPI) at $p < 0.01$ over 2021–2050 using the REMO RCM driven by the Had-CGCM2-ES for RCP8.5 [69]	Decreasing annual precipitation
Discharge trends - Trend in annual discharge over 1981–2020 ([69] adapted from [65])	Sudden increase in river flows *(current flash floods)*
Glacier meltwater contribution to river - Modelled discharge (Q) at the subbasin level ([69] adapted from [88])	Sudden increase in river flows *(future flash floods)*
Change in water discharge - RCP 8.5 ([69] adapted from [65])	Water deficit
Soil water erosion [89]	Soil erosion
Mass movement susceptibility map [90]	Landslide susceptibility
Land use and land cover classification [91]	Land-use classification
National Protected Areas [92]	Protected areas
Map of Opportunity Areas for the restoration and conservation of natural infrastructure [93]	Areas for conservation and restoration

Procedure for deriving intervention packages

The procedure for deriving intervention packages is grounded on a practical approach, structured in an *easy-to-follow* way around two key aspects: selecting and prioritizing suitable measures for a specific context and grouping compatible measures together regardless of the number of measures to combine.

As a result, the procedure to derive intervention packages consists of 8 steps (see Fig. 6) divided into selection and combination and closes with a field validation in each intervention site.

The procedure starts with identifying the intervention area (step 1) and understanding some relevant localized features by doing an explorative, qualitative spatial analysis of the landscape (step 2). The spatial analysis focuses on identifying the socio-economic conditions, ecosystem characteristics, current climate variability and future trends influenced by climate change in the intervention area to describe the climate risk.

The procedure relies on an impact chain (step 3) to have a clearer picture of the climate risk factors intended to address, such as ecosystem degradation dynamics and other non-climatic processes that affect people's vulnerability to the respective climate risk. Identifying those factors suggests entry points for scoping NbS (step 4). Based on the identified entry points and information gathered for the intervention area (i.e., administrative jurisdiction, ecosystems, climate signals, intermedium impacts, and land use), the list of measures can be filtered using the scoping matrix (Table 3).

After that, the compatibility between the filtered measures is analysed using Table 4 (step 5) to combine locally valid NbS into potential intervention packages. As part of this step, one of the filtered measures should be chosen as a "*reference measure*". The purpose of selecting a reference measure is to examine the compatibility of the other remaining measures against this one. In this regard, a reference measure should: (I) be consistent with the predominant ecosystem in the intervention area; (II) address a wide range of risk factors effectively; and (III) have few potential trade-offs and the least maladaptive effect. Accordingly, the intervention package is compounded only from measures compatible with the reference measure, without neglecting that left-out measures can also be applied, but through another intervention, apart from the respective intervention package.

Once the intervention package is defined, it is necessary to identify its potential benefits and expected functions (i.e., *ecosystem services)* in terms of CCA and DRR (step 6). Subsequently, the impact chain is revisited to mark the risk drivers addressed through the benefits and functions of the intervention package (step 7). Doing this helps to understand how the targeted risk is addressed and to recognize limitations and shortcomings (i.e. drivers not addressed) in the intervention.

To further refine the intervention strategy, the procedure allows identifying potential intervention sites (step 8) using the spatial analysis model (*see* Section 3.3 and Fig. 5). It was assumed that intervention sites are feasible and optimal zones to implement an intervention package since these areas meet all the applicability and feasibility criteria used in the previous steps. Recognizing intervention sites in the whole landscape narrows down future field activities related to the feasibility study, project inception, and intervention design while efficiently using available resources.

Finally, the intervention package needs to be validated in the field through a co-planning, bottom-up, multi-stakeholder approach. Since each measure has specific requirements (e.g., topography,

Table 3
Selected measures for the Puna region and their conditions for implementation (marked green cells).

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Measures	Local applicability (Department)				Ecological appropriateness (Ecosystem types)							Climate relevance (Hazards)			Adaptive functionality (Impacts)					Territorial coherence (land use)					
	Apurimac	Arequipa	Cusco	Puno	Glacier and peri-glacier zone	Grasslands	Bofedal	High Andean Forest	Meso Andean Forest	Shrubland	Lagoons and wetlands	Decreasing annual precipitation	Increasing temperature	Heavy rainfall	Erosion	Landslides	Sudden increase in river flows	Deficit of water	Decreasing land productivity	Croplands	Pasturelands	Forest lands	Bare lands	Glacier	Water bodies
Conservation and restoration of bofedales	+	+		+			+				+	+	+	+	+	+	+	+			+				+
Sustainable grassland management	+	+	+	+		+	+			+		+			+	+		+	+	+	+				
Agroforestry	+	+	+	+		+		+	+	+			+	+	+			+	+	+	+	+			
Reforestation with native species	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+			+			
Creation of conservation areas	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+			+	+		+	+
Crop diversification	+	+	+	+		+	+	+	+	+	+	+	+						+	+					
Eco- and agrotourism	+	+	+	+	+	+	+	+	+	+	+	+	+				+	+	+	+	+	+	+	+	+
Integrated soil fertility management	+	+	+	+		+		+	+	+				+	+			+	+	+	+				
Camellones (Waru-waru)*			+		+	+	+				+	+	+	+			+	+		+					
Conservation agriculture	+	+	+	+		+	+	+	+	+	+	+	+	+	+		+	+	+	+					
Contour farming	+		+		+	+		+	+			+		+	+	+			+	+					
Bioengineering for gully control		+	+		+	+	+	+	+	+		+		+	+	+	+	+		+	+	+	+		
Qochas (i.e.,micro-reservoirs)	+	+	+	+	+	+	+	+			+	+	+	+	+	+	+	+	+		+		+	+	+
Amunas/ Mamanteo**		+			+	+	+	+			+	+			+	+	+	+		+	+	+	+	+	+
Infiltration ditches			+	+				+	+			+		+	+	+	+	+	+	+		+			
Andenes (i.e., terraces)			+					+	+				+	+	+	+		+	+	+	+				
Irrigation management	+		+	+		+	+	+	+	+		+	+		+	+		+	+	+	+				
Slow-forming terraces			+			+	+	+				+		+	+	+		+	+	+	+	+			
Fitotoldos***	+	+	+		+	+	+	+	+	+				+						+	+	+	+	+	
Afforestation	+		+			+	+	+	+	+	+		+	+	+	+	+			+	+	+	+		

* Millenary practice consisting of raising embankments interspersed with canals to improve water-soil-climate-plant-human interaction.
**Pre-Hispanic systems for recharging aquifers artificially through a network of permeable channels that connects the upper part of a watershed to infiltration areas in lower areas.
*** Structures made of adobe walls with a transparent roof that allow, like a glass greenhouse, to control the technical and environmental conditions (temperature, humidity, luminosity) for vegetable production.

implementation scale, land tenure, labour availability, soil conditions, water access) and each context is different, an evaluation at the site level with the local community is needed. Furthermore, stakeholders' priorities, needs, perspectives and interests should be integrated to adjust the intervention package and fine-tune the intervention strategy in terms of objectives, requirements, scale, timing, timeframes, location, participants, trade-offs, barriers, limitations, costs, timeline, expected outcomes and enablers needed. Local participation and timely and continuous engagement of stakeholders increases the likelihood of a successful CCA or DRR measures [79].

At this point, principles and safeguards of the CBD Voluntary Guidelines [23] and the second part of the criteria of the Practical Assessment Framework [73] are recommended for defining the on-site intervention and the application of each measure from the

Table 4
Compatibility matrix of the selected measures for the Puna region, showing complementary pair combinations with positive effects (marked green cells).

Measures	Cons. & rest. of bofedales	Sust. Grassland Management	Agroforestry	Reforest. with native sp.	Creation of conservation areas	Crop diversification	Eco- and agrotourism	Integrated Soil Fertility Manag.	Camellones (Waru-waru)	Conservation agriculture	Countorn farming	Bioengineering for gully control	Qochas/ micro-reservoirs	Amunas/Mamanteo	Infiltration ditches	Andenes/terraces	Irrigation management	Slow-forming terraces	Fitotoldos	Afforestation
Conservation and restoration of bofedales																				
Sustainable Grassland Management	+																			
Agroforestry		+																		
Reforestation with native species		+	+																	
Creation of conservation areas	+	+	+	+																
Crop diversification																				
Eco- and agrotourism	+	+	+	+	+	+														
Integrated Soil Fertility Management	+	+	+			+														
Camellones (Waru-waru)							+	+												
Conservation agriculture		+	+			+	+	+												
Countorn farming			+	+		+	+	+												
Bioengineering for gully control		+	+	+				+			+									
Qochas/ micro-reservoirs	+	+	+	+	+		+			+										
Amunas/Mamanteo		+		+		+	+			+	+		+							
Infiltration ditches		+	+	+		+		+			+	+	+							
Andenes/terraces		+	+	+		+	+	+		+		+	+	+	+					
Irrigation management	+	+	+						+	+	+			+						
Slow-forming terraces			+	+		+		+			+	+		+						
Fitotoldos			+	+		+				+										
Afforestation		+	+	+	+		+			+	+	+	+	+	+	+		+		

intervention package. Additionally, it is worth mentioning that some soft measures (e.g., awareness raising, financing mechanisms, institutional capacity strengthening) can also be included as part of the resilience-building intervention to climate change.

Example of an intervention package to mitigate the risk of reduced water provision

This section demonstrates the application of the developed methodological approach (Chapter 4.2) for the example of the Challhuahuacho district (department of Apurimac). Following the procedure described above and as the first step, this district was selected as an intervention area due to its *very high* risk of reduced water provision, based on the hotspot map for water provision risks (Fig. 7) generated during the CCRA [67].

As part of the step 2, related geodata was analysed (*see* Appendix A*)*, showing relevant landscape aspects in the intervention area, like a predominant grassland ecosystem (*Pajonal*) with some patches of shrubland and *bofedales* (*see* Fig. A.1). Also, the district's primary land-use class is *green areas* which corresponds to grasslands and wetlands, combined with scattered croplands, a concentration of bare land in the south and a large copper mining area in the north (*see* Fig. A.2). Furthermore, the intervention area has a widespread presence of peasant communities (*see* Fig. A.3), *high* soil erosion intensity (*see* Fig. A.4), *moderate* and *high* susceptibility to landslides (*see* Fig. A.5), and *very high* degradation trend of bofedales and grasslands (*see* Fig. A.6). Besides that, within the intervention area, many zones are mainly prioritized for conservation, with more minor spots for restoration according to the Map of Opportunity Areas for the restoration and conservation of natural infrastructure (*see* Fig. A.7). Regarding climate hazards, the likelihood that Challhuahuacho will experience a decrease in the annual precipitation by 2025 is *very high* (*see* Fig. A.8), which is associated to potential water scarcity,

In step 3, the climate impact chain for the risk of reduced water provision from the CCRA (*see* Fig. A.9) was examined to understand better the interrelated vulnerability factors and drivers that lead to the risk condition, including climate hazards and their cascading effects. Consequently, some identified entry points were: *deliberate drainage of wetlands, expansion of agricultural land into grasslands, presence of mining,* and *the loss of high-quality wetlands, peatlands and grasslands*.

As a result of step 4, nine measures were identified for Challhuahuacho using the information from the district characterization and the scoping matrix (*see* Table A.1). The measure called "*Creation of a conservation area*" was chosen as a reference measure, considering primarily: (I) the advanced degradation of grasslands and bofedales within the hotspot; (II) the indication of mining activity in the vicinity of bofedales; (III) the high intensity of soil erosion, and (IV) the high need for conservation efforts in the intervention area.

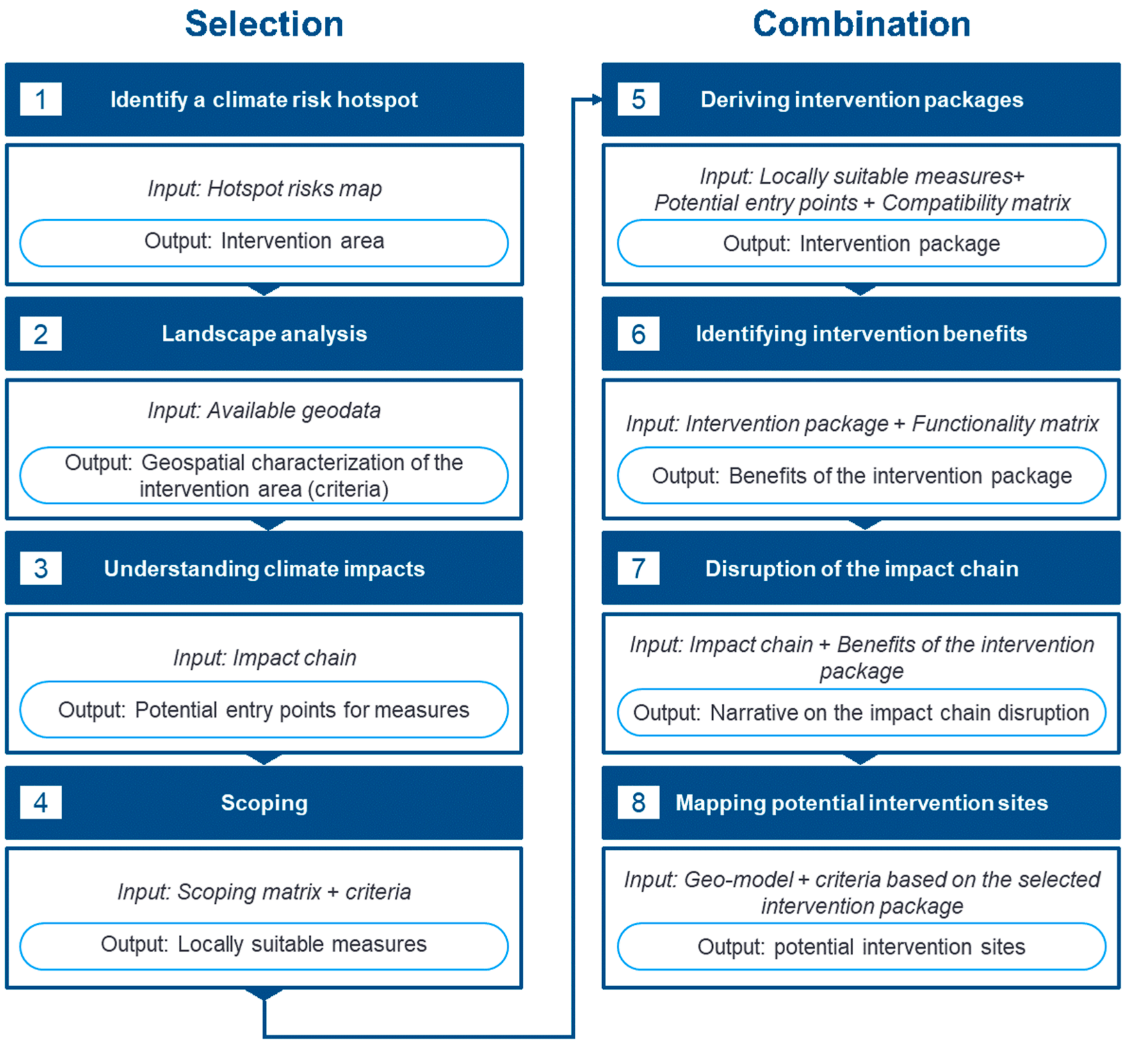

Fig. 6. Procedure to derive intervention packages.

For step 5, the identified entry points of the impact chain were considered when analysing the compatibility of the filtered measures versus the reference measure (*see* Table A.2). The result of using the compatibility matrix was an intervention package for Challhuahuacho consisting of five measures (i.e., creation of conservation areas; conservation and restoration of bofedales; sustainable grassland management; eco- and agrotourism; and Qochas/ micro-reservoirs).

Afterwards, expected benefits from the intervention package were identified (step 6) (*see* Table A.3) and placed within the impact chain (step 7), highlighting breakpoints in which the joint action of the intervention addresses vulnerability drivers and factors (including cascading effects), as well as intermedium impacts (Fig. 8). For example, the intervention package aims to tackle the reduced water quantity by fostering aquifer recharge (through *Qochas*) and enhancing water regulation (through *conservation and restoration of bofedales*). Also, the intervention package aims to improve the income of rural communities through eco- and agrotourism, as well as to regenerate vegetation cover on high-quality wetlands, peatlands and grasslands throughout a conservation area.

Finally, in step 8, the spatial analysis model was run to identify intervention sites. For that purpose, multiple layers were extracted from the geodata used in step 2 (*input attributes),* representing each of the intervention package's combination indicators (see Table 1). These layers were spatially intersected to identify potential intervention sites for each measure, and subsequently, all the output features were compiled and displayed on a map (Fig. 9). The map represents, therefore, the potential intervention sites in Challhuahuacho where the derived intervention package can be implemented to address the risk of reduced water provision.

Discussion

The methodological approach to derive intervention packages explained above illustrates a novel, pragmatic, and replicable way to design resilience-building integrated solutions based on measures' applicability, appropriateness, functionality, compatibility, relevance, territorial coherence, and local knowledge. Through a straightforward procedure for combining NbS and identifying suitable sites for their implementation based on biophysical conditions, social acceptability and local climatic vulnerability drivers, the proposed methodological approach aims to produce effective, sustainable, robust and flexible resilience-building interventions. Likewise, this approach seeks to minimize maladaptation risks by integrating multiple, complementary and compatible low-regret actions so each measure's weaknesses, limitations and trade-offs can be balanced in a joint implementation. Low-regret actions, such as NbS, that keep adaptation options open and have an inclusive multi-stakeholder vision tend to be less maladaptive by delivering systemic benefits, ensuring local ownership and enabling long-term climate adaptation [25].

Moreover, the methodological approach involves shifting the

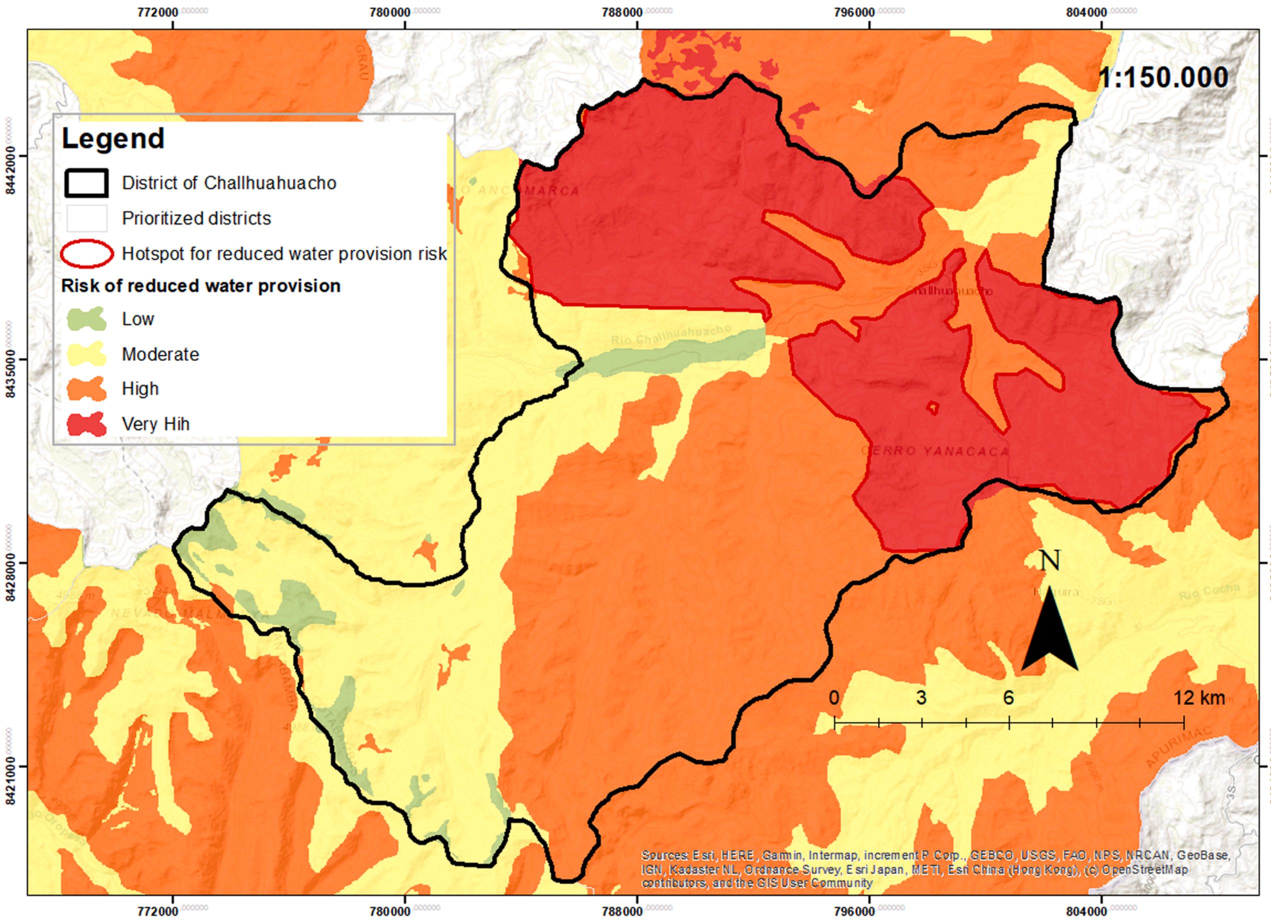

Fig. 7. Risk of reduced water provision in Challhuahuacho district.

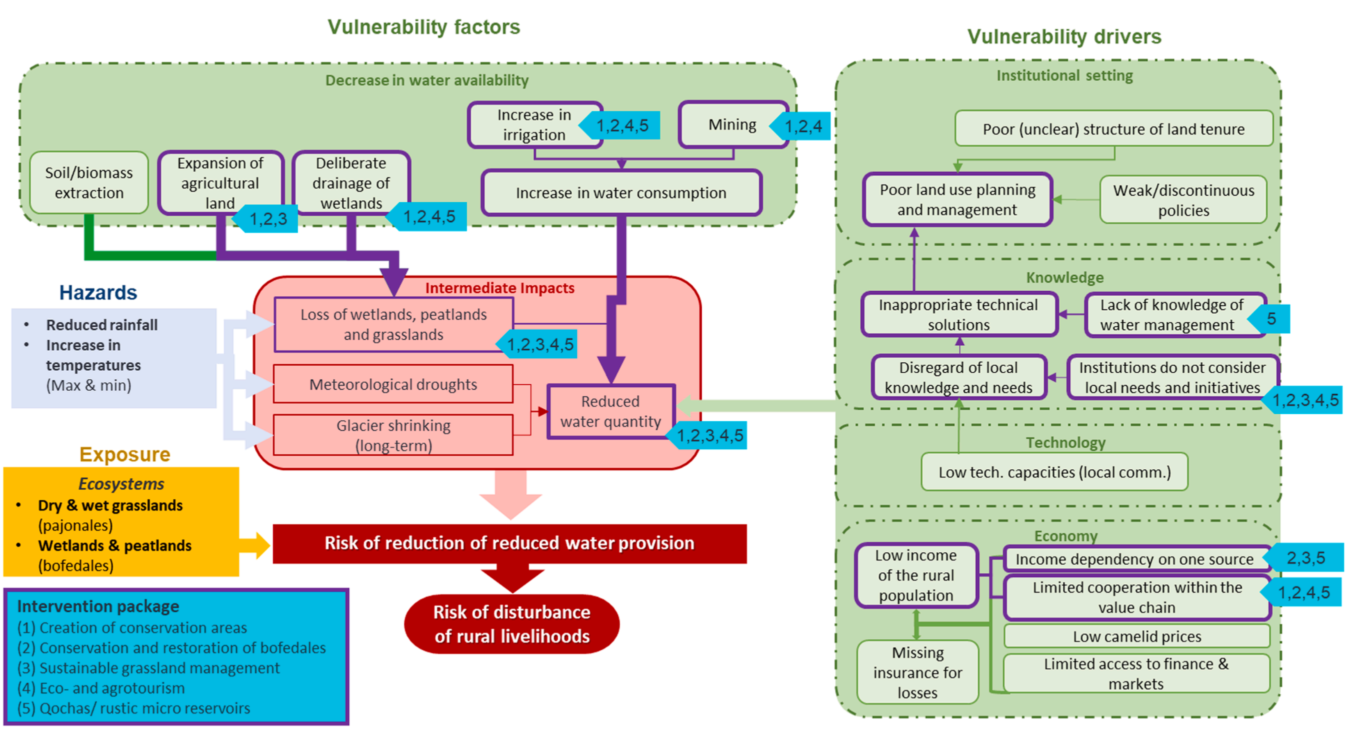

Fig. 8. Impact chain model of the risk of reduced water provision for the Puna Region. Effects of the Challhuahuacho's intervention package (light blue boxes) on the vulnerability drivers and intermediate impacts (purple boxes) associated with the impact chain for the risk of reduced water provision.

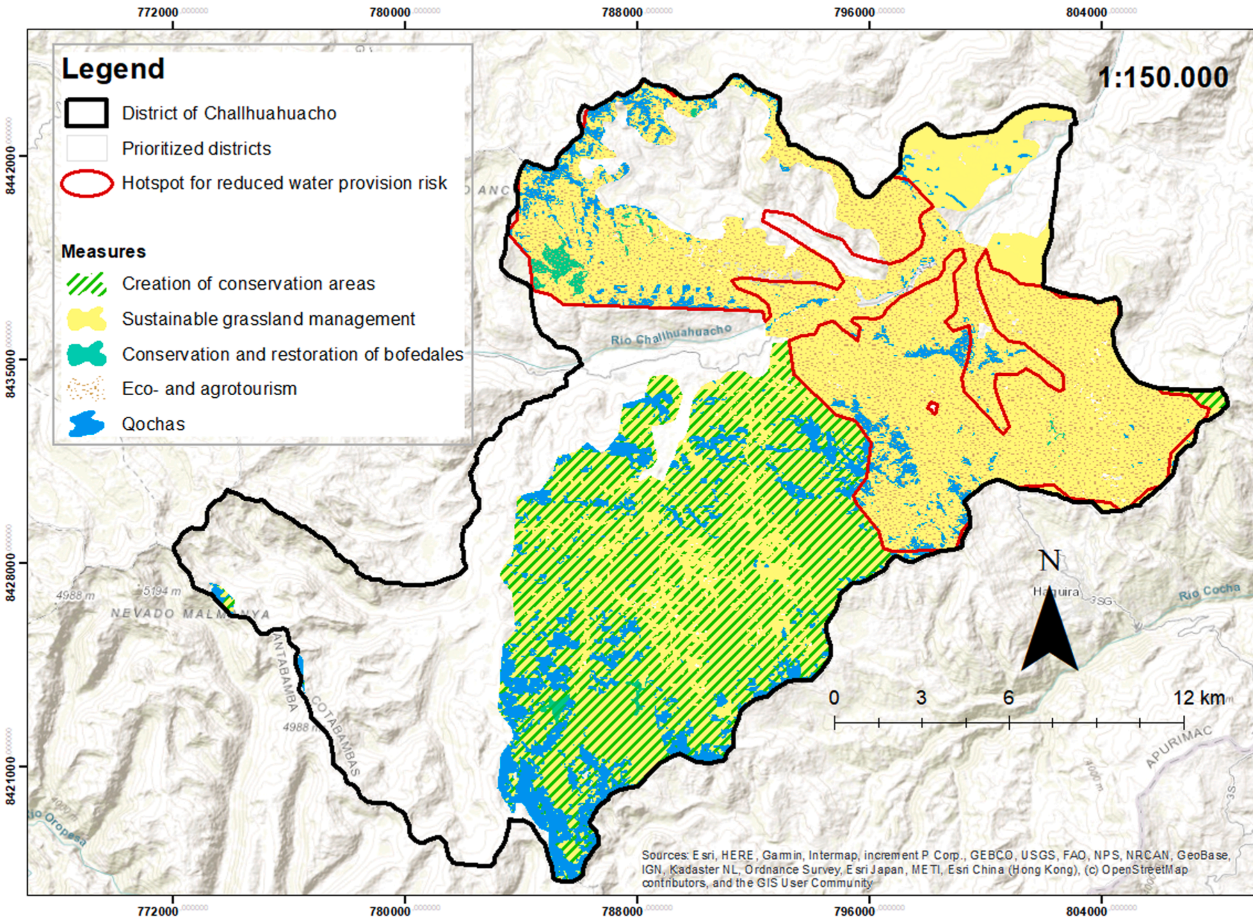

Fig. 9. Potential intervention sites for implementing the intervention package.

perspective from activities focused on "one-size-fits-all solution" to "multi-solution" strategic interventions that address risk factors from different angles while triggering untapped synergies with novel adaptation benefits. Adopting this multi-solution thinking will foster mutual learning amongst disciplines, an active expertise exchange between scientists and practitioners, and converging knowledge systems (e.g., modern science and traditional knowledge). In that sense, to successfully develop solutions to build resilience, it is necessary to promote knowledge sharing, exchange, and transfer and further progress in knowledge generation and dissemination that helps better understand the social-ecological systems, local climate change impacts, and the outcomes of management actions [36].

Under those premises, the methodological approach can help fill gaps in the science-practice interface. At the local level, the methodological approach seeks to ensure that the CCA and DRR priorities identified from scientific information are aligned with local stakeholders' perspectives, wisdom, and interests. On the other hand, at a more general level, the replication of the methodological approach in different contexts can stir implementing agencies, governments, donors and adaptation funds to embrace integrated solutions amongst their portfolios and calls for proposals –an existing gap for addressing compound risks [98].

Furthermore, the methodological approach presented here can be a tool that helps practitioners to optimize timelines, fieldwork, and deployed resources in the initial planning stages of CCA and DRR interventions. For example, a thorough analysis of the ecosystem's state and the ecosystem services' functionality is recognized as the most solid feasibility assessment of measures involving ecosystems [99]. But conducting fieldwork for community engagement and ground data collection in large areas (e.g., at the district level) can involve significant money, time and effort. In this regard, the methodological approach attempts to focus and optimize resources in the next stage of the planning process by spotting potential intervention sites and, therefore, narrowing activities related to field data collection and local stakeholders' consultation.

Even though the methodological approach is an agile and pragmatic tool for prioritizing measures and intervention zones, it still has some limitations that are worth covering in future studies. For instance, the methodological approach is built on the assumption of ecosystem invariability despite climate change effects, and NbS are therefore expected to be functional and suitable alternatives for future climate scenarios. However, it is well known that ecosystems are resilient at low levels of climate change ($<2\,^{\circ}$C), and beyond that, numerous impacts on ecosystems will be irreversible and severe [25,100]. Consequently, future improvements in the procedure must integrate ecosystem change models in various climate scenarios. For instance, including climate-resilient development pathways to consider different adaptation options dynamically through changing conditions can provide more flexibility, anticipation and understanding in planning intervention strategies [101].

Another limitation is that the methodological approach illustrates the disruption of the climate risk impact chain through the expected benefits, but it does not estimate the capacity of intervention packages to reduce the addressed climate risks (e.g., how much water deficit can be addressed) nor indicates the disruption level of risk drivers (e.g., in how much it improves household income or prevents agricultural encroachment). The methodological approach also does not estimate the extent to which measure of the intervention package should be implemented to reduce risk, nor suggests timeframes when the measures work effectively. These aspects are relevant for determining the need for additional CCA and DRR measures over time [26], as well as for designing an effective, strategic and responsive intervention that achieves the desired resilience outcomes as the system's adaptation needs change with the dynamic climatic conditions.

The methodological approach also lacks accounting for the side effects of resilience-building interventions. Any measure –as any anthropogenic intervention—can potentially cause inadvertent adverse consequences on human health, the environment, and social well-being and harm the existing and future system's adaptive capacity [5,102]. For such reason, it is crucial to assess and consider the side effects, trade-offs, limitations, and risks emerging from the intervention package to avoid implementing maladaptive actions [17,23,30,102]. In this regard, aspects such as exacerbation of inequality, disruption of local dynamics, locking-in of future development options, stimulation of (new) vulnerability drivers, and relocation of impacts or redistribution of risks are some criteria that could be integrated into the methodological approach. However, to this end, the maladaptive potential of NbS (particularly EbA and Eco-DRR measures) should be studied and evaluated with the same attention as co-benefits [17,23,30].

Future perspectives for the methodological approach are consolidating the combination criteria and widening the range of CCA and DRR options. On the one hand, adding criteria such as ecosystem condition (e.g., [103]), local adoption potential (e.g., [104–106]), climate mitigation capacity (e.g., [20]), land availability and detailed geomorphology (e.g., [107]) can improve the robustness and feasibility of resilience interventions [99]. Also, it can create opportunities to report to other environmental-related targets (i.e., land degradation neutrality, ecosystem restoration, climate mitigation, food and water security) and, consequently, attract related financing to sustain and scale up the intervention. On the other hand, integrating other CCA and DRR options (e.g., grey infrastructure, hybrid solutions, soft measures, and climate mitigation measures) can deal with risk factors and local concerns that NbS cannot address on its own [9,16,72], such as immediate protection, institutional support, or loss and damage compensation. In that case, only measures with low maladaptive risks and few trade-offs should be considered, as they help reduce future impacts of climate uncertainties [28].

Additionally, selecting measures and identifying their respective intervention sites can be improved with more complex MCA techniques and more precise geoprocessing. For example, using Analytic Hierarchy Process allows the integration of local stakeholders' needs in identifying intervention areas [108] by facilitating the criteria weighting and, therefore, the weighted overlay in the spatial analysis. Lastly, the proposed methodological approach is a first approximation in the search for integrated interventions to address climate-related challenges. Therefore, researchers and practitioners are encouraged to replicate this methodological approach and adjust it to other contexts. Along with the progress in NbS knowledge, this experience would improve the design of the next generation of CCA and DRR interventions and advance their effective and sustainable implementation.

Conclusions

In a participatory manner, 20 locally valid prospects of NbS for CCA and DRR in the Puna region communities of Peru were identified. These measures are described in detail in a catalogue of NbS for CCA and DRR in the southern high Andean region of Peru, emphasizing the importance of local and traditional knowledge in CCA and DRR strategies.

Furthermore, a practical and easy-to-follow procedure has been developed to derive place-based intervention packages of NbS for CCA and DRR. This procedure is based on relevant literature, stakeholders' perspectives, and well-defined criteria. It involves 8 steps to select and prioritize a suitable combination of NbS for CCA and DRR for a specific context. To better illustrate the proposed procedure, an intervention package was developed for addressing the risk of reduced water provision in the Challhuahuacho district. This example serves to highlight the practical use of the procedure and its applicability beyond the Puna region while shedding the light on its limitations and needs for improvement.

Overall, the proposed methodological approach can serve as a helpful resource for practitioners and policymakers involved in CCA and DRR efforts to prioritize more systemic interventions for the wide range of climate-related risks in a multi-targeted and context-specific manner. Moreover, by stressing the importance of exploring compatibility and synergies amongst the measures, this study provides a strong foundation for further research and calls for a better understanding of how to effectively utilize, implement, and combine NbS to build resilience to climate change.

NBS impacts and implications

- Environmental: the article highlights the need for more resilient ecosystems to address emerging climate risks effectively. It also promotes conservation, sustainable use, and restoration of ecosystems as an adaptation solution to the changing climate.
- Economic: the proposed methodological approach presents a cost-effective and affordable process to derive adaptation packages. The authors also emphasize its potential role as a decision-support tool that can help practitioners to optimize resources in the initial stages of the adaptation strategy planning.
- Social: the proposed methodological approach underlines the importance of participatory processes and the involvement of local stakeholders in the identification of climate change adaptation measures. Additionally, the article advocates for valuing traditional and local knowledge of rural communities to face the effects of climate change.

CRediT authorship contribution statement

Oscar Higuera Roa: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Davide Cotti:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing. **Natalia Aste:** Resources. **Alicia Bustillos-Ardaya:** Investigation, Resources, Project administration. **Stefan Schneiderbauer:** Investigation, Resources, Writing – review & editing, Funding acquisition. **Ignacio Tourino Soto:** Writing – review & editing, Project administration, Funding acquisition. **Francisco Román-Dañobeytia:** Resources, Writing – review & editing, Funding acquisition. **Yvonne Walz:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2023.100090.

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