Universidade de Brasília
Instituto de Ciências Humanas
Departamento de Geografia
Programa de Pós-Graduação em Geografia

UNIVERSIDADE DE BRASÍLIA
PÓS-GRADUAÇÃO EM GEOGRAFIA

A RELEVÂNCIA DOS NEVADOS DA AMÉRICA DO SUL PARA O GEOPATRIMÔNIO

Gabriella Emilly Pessoa Nunes Martins
Dissertação de Mestrado

Brasília, DF: Julho de 2023

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Aprovado por:

____
Valdir Adilson Steinke, Doutor (Universidade de Brasília)
Orientador

____
António Vieira, Doutor (Universidade do Minho)
Examinador Externo

____
Leandro Díaz, Doutor (Universidade Nacional de Tucumán)
Examinador Externo

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1. Geossistema
2. Os Andes
3. Geobiodiversidade
4. Cordilheira

Gabriella Emilly Pessoa Nunes Martins

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RESUMO

Geopatrimônio é um conceito crucial para preservar formas de relevo e elementos abióticos excepcionais. A água, entre outros elementos, desempenha um papel significativo para o Geopatrimônio, pois é um elemento transformador da paisagem e essencial para a vida na Terra. Considerando a importância da água, esta pesquisa apresenta um geosítio para o Geopatrimônio inovador: os Nevados. Localizados em picos de montanhas, os Nevados consistem em gelo e neve que fornecem água rio à jusante durante a temporada de derretimento e servem como divisores e conectores de bacias hidrográficas. Devido à sua relevância e vulnerabilidade, eles representam importantes geosítio para o Geopatrimônio. Os Nevados da América do Sul foram avaliados usando variáveis com correlações estatísticas geoespaciais e ferramentas de geoprocessamento, resultando na determinação de quais nevados devem ser priorizados para o Geopatrimônio. O Randolph Glacier Inventory foi usado para determinar a localização dos Nevados. Após a coleta de dados, as informações foram divididas em três grupos de variáveis para análise estatística e interpretação dos resultados: o primeiro grupo está relacionado a elementos geológicos, o segundo a elementos geomorfológicos e o terceiro a variáveis ambientais. Após o agrupamento dessas características, uma correlação estatística geoespacial foi realizada usando o índice de Moran por meio de uma matriz de análise. Isso mostrou que os Nevados em latitudes mais baixas possuem o maior valor de prioridade para o Geopatrimônio, enquanto aqueles em latitudes maiores, os do Sul, possuem um valor de prioridade mais baixo. Esses resultados sugerem que os Nevados devem ser incluídos nos esforços de Geopatrimônio e geoconservação.

Palavras-chave: Os Andes; cordilheira; geodiversidade; geossistema; geobiodiversidade.

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ABSTRACT

Geoheritage is a crucial concept for preserving outstanding landforms and abiotic elements. Water, among others, plays a significant role in geoheritage because it is a transformative element of the landscape and is essential for life on Earth. Acknowledging the importance of water, this research presents an innovative geoheritage site: the nevados. Nevados, which are located on mountain peaks, are composed of ice and snow that provides water during the melting season and serve as both dividers and connectors of hydrographic basins. Due to their relevance and vulnerability, they are an important geosite for geoheritage. South America's priority nevados for geoheritage were evaluated using statistical geospatial correlation of variables and geoprocessing tools. The Randolph Glacier Inventory was used to determine the location of nevados. Three groups of variables were assembled: the first is concerned with geological elements, the second with geomorphological elements, and the third with environmental variables. Following the grouping of these characteristics, a statistical correlation was performed using the Moran index via an analysis matrix. As a result, nevados in low latitudes have the highest geoheritage value, while southern nevados have a lower geoheritage value. These findings suggest that nevados should be included in geoheritage and geoconservation efforts.

Keywords: The Andes; mountain range; geodiversity; geosystem; geobiodiversity.

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INTRODUÇÃO

Ao debruçar-se pelo conceito de Geopatrimônio, muitos teóricos o definem como mero patrimônio geológico. Embora a geologia seja, de fato, uma parte de suma relevância para os estudos de Geopatrimônio, reduzir este conceito a uma só ciência – no que pese a complexidade e a multiface da ciência – pode restringir, empobrecer e mascarar o real potencial do Geopatrimônio.

O Geopatrimônio deve ser pensado e apresentado sobre uma perspectiva sistêmica, englobando tanto os sistemas naturais quanto sociais da Terra. Por meio deste entendimento, é possível vislumbrar a capacidade integradora e sustentável que o Geopatrimônio possui. Afinal, o prefixo "geo" não deve ser visto como sinônimo de geologia, mas do grego "gê", que significa "Terra".

Por isso, é necessário perceber o potencial que o conceito conceito possui de abranger diversas áreas científicas (CORATZA et al., 2018; GORDON et al., 2018). Ciências como a Pedologia, Geomorfologia, Hidrologia, Geografia, Glaciologia, além das clássicas como Geologia, Petrologia, Mineralogia, Paleontologia e Estratigrafia, possuem alta relevância para atuar de forma conjunta, sistematicamente, no âmbito do Geopatrimônio.

Para entender melhor essa dinâmica, o Geopatrimônio deve ser entendido como elementos abióticos e paisagens com características excepcionais, consequentes da geodiversidade existente na Terra, que possuem elevado valor científico, bem como valor estético, recreacional, educacional, funcional, ecológico e cultural (BRILHA, 2016; GRAY, 2004; LIMA E CARVALHO, 2020; REYNARD E GIUSTI, 2018; SHARPLES, 2002) que podem e devem ser legado às gerações futuras. A partir dos últimos valores, o Geopatrimônio move-se em direção à sociedade, deixando de ser restrito ao ambiente acadêmico.

Geossítios – locais delimitados na geosfera com características expressivas para o Geopatrimônio – possuem sua relevância a partir da sua capacidade de contribuição para o entendimento da história e evolução da Terra (BERAAOUZ, 2017; DE WEVER et al., 2006; BRILHA, 2016; ProGEO, 2011; STRASSER et al., 1995).

Para além disso, os geossítios podem apresentar valores cênicos e recreativos altos, sendo ferramentas importantes para o geoturismo (BRAHOLLI & MENKSHI, 2021; RUBAN et al., 2020; TESSEMA et al., 2021; VUJIČIĆ et al., 2011). Este, por sua vez, contribui para o fomento de desenvolvimento socioeconômico local (FARSANI et al., 2011; MARTÍNEZ-GRAÑA, 2016; RÍOS et al., 2020). Dessa forma, ao mesclar Geopatrimônio, Geodiversidade, Geoturismo, Geoconservação e Geossítios, é assegurado a preservação de locais relevantes e, em consequência, recursos ambientais e ecológicos podem ser utilizados de forma sustentável e consciente pelas gerações presentes e futuras.

Nesse sentido, torna-se imprescindível fornecer definições sobre esses conceitos supracitados, sendo considerados pilares do Geopatrimônio. A Geodiversidade refere-se à diversidade de elementos abióticos presentes na Terra, tais como a litologia, tectônica de placas, geomorfologia, solos, hidrologia, topografia, geologia e processos físicos terrestres, marítimos e oceânicos (SERRANO & RUIZ-FLAÑO, 2007; GRAY, 2004). Por isso, este conceito consegue perpetuar diversas esferas (KOZŁOWSKI, 2004).

Além disso, a geodiversidade abrange sistemas gerados por processos naturais, endógenos e exógenos, bem como processos antropogênicos, que compreendem a variedade de partículas, elementos e locais presentes na natureza, considerando a escala adequada para a aplicação do conceito (SERRANO & RUIZ-FLAÑO, 2007). Adicionalmente, a geodiversidade desempenha um papel relevante para a biosfera, na preservação e conservação da biodiversidade e na garantia de serviços ecossistêmicos e geossistêmicos (CROFTS & GORDON, 2015; HJORT et al., 2015; MATTHEWS, 2013; PIACENTE, 2005).

A Geoconservação, derivada do Geopatrimônio, está ligada a necessidade de preservação e gestão dos elementos da geodiversidade, reconhecendo seus valores intrínsecos e garantindo sua preservação e uso sustentável, visto que há ameaças a eles (BROCX E SEMENIUK, 2007; GRAY, 2005; SHARPLES, 2002). Dessa forma, a Geoconservação é a implementação de medidas métodos e estratégias científicas necessárias a conservação e preservação de geossítios (BRILHA, 2015).

Existem inúmeras consequências relacionadas à exploração inadequada ou exploratória do Geopatrimônio, embora ainda não seja muito documentada devido a percepção errônea de que o Geopatrimônio não necessita de proteção pois é imutável (CROFTS & GORDON, 2015; MATSHUSA & LEONARD, 2023). Algumas das ameaças e pressões sofridas pelo Geopatrimônio são a urbanização, construção civil, mineração, mudanças no uso da terra, mudanças climáticas e outras atividades antropogênicas (BRUSCHI & CORATZA, 2018; CROFTS & GORDON, 2015; CROFTS et al., 2021; GORDON et al., 2022; MATSHUSA & LEONARD, 2023).

Nesse sentido, é fundamental que haja estratégias fundamentadas em conceitos científicos sólidos para a proteção do Geopatrimônio. Por exemplo, a utilização de métodos de geoconservação permitem a identificação, gestão e conservação dos recursos naturais relacionados ao meio abiótico (FASSOULAS et al., 2012; SANTOS et al., 2020; SELMI et al., 2019), promovendo o equilíbrio entre a sociedade e a natureza através do desenvolvimento sustentável (BRILHA, 2017; HENRIQUES et al., 2011; NETO & HENRIQUES, 2022).

Como mencionado anteriormente, a geoconservação pode ser utilizada como um dos princípios para a preservação da biodiversidade e conservação dos habitats (CROFTS, 2019). A proteção dos elementos abióticos contribui para a manutenção dos ecossistemas (GARCIA et al., 2022), podendo ser um conceito-chave para manter a diversidade biológica existente de um determinado local. Nesse contexto, é necessário que áreas protegidas já instituídas ou em processo de implantação devam considerar tantoo meio biótico quanto o abiótico (BRILHA, 2002).

Ao considerarmos a importância da proteção do geopatrimônio, destaca-se que as mudanças climáticas representam um desafio significativo (BRAZIER et al., 2012; GORDON et al., 2022; PROSSER, 2010). As mudanças climáticas causam a perturbação do sistema terrestre – incluindo ecossistemas e geossistemas – e vice-versa (FIELD et al., 2007; LEVINE et al., 2016; PIELKE et al., 1998; POST, 2013; WALKER et al., 1997), com o aumento generalizado das temperaturas globais, resultando em perda de biodiversidade (IPCC, 2022), mudanças na paisagem (OPDAM & WASCHER, 2004; WOBUS et al., 2010) e em aumento da frequência e intensidade de eventos climáticos extremos, como tempestades, estiagens prolongadas e ondas de calor (IPCC, 2023; MEEHL et al., 2000; MEEHL & TEBALDI, 2004; SMITH, 2011; TRENBERTH et al., 2015).

As mudanças climáticas podem afetar os geossítios de diversas formas, principalmente em alterações nos em processos geomorfológicos – ligados tanto a hidrosfera e a criosfera – e em cobertura do solo (GORDON et al., 2022a; GORDON et al., 2022b). Em um mundo em que o clima está se alterando, a paisagem e a geodiversidade será alvo de grande modificação. Geossítios expostos podem sofrer com intemperismo com maior magnitude, considerando temperaturas, chuvas mais intensas (incluindo inundações) e períodos de estiagem. Com o aumento do nível do mar, geossítios localizados em zonas costeiras podem desaparecer. Geossítios ligados aos sistemas fluviais ou marítimos podem sofrer com mudanças geomorfológicas, principalmente relacionadas ao aumento do nível do mar e enchentes de rios, além do aumento da erosão (GORDON et al., 2022a; PROSSER et al., 2010).

Diante desses impactos, torna-se cada vez mais crucial a adoção de medidas de geoconservação em um contexto de mudanças climáticas (GORDON et al., 2022b). A pesquisa e monitoramento contínuos sobre impactos das mudanças climáticas sobre o Geopatrimônio devem ser realizadas com afinco, a fim de orientar a tomada de decisões e políticas públicas para garantir o acesso das futuras gerações ao Geopatrimônio.

As montanhas, como elementos do Geopatrimônio, são de particular importância e sensibilidade às mudanças climáticas (BENISTON, 2003; BENISTON, 2005; RANGWALA & MILLER, 2012), requerendo uma atenção especial devido a sua significância única e complexa em termos de valor geológico, biológico, cultural, cênico, educacional, científico e recreativo. Montanhas, também chamadas de torres de água, são responsáveis pela regulação dos fluxos de água (VIVIROLI et al., 2007; VIVIROLI & WEINGARTNER, 2008) e pela manutenção da biodiversidade local (ANTONELLI et al., 2018; PERRIGO et al., 2019; RAHBEK et al., 2019). Nesse sentido, as montanhas conseguem englobar relevância tanto para o meio abiótico quanto para o meio abiótico.

Embora haja um número significativo de estudos sobre a Cordilheira dos Andes, a maioria desses estudos não aborda sua relevância enquanto geopatrimônio. Os Andes possuem uma importância primordial para o fluxo hidrológico da parte tropical da América do Sul, desempenhando, através dos seus nevados, a capacidade de armazenar água em neve e gelo e liberar gradualmente a água ao longo do ano, dependendo da estação do ano (BARNETT et al., 2005; COUDRAIN et al., 2005; RANGECROFT et al., 2013; RODRIGUEZ et al., 2016).

As montanhas possuem relações estreitas com o fluxo de água de diversas bacias hidrográficas do mundo (IMMERZEEL et al., 2019; VIVIROLI & WEINGARTNER, 2004; VIVIROLI & WEINGARTNER, 2008), como os Himalaias no continente asiático (BOLCH et al., 2012; KEHRWALD et al. 2008; IMMERZEEL et al., 2010; PRASCH et al., 2013); as Montanhas de Rwenzori e Atlas no continente africano (BOULDAR et al., 2009; EGGERMONT et al., 2009; SCHULZ & JONG, 2004; TAYLOR et al., 2009); as Montanhas Rochosas na América do Norte (CASTELLAZZI et al., 2019; HOPKINSON

& DEMUTH, 2006; INTSIFUL & AMBINAKUDIGE, 2021; LUCE, 2017; MARSHALL, 2014); os Alpes, localizados na Europa (CHEN & OHMURA, 1990; COLLINS, 1979; DIOLAIUTI et al., 2006; HUSS, 2011; VANHAM, 2012); entre outros.

Além disso, o sistema complexo existente nas montanhas contribui para a captura de dióxido de carbono e outros gases do efeito estufa na atmosfera (MAES et al., 2013; PADILLA et al., 2010; SIL et al., 2017; WARD et al., 2019; ZHIYANSKI et al., 2016). A vegetação existente em montanhas atua como um regulador da qualidade da água, pois essas vegetações conseguem reter sedimentos e outros poluentes (CALDER et al., 2008; LINIGER & WEINGARTNER, 2000; ŠACH et al., 2014).

Considerados ambientes extremos devido a elevada altitude e baixas temperaturas (FATTORINI et al., 2020), as montanhas possuem grande geodiversidade e biodiversidade. Por causa disso, as montanhas são áreas de grande relevância biótica, visto que conseguem abrigar diversas espécies de fauna e flora, muitas vezes endêmicas (KÖRNER, 2004; PERRIGO et al., 2020; RAHBEK et al., 2019). A geoconservação de montanhas no âmbito do geopatrimônio consegue atuar para a preservação tanto da biodiversidade quanto a geodiversidade. Nesse sentido, a geoconservação atua também em prol da biodiversidade, garantindo a continuidade dessas espécies e o seus geossistemas (HJORT et al., 2015; SCHRODT et al., 2019; TUKIAINEN et al., 2017; ZARNETSKE et al., 2019).

As montanhas, por serem percebidas como imutáveis por observadores desavisados, muitas vezes são vistas como um ambiente simples que não estão em risco de degradação (BLYTH, 2002). Pelo contrário, as áreas montanhosas estão em ameaça crescente por serem frágeis (ECKHOLM, 1975; ZURICK et al., 1999), principalmente por serem sensíveis às mudanças climáticas (BENISTON, 2003; KOHLER, 2010; PAULI et al., 1996; VIVIROLI et al., 2011).

No âmbito das áreas montanhosas, um elemento de destaque são os nevados. Os nevados são os principais reguladores de água no que diz respeito às montanhas, já que são os principais receptores, armazenadores e distribuidores de água de bacias hidrográficas (IMMERZEEL et al., 2010; HUSS & HOCK, 2018; SCHMALE et al., 2017; VIVIROLI et al., 2007). Os nevados são corpos de água extremamente sensíveis, visto que alterações na temperatura e precipitação podem gerar desequilíbrio em seu regime hidrológico (RADIĆ & HOCK, 2011).

Os nevados são elementos geográficos localizados em picos de montanhas permanentemente cobertos com neve ou gelo, sendo essenciais para a regulação das bacias hidrográficas (NESJE et al., 2008; OWEN et al., 2009). A relevância desses nevados se encontra na capacidade de armazenamento e distribuição de água, no qual é gradualmente liberada nos meses mais secos, abastecendo rios e lagos em regiões à jusante das regiões montanhosas (IMMERZEEL et al., 2009; IMMERZEEL et al., 2010; MARK et al., 2017; STAHL et al., 2008).

Devido as mudanças climáticas, os nevados estão sofrendo um grande risco de serem extintos (DYURGEROV, 2005; ZEMP et al., 2006). Como elementos geográficos sensíveis, temperaturas mais elevadas fazem com que haja um derretimento da neve e do gelo com mais frequência e intensidade (THOMPSON et al., 2011). A partir do rápido derretimento de neve, pode haver consequências à jusante das bacias hidrográficas relacionadas aos nevados, como a rápida elevação do volume de água dos rios, gerando riscos de inundações, e, a longo prazo, a diminuição do volume d’água (BARAER et al., 2012; BRADLEY et al., 2006; HOCK, 2005; STAHL et al., 2008).

Além de serem afetados pelas mudanças climáticas, o declínio dos nevados pode intensificar as mudanças climáticas. Isso porque a neve e o gelo possuem efeito sobre o clima através de mecanismos de feedback, por exemplo, o albedo elevado da neve tem como consequência a alta reflexão da radiação solar de volta para a atmosfera sem haver uma absorção terrestre significativa (HOCK et al., 2005). Sem a cobertura de neve, a incidência solar irá ser absorvida pela Terra, podendo impactar o clima global e acelerar o derretimento dos nevados (ZHANG et al., 2021). Indo além, os nevados também são responsáveis pelo ciclo do carbono terrestre, fazendo com que eles sejam cruciais para o clima (GAILLARDET & GALY, 2008; HOOD et al., 2015).

Os nevados possuem características abióticas particularmente únicas em qualquer lugar do mundo (CEBALLOS et al., 2006; KASER et al., 2005). Isso se dá pela grande geodiversidade presente nos nevados, tais como elementos geomorfológicos, pedológicos, geológicos, petrográficos, mineralógicos, entre outros, que se tornam relevantes e possuem grande potencial para o Geopatrimônio (BOLATTI et al., 2023; GORDON, 2018). No que diz respeito à história e evolução da Terra, os nevados podem possuir registros de milhares de anos sobre aspectos do clima e atmosfera (BERTLER et al., 2017; HEISTERKAMP et al., 1999; LEGRAND & DELMAS, 1986). Socialmente, os nevados possuem relevância cênica, educacional, turística e cultural (CAREY, 2007;

CARRIÓN-MERO et al., 2021; CORONATO et al., 2021; DOWNLING & NEWSOME, 2018). Indo além, a conservação torna-se crucial a partir do momento em que é entendido que os nevados são responsáveis pelo abastecimento de pelo menos 10% das bacias hidrográficas da Terra (SCHANER et al., 2012).

No entanto, necessário compreender que apenas utilizar estratégias de geoconservação para os nevados não é, por si só, eficiente. É preciso que existam políticas públicas que mitiguem com urgência os efeitos das mudanças climáticas e que haja uma redução significativa de gases traços na atmosfera, visto que os nevados são extremamente sensíveis às mudanças climáticas (BACH et al., 2018; GERBAUX et al., 2005; YANG et al., 2015).

A preservação dos nevados no âmbito do Geopatrimônio é uma questão urgente para a comunidade científica e para a sociedade como um todo. O Geopatrimônio compreende um vasto conjunto de recursos naturais que se relacionam, de uma forma ou outra, com a cultura. Os elementos abióticos encontrados em nevados e sua formação da paisagem possuem, como consequência, uma potencialidade gigantesca para o Geopatrimônio, que podem contribuir para o entendimento da evolução da Terra e para a mitigação dos efeitos das mudanças climáticas.

A motivação do presente estudo surgiu com base na relevância dos nevados, principalmente no continente da América do Sul – local uma grande disponibiliudade de recursos hídricos. Ao perceber as características abióticas únicas que os nevados possuem, foi possível investigar a potencialidade dos nevados para o Geopatrimônio, focando na necessidade de protegê-los em um contexto cada vez mais intenso de mudanças climáticas.

Nesse contexto, os nevados são importantes corpos geográficos localizados nos topos de montanhas, continuamente cobertos por gelo e neve e sendo nascentes para bacias hidrográficas importantes para a América do Sul. Essas regiões apresentam características geológicas, geomorfológicas, mineralógicas, litológicas, glaciais e climáticas únicas (BOLATTI et al., 2023; CEBALLOS et al., 2006; GORDON, 2018; KASER et al., 2005), que tornam os nevados uma rica fonte de estudo e compreensão do sistema terrestre. Nesse sentido, os nevados possuem características abióticas e bióticas únicas, tornando-os elementos com alto valor para o Geopatrimônio.

O estudo dos nevados nos Andes da América do Sul como Geopatrimônio é relevante por várias razões. Em primeiro lugar, a compreensão das características geológicas e glaciais dos nevados pode fornecer *insights* importantes sobre a evolução do clima e do ambiente ao longo do tempo, bem como sobre as mudanças ambientais atuais e futuras. Além disso, o estudo dos nevados como Geopatrimônio pode contribuir para a conservação dessas áreas, promovendo a conscientização pública e a valorização do patrimônio natural e cultural dos Andes.

Assim, justificativa desta pesquisa se concentra na importância da contribuição para o conhecimento científico dos nevados dos Andes da América do Sul como Geopatrimônio, e nas possíveis aplicações práticas desse conhecimento para a conservação, educação e valorização cultural das áreas de estudo. Também chama atenção para o olhar geográfico sobre os nevados tropicais.

A pesquisa proposta pode desempenhar um papel fundamental na identificação dos nevados mais sensíveis aos efeitos das mudanças climáticas. Por meio da análise de dados geológicos, glaciais e climáticos, é possível avaliar a vulnerabilidade dos nevados às mudanças ambientais, como o aumento da temperatura média, a diminuição do volume de gelo e neve, e as alterações no regime de chuvas e precipitações. Com base nessa análise, a pesquisa pode contribuir para identificar quais nevados estão enfrentando os maiores impactos e são mais suscetíveis às mudanças climáticas, tornando-se, assim, áreas prioritárias para ações de geoconservação.

Com base nos resultados da pesquisa, é possível priorizar os nevados mais sensíveis. A identificação dessas áreas pode auxiliar na definição de estratégias de conservação e gerenciamento eficazes, que busquem mitigar os impactos das mudanças climáticas e proteger os valores geológicos, glaciais e culturais desses nevados. As informações obtidas pela pesquisa podem subsidiar a tomada de decisão em relação à alocação de recursos e esforços de conservação, direcionando-os para as áreas que enfrentam as maiores ameaças e que possuem maior necessidade de proteção.

Os resultados da pesquisa podem também contribuir para o desenvolvimento de políticas de conservação e adaptação às mudanças climáticas em âmbito regional e global. Ao fornecer informações detalhadas sobre a sensibilidade dos nevados aos efeitos das mudanças climáticas, a pesquisa pode embasar a elaboração de estratégias de conservação integradas e a implementação de medidas de adaptação que levem em consideração as particularidades desses ambientes únicos. Dessa forma, a pesquisa pode ter um impacto significativo na formulação de políticas públicas voltadas para a geoconservação dos nevados, contribuindo para a proteção desses importantes patrimônios naturais e culturais.

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ORIGINAL ARTICLE

The Relevance of the South American Nevados for Geoheritage

Gabriella Emilly Pessoa[1] · Valdir Adilson Steinke[1]

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Abstract

Geoheritageis a crucial concept for preserving outstanding landforms and abiotic elements. Water, among others, plays a significant role in geoheritage because it is a transformative element of the landscape and is essential for life on Earth. Considering the significance of water, this research presents an innovative geoheritage site: the Nevados. Located on mountain peaks, the Nevados consist of ice and snow that provide water downstream during the melting season and serve as both dividers and connectors of hydrographic basins. Due to their relevance and vulnerability, they represent important geosites for geoheritage. South American Nevados were evaluated using statistical geospatial correlations of variables and geoprocessing tools, resulting in a determination of which Nevados should be prioritised for geoheritage. The Randolph Glacier Inventory was used to determine the location of the Nevados. Three groups of variables were assembled: the first was concerned with geological elements, the second with geomorphological elements, and the third with environmental variables. Following the grouping of these characteristics, a statistical correlation was performed using the Moran's index via an analysis matrix. This showed that the Nevados at low latitudes had the highest geoheritage value, while those at southern high latitudes had a lower geoheritage value. These findings suggest that Nevados should be included in geoheritage and geoconservation efforts.

Keywords The Andes · Mountain range · Geodiversity · Geosystem · Geobiodiversity

Introduction

Geoheritage is a growing subject among the topics studied by geoscientists. The discussion of geoconservation concepts, methods, and strategies sheds light on the promotion of a heritage perspective of natural abiotic elements, referred to as geodiversity (Sharples 1993; Gray 2004). The way that geodiversity is currently being preserved will leave a legacy for future generations, allowing them to learn about Earth's history and experience geosites.

By expanding the scope of the heritage concept, geodiversity elements with exceptional characteristics have been assigned the designation of geological and geomorphological heritage. They have recently been attributed the designation of geoheritage, which is a synonym for the set of geodiversity elements that present a significant societal value (Sharples 2002; Gray 2004).

In any case, abiotic element heritage appreciation should be based on three fundamental aspects. The first aspect is geoknowledge, which translates into essential research for the scientific knowledge of geodiversity elements and their evaluation from a heritage standpoint. The second aspect is geoconservation, which is concerned with developing strategies and implementing protection and conservation measures. Lastly, the aspect of geopromotion supports the promotion and scientific dissemination of geoheritage (Vieira and Steinke 2021).

According to Pereira (2006), the conservation of geoheritage is constantly hampered by a lack of appreciation in the face of the appreciation of biological components. This is clearly illustrated by the large number of conservation areas destined for biodiversity protection (protected areas or other effective area-based conservation measures cover 16.64% of land and inland waters and 7.74% of coastal waters) versus the number of areas destined for geodiversity (177 UNESCO Global Geoparks) (Bingham et al. 2021; UNESCO 2021). Consequently, the lack of legislative protection for geoheritage endangers

Gabriella Emilly Pessoa
gabriellaemilly@gmail.com

Valdir Adilson Steinke
valdirsteinke@gmail.com

[1] Department of Geography, University of Brasília, Brasília, Brazil

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biodiversity and ecosystem functioning (Crofts 2019). Better methods of geoconservation therefore require a deeper comprehension of geoheritage.

New geoconservation strategies are required since environmental degradation is unprecedent in Earth's history. As a result of the pressure caused by economic growth, which depletes finite natural resources, the deterioration of nature has become a continuous source of concern. International organisations, non-governmental organisations, and individuals have all become involved in significant conservation efforts. However, these actions are more likely to focus primarily on biodiversity (Crofts 2014).

Biodiversity and geodiversity are complementary concepts. Because all life on Earth is inextricably linked with abiotic elements, geoconservation is critical for biodiversity conservation (Rivas et al. 1997; Wimbledon et al. 2001; Anderson and Ferree 2010; Gray 2011; Németh et al. 2021). There can be no proper conservation of a habitat if it is not conserved because all systems on the planet are interconnected in a holistic, systematic way (Wimbledon 1996; Fassoulas et al. 2012; Gray et al. 2013).

The discussion of concepts, methodologies, and strategies for nature conservation and geoconservation have also resulted in the promotion of a heritage perspective on these nature abiotic elements, referred to collectively as "geodiversity elements" (Sharples 1993; Gray 2004). With the expansion of the concept of heritage, those geodiversity elements with exceptional characteristics have been designated as geological heritage or geomorphological heritage, depending on the focus of the study area.

Over the years, the concept of geodiversity has been defined by numerous researchers (Sharples 1993; Duff 1994; Nieto 2001; Gray 2004, 2008, 2013, 2018; Panizza 2001; Panizza and Piacente 2008; Panizza 2009; Hjort and Luoto 2012; Brilha et al. 2018). Although several scientists and scholars, notably geologists, endorse this concept, it does not rule out new approaches or future breakthroughs in terms of conceptual formulation. Forte (2014) provided an excellent state of the art on this concept. Ultimately, geodiversity can apply to a variety of geological characteristics (rocks, minerals, geological structure, and fossils), geomorphological features (landscapes, topography, and physical processes), soils, and hydrological characteristics.

Contrary to what some studies claim, the concept of geoheritage should not be confused with that of geological or geomorphological heritage. Geological heritage can only be applied to the Earth's structure, processes, and what lies beneath the planet's surface. The same is true for geomorphological heritage, which can only be applied to describe the origin and evolution of topographic and bathymetric features. Geoheritage is a broader concept that encompasses many scientific fields concerning the Earth, including cultural value — an anthropological and sociological concept. Thus, "geo" does not refer to "geology", but rather to the Greek word "*gē*", which means "Earth".

This distinction is essential to build a more integrated scientific community that works collaboratively across disciplines to better understand and strengthen geoconservation strategies. Geoheritage can thus be regarded as a component of a larger and more complex system known as the geosystem.

Geoheritage, like many other systems around the world, is not limited by national boundaries. Geoconservation must therefore become an international responsibility, as many geosites can be of national, regional, or global significance (Wimbledon 1996; Wimbledon et al. 2001).

While proposing the term "Nevados", which emphasises the importance of mountain snowmelt headwaters, this research aims to analyse the hydrological geoheritage of Andean Nevados, providing a new paradigm for hydrological geoheritage sites. In this context, we will demonstrate the importance of South America's Nevados as primary water sources on the continent, better understand their potential and vulnerabilities, and advocate for the importance of preserving their geoheritage. Therefore, this study will present how Nevados can be assessed for geoheritage protection around the globe.

Background

Numerous geosites worldwide are threatened by human activity (Gray 2004, 2008; Brilha 2016; Németh et al. 2021). Geosites must be preserved considering the length of time it takes to form geological, geomorphological, pedological, and hydrological sites. This effort is required so that geoscientists can better understand the evolution of the Earth and how society can relate to geoheritage. This can benefit both current and future generations by improving economic sustainability, and promoting scientific progress and conservation (Wimbledon 1996; Coratza and Giusti 2005; Brilha 2016).

Geodiversity is defined by the diversity of abiotic elements. There is no comparable planet in the Solar System with such geodiversity (Gray 2008; Brilha 2016). The intricate system of the Earth explains this geodiversity because the lithosphere, atmosphere, cryosphere, biosphere, and pedosphere are all interconnected. Although human activities have accelerated most processes, particularly after the first Industrial Revolution, natural changes have occurred and will continue to occur.

Rocks consist of a complex variety of minerals that support multiple soils and geomorphological formations (Gray 2008, 2011), resulting in complex and diverse landscapes as a result of Earth's dynamic system. Geoconservation is required to conserve nature on many scales and to ensure human well-being (Brilha 2018) due to its complexity and high risk of deterioration (Gray 2011). Therefore, public policies are essential for safeguarding geodiversity (Booth and Brayson 2011; Crofts 2018; Gordon et al. 2021).

Ecosystem and geosystem services are comparable (Gray 2008, 2011). Geosystem services have geodiversity materials that can provide goods and services to life, such as knowledge about the Earth's evolution and the regulation of many physical processes, as well as supporting life and culture, and supplying construction materials and products (Gray 2008, 2011). Moreover, some ecosystem and geosystem services are facilitated by the action of biotic and abiotic factors and are referred to as "nature services" (Gray 2011; Fassoulas et al. 2012).

Geoheritage is described as comprising natural and social features that have high scientific, educational, cultural, and aesthetic values associated with geological, pedological, hydrological, and geomorphological structures (Panizza 2001; Brocx and Semeniuk 2007; Pereira et al. 2007; Reynard et al. 2007; Fassoulas et al. 2012; Geological Society of America 2022).

When it comes to research, the quality of the selection of geosites will be guaranteed by certain parameters. In other words, geosites may consist of remarkable and/or representative locations that describe the evolution of life on Earth, including its processes, periods, and events that have occurred (Wimbledon 1996). The main task is to assess the rarity of the geosite and systematically inventory the geosite's valuable variables in order to manage and plan the development of those locations while protecting them from deterioration (Prosser et al. 2006; Štrba et al. 2015; Brilha 2018; Ruban et al. 2021; Wolniewicz 2021). In this context, geosites must have distinguishing geological characteristics. To be considered geoheritage, years of work and research are needed to thoroughly investigate the unique characteristics of an assessed geosite (Ruban et al. 2021).

According to Bruschi and Cendrero (2005), having defined criteria for recognising and protecting geosites is paramount. As stated by the abovementioned authors, these parameters require a scientific consensus as a form of safeguarding against stakeholder groups. Therefore, geoconservation can be accomplished by utilising number indices to confirm geoheritage sites and to achieve a scientific consensus (Bruschi and Cendrero 2005; Tlhapiso and Stephens 2020; Zwoliński et al. 2018).

Numerous authors have contributed to establishing quantitative methods for assessing and inventorying geoheritage (e.g. Rivas et al. 1997; Panizza 2001; Bruschi and Cendrero 2005; Coratza and Giusti 2005; Pralong 2005; Serrano and González-Trueba 2005; Pereira et al. 2007; Reynard et al. 2007; Bruschi et al. 2011; Fassoulas et al. 2012). Such efforts were made to reduce subjectivity in geoheritage assessments and inventorying, with value scores proposed for both geosites and geomorphosites (Rivas et al. 1997; Štrba et al. 2015).

A successful inventory must establish four goals: the topic, the value, the scale, and the aim (Lima et al. 2010; Brilha 2018). It is vital to remember that geosites are not static, and thus their respective inventories should not be either; they will require updates (Martin et al. 2014).

Comparing certain quantitative methods, Štrba et al. (2015) affirmed that different applied methods would yield different results, which could lead to a debate concerning whether methods for assessing geoheritage are of high quality and accuracy. Geosites, on the other hand, require a geoconservation strategy based on their characterisation, relevance, protection, conservation, valuation, interpretation, and monitoring (Lima et al. 2010).

Furthermore, qualitative methods or methods that combine qualitative and quantitative data have been developed to assist geoheritage scientists (White and Wakelin King 2014). The foundation of qualitative methods is the description of geosites and geomorphosites (Štrba et al. 2015). The main objective of geoheritage inventories and assessments, for both methods, is to conserve and utilise it by disseminating knowledge and promoting long-term sustainable economic growth (Filocamo et al. 2019).

Considerable efforts are being made to hold the global community accountable for geoconservation. The Joint Nature Conservation Committee (JNCC) created a procedure called the Geological Conservation Review (GCR) in the 1970s, which was one of the first movements to promote geodiversity conservation. This procedure aids in identifying areas of interest with a distinctive geology or geomorphology, especially in the UK (JNCC 2020).

This approach was a part of a larger global movement known as the "environmental revolution", which gained societal attention in the 1960s. This change increased in the 1970s, culminating in the 1972 Stockholm United Nations Conference on the Human Environment. In the same year, UNESCO hosted the Protection of the World Cultural and Natural Heritage conference in Paris. A committee and a fund for world heritage were then established in 1976 (Badman et al. 2005). The International Declaration of the Rights of the Memory of the Earth was promulgated in 1991, stating unequivocally that geoheritage is a human right and it is society's responsibility to preserve it.

The International Association for the Conservation of Geological Heritage (ProGEO) was founded in 1993 to conserve geosites in Europe (ProGEO 2021). ProGEO has since evolved into one of the greatest geoconservation agencies in the world, demonstrating the relevance of geoconservation for present and future generations through the scientific method. The action of ProGEO resulted in the inventory of European geoheritage, and consequently, the Global Geosites Working Group (GGWG) of the International Union of Geological Sciences (IUGS) was formed in 1995 as part of the Geosites Programme created 2 years earlier with the support of UNESCO (IUGS 2013). As a result, the GGWG was responsible for the majority of geoheritage inventories and assessments in Europe (Díaz-Martínez et al. 2015).

The Regionally Impor t ant Geological and Geomorphological Sites (RIGS) method for identifying geodiversity sites was developed and predominantly applied in the UK in the 1990s. The RIGS, unlike the GCR process, is not legally protected (Government Digital Service 2022a, b) but it has nonetheless increased geoconservation activity (Burek and Prosser 2008).

One of the most important environmental and sustainable development conventions took place in Rio de Janeiro, Brazil, in 1992. The Earth Summit convention declared the value of mountains to society and the global ecosystem, recognising mountains as vulnerable ecosystems. In this sense, mountains provide multiple uses such as providing water, energy, biodiversity, minerals, nature services, leisure, and habitats for endangered species (United Nations Conference on Environment and Development 1992).

Aside from the methods and concepts developed, geoheritage studies achieved several milestones in the 1990s, especially after UNESCO's Geopark initiative in 1999 (Wimbledon et al. 2000; Jones 2008). Members of the United Nations Educational, Scientific and Cultural Organization (UNESCO) approved a new label called "UNESCO Global Geoparks", ratifying a 2001 proposal. UNESCO currently recognises 177 geoparks in 46 countries (UNESCO 2021).

Geoparks are defined areas that protect geosites and, consequently, geoheritage. In this sense, a geopark contains significant geofeatures and is responsible for promoting and protecting geoheritage while also supporting sustainable economic development and growth, mainly through geotourism (Zouros 2004; McKeever and Zouros 2005; Jones 2008). Due to the restrictive nature of the World Nature Heritage List, geoparks have emerged as a viable alternative for geoconservation areas (Eder and Patzak 2004; Jones 2008).

Geoconservation is significantly more prevalent in Europe, where concern and discussion about geoheritage conservation first originated. Aside from that, numerous efforts have been made to assess and inventory geosites on this continent, most notably through the European Geoparks Network in 2000. However, discussions about geoheritage and geoconservation are rising in popularity around the world, with a relevant number of geoparks being created in several countries with UNESCO's support and under the European Geoparks Network.

Geotourism is now practised in the majority of geoparks as a cultural response to the landscape (Gordon 2018). Geoparks enhance not only a geosite's protection but also that of geosystems. In other words, geoparks aid in the conservation of fauna, flora, and geofeatures while also encouraging economic development and educating visitors (Serrano and González-Trueba 2011; Tessema et al. 2021).

Water is a major catalyst in landscapes and, as a result, one of the most important elements of geotourism. Watersheds with mountain headwaters are even more crucial since they supply water to approximately 40% of the world's population, with snowmelt supplying water to half of the world's population (Rasul and Molden 2019). Water is associated with natural and anthropogenic processes at various spatial and temporal scales. Furthermore, because of their modelling force and coverage of a specialised, complex, and temporally changing ecosystem, rivers serve as the major geomorphic agents of landscapes (Howard 1967; Suguio 2003).

Mountains, in addition to being an essential water source, have high biodiversity and geodiversity values due to snow and ice in the soil, which cause sharp transitions and rapid changes. Mountains also have high cultural and economic values due to the large number of visitors seeking tourism and recreation (Beniston 2003).

Mountains are formed by the convergence of tectonic plates. They are the result of a unique process known as orogeny, which can lead to the formation of orogenic belts. Mountains all over the world will host unique occurrences of geology, topography, geomorphology, climate, biodiversity, culture, and socioeconomic significance. Mountains are extremely vulnerable to climate change and are home to one of the most important formations for life on Earth: the Nevados.

Because mountains are more sensitive to changes in temperature than terrestrial habitats, climate change is a major contributor to their deterioration (Wang et al. 2021; United Nations Framework Convention on Climate Change 2022). Mountains are also threatened by deforestation, livestock overgrazing, and cultivation on soils with limited reservoirs of nutrients and water available for native plants. Mountains are also vulnerable to soil erosion and landslides as a result of habitat deterioration, endangering their biodiversity (Beniston 2003).

For these reasons, and owing to their high educational and scenic values, mountains are a popular topic in geoheritage studies (Reynard and Coratza 2016). The high geodiversity and value to geotourism of the Apennines have been highlighted by Filocamo et al. (2019). Bollati et al. (2018) investigated the Alps and the Apennines, both in Italy, and their uses for education and recreation, while Reynard and Coratza (2016) investigated the

Italian Dolomites and the Swiss Alps, demonstrating the importance of mountain regions for environmental education. Panizza (2009) also examined the Italian Dolomites, emphasising their geodiversity. Feuillet and Sourp (2011) assessed the geomorphological heritage of the Pyrenees and their touristic value. In turn, Chlachula (2020) evidenced the geodiversity of East Kazakhstan by highlighting the presence of numerous mountains in the country. Triglav et al. (2020) investigated the importance for geoheritage science of very small glaciers located in Slovenian mountains. Finally, Ortega-Becerril et al. (2019) studied the geoheritage value of waterfalls in the Parque Nacional de Ordesa and Monte Perdido in Spain; waterfalls are typically located in mountainous regions with turbulent watercourses.

Nevados

Nevados are found at high elevations on mountain peaks. During the summer, ice and snow melt and drain into a drainage basin, making up the majority of mountain headwaters. Although melting is an important part of the dynamics of Nevados, they have a permanent cover of snow and ice. The terms "Nevado" and "mountain glacier" are easily confused. Mountain glaciers are glaciers that form on mountain slopes but do not flow into the main river (Bajracharya et al. 2019). Like Nevados, they require frequent snowfalls that accumulate and do not melt completely (Elias et al. 2021). One of the world's largest Nevados can be found in the South American Andes Mountain Range, also known as the Andean Cordillera (National Snow and Ice Data Ceneter 2022).

Nevados are essential for water storage and streamflow (Schaner et al. 2012). They not only provide fresh water for animals and humans but are also associated with an economic factor. Water powers numerous drainage systems and hydropower plants. Also, water is the main factor for flood forecasting, controlling sea-level fluctuations, sediment transport, nutrient transport, and sculpting landscapes (Jansson et al. 2003; Viviroli et al. 2007; Kaser et al. 2010; Immerzeel et al. 2020).

Nevados are important indicators of climate change since they are sensitive to changes in temperature and precipitation patterns. As a result of this sensitivity, the size of Nevados can decrease due to alterations in maximum and minimum snow accumulation (Barnett et al. 2005; Zemp et al. 2015; Duan et al. 2019). Changing precipitation patterns influence runoff volumes, while temperature changes influence when runoff occurs (Barnett et al. 2005). As the size of Nevados diminishes, water that should have been stored for autumn and summer is released during the spring or winter due to melting (Nijssen et al. 2001; Barnett et al. 2005; Duan et al. 2019). Given the foregoing, rising global air temperatures will affect how water is supplied around the world, particularly in areas where populations rely on snow-melted water (Barnett et al. 2005). Consequently, since Nevados are important water sources, they require special attention.

While useful for protecting mountains from local disturbances and educating people about Earth's history and geoheritage, geoparks are less effective in protecting Nevados. Nevados are determined by climate, geology, and geomorphology, and they provide numerous benefits to life. Fortunately, anthropogenic actions have a much lower impact on geology. Human activities, on the other hand, can have disastrous consequences for climate and geomorphology. Most Nevados may become extinct due to climate change (Beniston et al. 2018; Adler et al. 2019; D'Agata et al. 2020; Ding et al. 2019). Erosion can occur more easily and quickly as snowmelt runoff increases. Thus, the only way to protect Nevados goes beyond the foundation of geoparks: immediate action on climate change is required.

Study Area

The Andean Mountains were chosen as the study area because of their geological and geomorphological relevance. As the world's largest mountain range, the Andean Cordillera can be used as a natural laboratory to better understand and preserve geoheritage. Thus, in this study, this mountain range will be used as an example to demonstrate why the Nevados must be protected through the lens of geoheritage (Fig. 1). Having said that, it is worth noting that Nevados can be found in various mountain ranges around the world, each with its own geoheritage significance.

The motivation to investigate the Andean Nevados stems from their enormous importance for South America in every aspect. From the enormity of their geological genesis to millenary cultural interactions, passing through key pedological, geomorphological, hydrological, and biogeographic characteristics, the Andes are an open-air laboratory. Observing the Nevados situated on the peaks of South America's mountains helps investigate the processes behind the origin and evolution of this continent's landscapes.

The Andean orogenic system is part of the evolving Gondwana peri-cratonic belt (Frutos 1990). This mountain range is divided into three major unit sections according to geological differences and locations: the northern Andes (Colombia, Venezuela, and Ecuador), the central Andes (Bolivia, Colombia, Ecuador, and Peru), and the southern Andes (Argentina and Chile). The tectonic plates and the climate in the region are inextricably linked (Ramos and

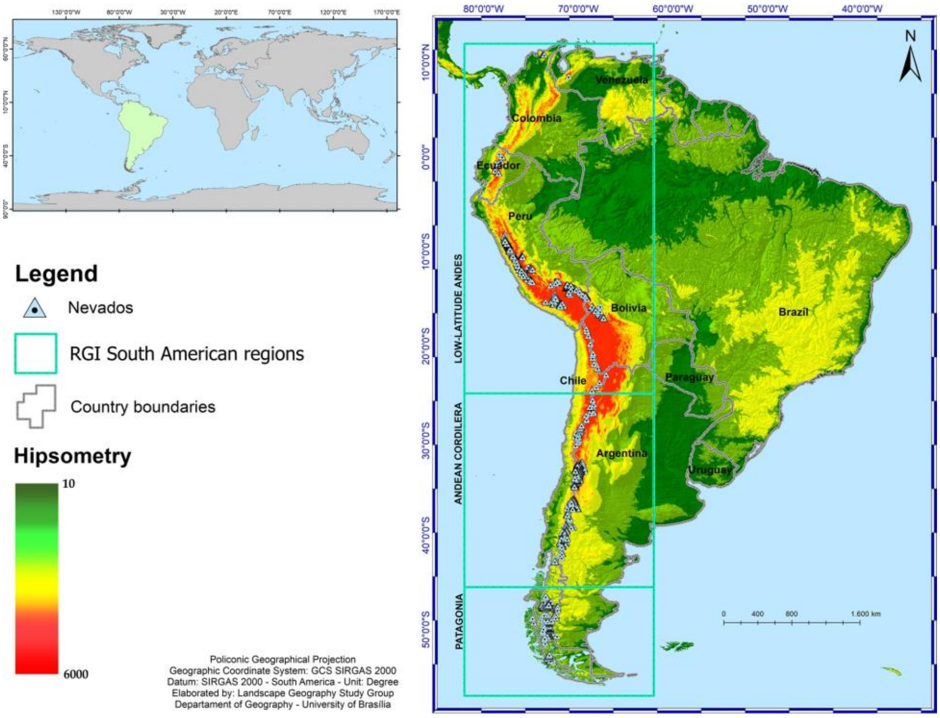


Fig. 1 Location of the Andean Mountain Range

Ghiglione 2008). The Andean Mountain Range extends over 8000 km between 12° N and 56° S (Orme 2007). The Andes must be protected through the lens of geoheritage because they contain the most complete records of geological history (Frutos 1990). Aside from that, the mountains serve as an open-air laboratory for the Earth sciences (Ramos 1999).

The Andean Cordillera was formed by four major geologic events: first, the accretion, amalgamation, and collision of terranes against the Gondwana margin occurred during the Proterozoic; second, the Gondwanides were formed through orogeny and the Alleghanian orogeny during the late Paleozoic, with terrane accretion and episodic subduction; third, the breakup of Pangea was accompanied by island arc collisions and batholith emplacement; and finally, in the late Mesozoic and Cenozoic, oceanic terranes were subducted beneath the South American plate, resulting in the closure of the trans-Andean seaways (Aleman and Ramos 2000).

The Andean Mountains are flanked at their margins by the convergence of two major tectonic plates: the Nazca oceanic tectonic plate and the South American continental tectonic plate. This convergence movement began during the Mesozoic period. The Nazca tectonic plate moves south-eastward, subducting beneath the South American Plate along the Peru–Chile Trench, while the continental plate moves westward.

In some parts of the continent, the subduction zone consists of a Wadati-Benioff zone (WBZ) (Barazangi and Isacks 1979; Engdahl et al. 1998; Taboada et al. 2000), which is an approximated plane with dips of at least 30° that generates earthquake hypocentres. According to Munoz (2005), the majority of WBZs are not sub-horizontal and are located below subcontinental seismic zones. Another exceptional geological feature of the Andes is the presence of aseismic rift zones in the WBZ at depths ranging from 100 to 200 km, depending on the dip angle of the latter. These areas correspond to regions of volcanic activity in the Andes. There is no active volcanic activity in the ridges and fracture zones opposite the oceanic plate (Frutos 1990).

The Nazca plate lies beneath western South America and exhibits alternating flat and normal subduction, as well as an unusual reverse curvature in some places (Engdahl et al. 1998). Seismic activity has also been observed at depths ranging from 70 to 110 km below the Andes, but not in other parts of the world (Munoz 2005).

Oceanic crust with allochthonous terranes was accreted in the northern Andes during the Jurassic, Cretaceous, and Paleogene periods. This section is made up of both volcanic and non-volcanic mountains. The Western Cordillera of Colombia and Ecuador is formed by an oceanic basement resulting from ophiolite obduction, penetration deformation, and metamorphism caused by the collision of oceanic volcanic arcs (Clapperton 1990; Frutos 1990; Ramos 1999; Orme 2007).

The Central Andes (14°–27° S) are shared by southern Ecuador, Peru, western Bolivia, northern and central Argentina, and Chile. This segment's tectonics are driven by subduction, which included Wadati-Benioff zones with varying geometries and different uplift mechanisms. The geology of the segment's centre is characterised by normal subduction and an active volcanic arc. The southern Central Andes exhibit significant variations in geology spanning the Late Miocene, Quaternary, and Late Cretaceous epochs. The High Cordillera, a thin-skinned Precordillera belt, and the Sierras Pampeanas form the area's flat slab. These basement blocks have been uplifted since the late Miocene as the flat slab has shrunk. The resulting crustal erosion has caused the migration of the magmatic arc (Allmendinger et al. 1997; Ramos 1999).

The Southern Andes are located between 46° 30′ and 52° S. The area is distinguished by an uplift with ridge collision and various ridge segments, as well as strike-slip deformation along the forearc. Due to the lack of magmatic activity in the arc, the ridge segments form a fold and thrust belt along the Patagonian foreland (Ramos 1989; Ramos and Kay 1992; Alvarez-Marrón et al. 1993; Gorring et al. 1997).

The geomorphology of the Andes is dominated by volcanic and glacial processes. According to Clapperton (1990), numerous calc-alkaline volcanic systems in the Andes appear to have evolved in a complex manner during the Pleistocene. As a result of large-scale debris avalanches generating eruptions, numerous Andean volcanoes have developed a distinctive topography and sedimentary formations, which could form key marker horizons in the volcanic and glacial stratigraphy in many parts of the Northern Andes. Recent ice-capped volcanoes may also be useful for studying glacier fluctuations (Clapperton 1990; Vogt et al. 2010).

Tectonism and volcanism are responsible for Andean landforms, while Pleistocene glacial and periglacial conditions have shaped most Andean landscapes. Glacier ice has sculpted the bedrock forming cirques and U-shaped valleys and depositing eroded materials as moraines downslope. Fluvioglacial processes have formed outwash plains, with winds redistributing fine debris as loess. In areas where glaciers did not exist, soils were heaved by freeze–thaw processes, and debris lobes were moved downslope by solifluction. Mass movements have shaped the steep slopes, with varying velocities ranging from persistent creep to episodic rockfalls and landslides. Rockfalls and landslides have been accelerated when swollen rivers or roads have cut into the sides of mountains (Young et al. 2007; Azócar and Brenning 2010; Perucca and Martos 2012).

The abovementioned processes, as well as volcanic-related processes, have shaped volcanic landscapes. Examples of such processes include lava flows, deep ash deposits, crater lakes, and lahars, which are flows of volcanic debris often intensified by melting glacier ice. Natural disasters such as volcanic eruptions and earthquakes are common in these areas (Young et al. 2007). Figure 2 shows the structural elements of the Andean Cordillera.

The climate of the Andes is very diverse, especially given the vastness of this cordillera. The Andean climate is primarily determined by interactions between topography and climatic elements such as the Intertropical Convergence Zone (ITCZ) and trade winds. These winds transport humid air from the Atlantic Ocean toward the Equator in north-westerly and south-westerly directions. Precipitation intensifies with high nebulosity when trade winds meet steep mountain slopes (Young et al. 2007; Rangecroft et al. 2013; Herzog et al. 2011; Ambrizzi et al. 2019; Cai et al. 2020).

Intermontane valleys and mountain slopes that do not receive trade winds tend to be seasonally or permanently dry due to rain shadows. Coldwater currents along the coasts of Peru and Northern Chile generate high-pressure areas, exacerbating the dry patterns and resulting in extensive coastal deserts. On the one hand, the Amazon basin is responsible for bringing humidity, nebulosity, and precipitation to the Andes during the austral summer. On the other hand, during the austral winter, the Andes have dry air and almost no nebulosity because the equatorial continental air mass loses force and the polar air mass gains force. During this season, polar air masses move onto the continent, resulting in much lower temperatures in the southern section of the Andes than in the tropical Andes (Young et al. 2007; Zaninelli et al. 2019; Cai et al. 2020).

Mountains at high elevations have a lower air pressure and cooler mean temperatures. The variation in the elevation belts of the tropical Andes has relatively

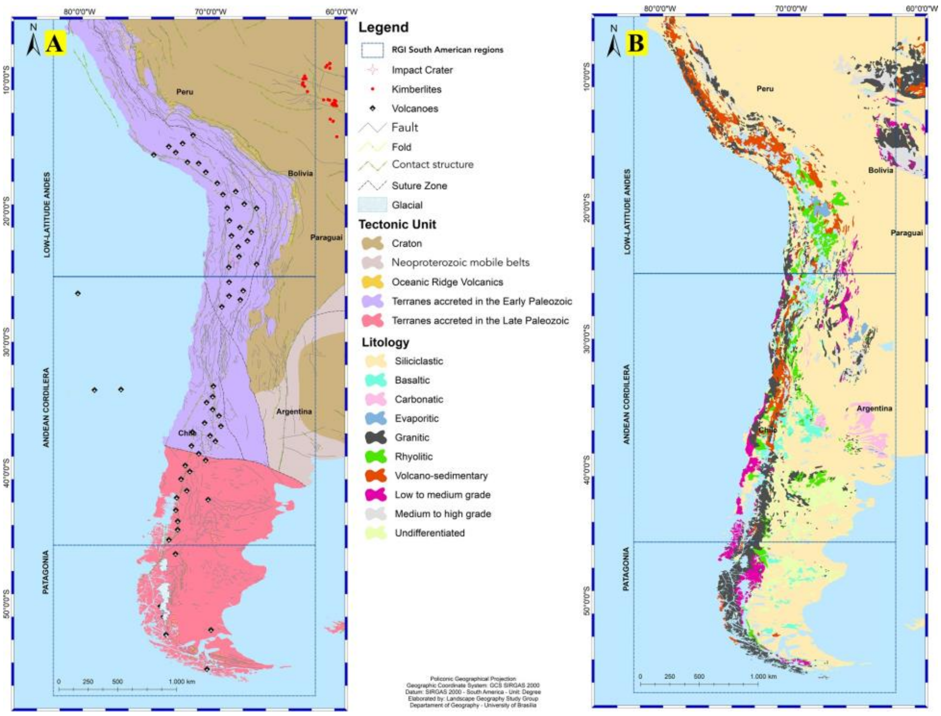


Fig. 2 Structural elements of the Andean region. (**A**) Representation of tectonic units; (**B**) representation of the lithology

constant mean temperatures but a pronounced seasonality in precipitation due to the shifting effects of the ITCZ and winds carrying humidity. Temperature and precipitation vary seasonally in the subtropical Andes (Young et al. 2007; Rangecroft et al. 2013; Herzog et al. 2011).

Although the soils of the Andes are impossible to generalise, the mountain range comprises distinct types of vegetation cover (Young et al. 2007). The vegetation types found in the Andes include montane forests, shrublands, grasslands, and wetlands. The High Andes have sparse vegetation types.

The Andes host numerous types of montane forest vegetation due to differences in precipitation, seasonality, latitude, and altitude. Wet environments are home to the majority of montane forests. In other words, the larger the area of montane forests, the wetter the environment. They can be found at altitudes ranging from 1000 to 3500 m in areas exposed to humid air. Other montane forests are fragmented due to the lack of connectivity of mountainous terrains (Young 1998) and are located in ravines, rocky sites, and on wetter slopes that would otherwise be covered by shrublands, grasslands, or agricultural landscapes. This fragmentation of the areas is aggravated or caused by the conversion of forests to pastures and croplands. The remnants of these vegetational formations are used for the extraction of forest products and provide important hydrological functions for watersheds (Young et al. 2007; Perez et al. 2010).

Shrublands are the most common type of vegetation in the Andes, but they vary greatly across the region. As a result of rain-shadow effects, they are associated with climatic conditions in which evapotranspiration exceeds precipitation, high solar radiation, and dry weather. They are common on slopes, taluses, and flat areas with coarse, rocky soil. Forests in shrublands are only found near rivers; otherwise, forests are not seen in this type of vegetation. Shrublands are also considered a transitional vegetation type because they transition to grasslands or montane forests. Shrublands with shrubby and spiny vegetation, succulent plants, and ephemeral herbs are more common on the inter-Andean valley flanks (Wardle et al. 2001; Young et al. 2007; Contreras 2010; Arkush 2011; Herzog et al. 2011).

The grasslands are open spaces mostly consisting of herbaceous plants that grow at a variety of altitudes and have a high biodiversity. Grasslands are typically dominant at high altitudes. The presence of grasslands on lower slopes is usually due to seasonal precipitation or other processes that prevent shrubs from establishing themselves. The presence of grasslands in areas with 1200 mm of annual precipitation may be linked to deliberate burning. Grasslands at high altitudes may have emerged during the Pliocene, and the floristic composition of the Andean grasslands has been influenced by climate and ancient tectonics movements (Wardle et al. 2001; Young et al. 2007; Gosling et al. 2009).

Wetlands in the Andes are characterised by water-saturated soils and are commonly associated with lake and river margins. This type of vegetation can be found at various elevations. Along with other vegetations types, they are affected by a variety of physical conditions such as slope, precipitation, and bedrock type. This vegetation type is influenced by historical and anthropogenic uses (Young et al. 2007).

The High Andes host numerous rocky substrates and sparse vegetation types that can form at elevations above 4500 m or right below elevations of snow or ice. The majority of them are island-like habitats that exist along or between mountain ranges. Low temperatures, high winds, scarcity of precipitation, and dry air have created a harsh biophysical environment within this region (Wardle et al. 2001; Young et al. 2007; Gosling et al. 2009).

Dataset and Methodological Approach

The main objective of this research was to determine which Nevados on the Andes Cordillera should be prioritised for geoheritage protection. It is important to note that the methodology applied here can be used to assess and prioritise Nevados all over the world. As previously stated, Nevados can serve both as relevant geosites for understanding the Earth and as important indicators of climate change. A quantitative method was used to evaluate South American Nevados, which included aggregating information on the Nevados' characteristics, statistical analyses in specialised software, and geoprocessing procedures for spatial analysis. As a result, it became clear just how vulnerable Nevados are and why they should be protected as geoheritage.

The methodological approach was based on a matrix analysis with specific elements. The integration of available geo-environmental and geospatialised data regarding snowfall,

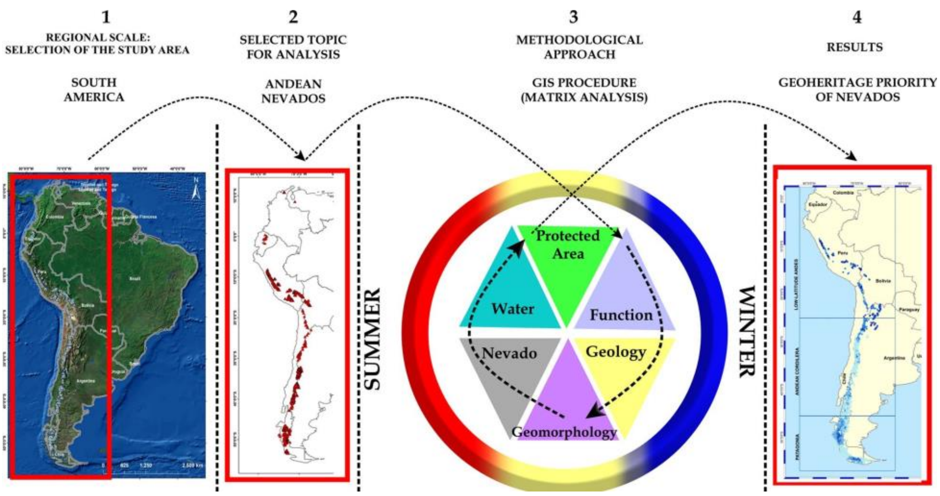


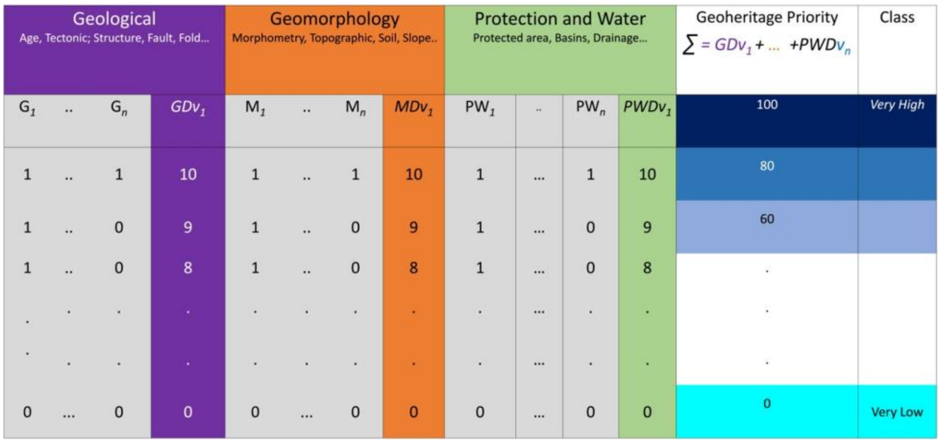
Fig. 3 Data interaction and information model. Adapted from Pessoa et al. (2019)

geology, geomorphology, hydrography, topography, climate, vegetation, and flora was considered in the matrix.

Figure 3 depicts the general steps of the methodological procedure. The diagram shows four phases: (1) the definition of the study area as South America; (2) the Nevados found on this continent; (3) the application of a matrix analysis based on the greatest number of variables in this scale; and (4) a presentation of the results.

The first stage was related to the definition of the study area. South America was selected during the first stage of the procedure based on extensive knowledge in the scientific literature regarding the relevance of this region's biodiversity, the large volume of water resources available on the South American continent, and the fact that no study has presented the theme of Nevados as geoheritage to date (Jha and Bawa 2006; Hanson et al. 2009; Bufalo et al. 2016; Hopper et al. 2016; Bidegain et al. 2019).

The second stage was inextricably tied to the primary objective of this discussion. It included the realisation that South American Nevados have a relevant set of physical features. This region's geological, geomorphological, and hydrological characteristics have been explored



Geological (Age, Tectonic; Structure, Fault, Fold...)				Geomorphology (Morphometry, Topographic, Soil, Slope..)				Protection and Water (Protected area, Basins, Drainage...)				Geoheritage Priority $\sum = GDv_1 + ... + PWDv_n$	Class
G_1	..	G_n	GDv_1	M_1	..	M_n	MDv_1	PW_1	..	PW_n	$PWDv_1$	100	Very High
1	..	1	10	1	..	1	10	1	...	1	10	80	
1	..	0	9	1	..	0	9	1	...	0	9	60	
1	..	0	8	1	..	0	8	1	...	0	8	.	
.	.	.	.	.	.	.	.	.	...	.	.	.	
.	.	.	.	.	.	.	.	.	...	.	.	.	
0	...	0	0	0	...	0	0	0	...	0	0	0	Very Low

Fig. 4 Interaction matrix index for geoheritage priority

Table 1 Variables used in each group and their value attribution

Group	Variable	Score (0–10)
Structure	Tectonics	The more tectonic records there are in the Nevado area, the closer the score is to 10
	Volcanism	The higher the records of volcanic activity in the Nevado area, the closer the score is to 10
	Lithology	The greater the lithological diversity in the Nevado area, the closer the score is to 10
	Geology	The greater the diversity of geological structures in the Nevado area, the closer the score is to 10
Geomorphology	Amplitude	The greater the altimetric amplitude in the Nevado area, the closer the score is to 10
	Topography	The greater the altitude in the Nevado area, the closer the score is to 10
	Morphometry	The higher the relief roughness index (Ri) of the Nevado area, the closer the score is to 10
	Area	The greater the area of the Nevado in square kilometres, the closer the score is to 10
	Slope	The greater the average slope of the Nevado area, the closer the score is to 10
	Hillshade	The higher the relief shading index in the Nevado area, the closer the score is to 10
Environment	Water	The greater the hydrological features in the Nevado area, the closer the score is to 10
	Water Basin	The greater the Nevado's contribution to the basin's headwaters, the closer the score is to 10
	Protected Areas	The greater the presence of protected natural areas, such as national parks or reserves, in the Nevado area, the closer the score is to 10
	Vegetation	The greater the presence of native vegetation in the nevado area, the closer the score is to 10

relatively little for geoheritage purposes, and this vast set of Nevados should be observed from multiple aspects. Nevados are key sites for identifying priority areas for the maintenance, conservation, and protection of geological natural resources that bear witness to anthropogenic processes.

The third stage of this study involved the use of an analysis matrix. This matrix, adapted from Pessoa et al. (2019), allowed for the analysis of the interaction of Nevado elements and provided consistent data for the research findings. Based on the spatial statistical correlation between the geographic location of the Nevados and their respective physiographic characteristics, a set of variables capable of indicating priority levels was listed at this stage. The variables, gathered from official databases, are divided into three major groups. Each variable has a matching layer in the GIS environment, and the score for each one ranges from 0 to 10. Figure 4 and Table 1 attempt to visually represent the interaction matrix index proposed in this study.

The first group of variables focuses on the structure of the Nevados and includes four variables: tectonics, volcanism, lithology, and geology. A better score is given when there are numerous records of tectonic activity in the Nevado region. Similarly, when there are numerous records of volcanic activity in the region and the lithological diversity is larger, a higher score is assigned. A higher score is also given when there are numerous geological structures in the region.

The second group is related to the geomorphology and includes six variables: amplitude, topography, morphometry, area, slope, and hillshade. The score is assigned based on the numerical data of each variable. The higher the score, the more relevant the numerical data is.

The last group is related to the environment and includes four variables: water, water basin, protected areas, and vegetation. A greater score is assigned when the water variable has more hydrological features in the Nevado area, bringing the variable score closer to 10. Similarly, a higher score is assigned when there are more protected areas and more diverse vegetation in the area (Fig. 5).

The variables were selected using the principle of availability at the chosen scale and availability in cartographic databases. The statistical approach was used to reduce subjectivity, ensuring that the method and data could be tested and replicated by other scientists. Geoprocessing tools and software were used to analyse the geology and geomorphological processes of the study area, providing greater robustness to the evaluated data.

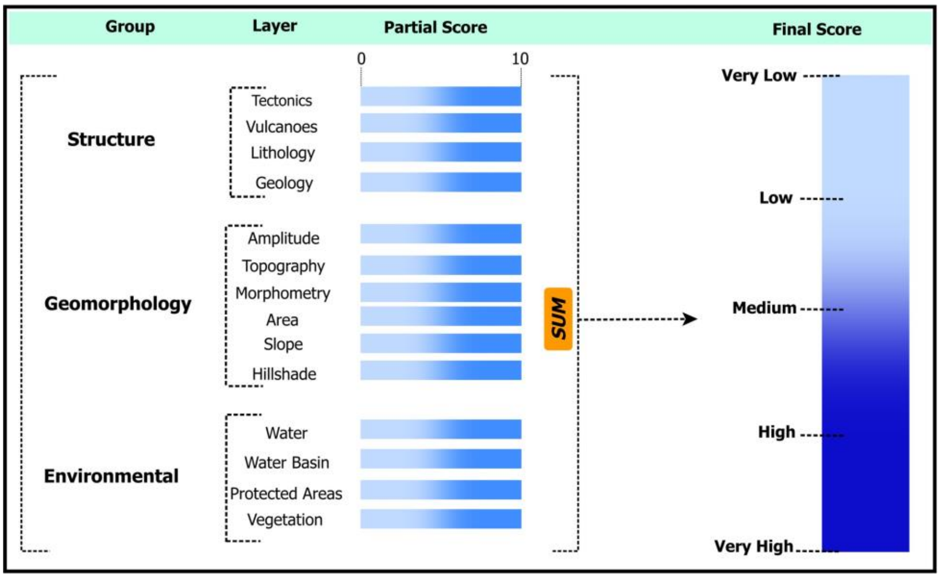


Fig. 5 Details of the sum of variables in the interaction matrix

Information on the geology, geomorphology, hydrography, topography, climate, vegetation, fauna, and the location of South America's glaciers were all gathered. The geological and geomorphological data were obtained from the USGS. The glacier data were acquired from the Global Land Ice Measurements from Space (GLIMS) project. The GLIMS project is supplemented by the Randolph Glacier Inventory (RGI), which provides a global overview of glaciers. The National Snow and Ice Data Center (NSIDC) is in charge of its overall coordination as well as technical and data development; however, the project is further supported by numerous institutions worldwide.

The Brazilian Geological Survey (CPRM) and the Brazilian Institute of Geography and Statistics (IBGE) also provided data for the matrix, which included hydrography, topography, climate, vegetation, and flora. The flora data was collected from the Chico Mendes Institute for Biodiversity Conservation (ICMBIO)'s biogeography mapping for South America.

Since Nevados exhibit diverse characteristics that vary depending on each individual Nevado or set of Nevados, a cartographic scale of 1:1,000,000 was used as a standardisation parameter. It should be noted that South American countries need to put in more effort to map this region, but the data and variables chosen were considered appropriate for this study. The variables and their subgroups were combined using GIS software to identify the Nevados that are geoheritage priorities.

The following step was to remove any inconsistencies, such as null data for minimum and maximum altitudes. Because mountain formation is only possible at a zero altitude near the coast, data with values close to 0 m — i.e. sea level — were only kept if they represented a point on the coastal strip.

One aspect of the GLIMS project that should be highlighted is the lack of clear guidance on the type of glacier considered. As a result, the data from GLIMS glaciers, hypsometry, and hydrography were crossed to determine whether they were, in fact, Nevados — bodies of ice and/or snow that are permanently found under these conditions and are located at the peaks of mountains that drain snowmelt water to drainage basins. The hypsometry and hydrography data were combined to determine whether the glaciers were at an acceptable altitude and whether snowmelt water flowed to a river. If these data were compatible, then the glaciers were considered Nevados.

The Randolph Glacier Inventory — A Dataset of Global Glacier Outlines: Version 6.0 Technical Report was used in addition to these data crossings. Information was gathered from regions 16 and 17, which corresponded to low latitudes and the Southern Andes, respectively. Since the report mentions detailed characteristics of the Nevados, such as morphometry and hypsometry, this information is extremely relevant for the understanding of the study area, mostly for adjustments of inconsistencies and general data analysis.

The final step involved using a value matrix to quantify the significance of geoheritage in relation to Nevados. Each Nevado was correlated with a set of available variables, and each variable was assigned a score between 0 and 10 based on its intersection with the Nevados.

The Moran's Index was used as the statistical technique, which is widely used to measure the spatial autocorrelation of phenomena with geographic proximity. The Moran scatter plot compares the normalised values of a specific attribute across all geographical areas. This tool uses the mean values of the surrounding region to generate a two-dimensional plot of normalised values (z) normalised by the mean of their neighbours (Wz). The Moran's correlation was calculated using GeoDa software, and the intersections and thematic map were created using the ArcGIS software.

GIS procedures relied on layer articulation and overlay via intersection. The percentage of interaction between variables was used to apply quantitative and qualitative spatial analysis methods based on these intersections. The criteria for determining the rarity of a Nevado were based on identifying those with the greatest number of variables present, such as older nevados with greater geological and geomorphological evidence, higher topographic amplitude, greater geomorphological diversity, greater conservation, and greater water availability. Thus, the rarest nevados demonstrate a connection between their origins, genesis, traits, and conservation status.

The rarity value includes the relationship between the origin processes and geological structure, the terrain morphometry aspects related to geomorphology, and the main environmental aspects of the Nevados. The rarity of a Nevado decreases when multiple Nevados are discovered to have the same geological, geomorphological, and environmental features; when only a few Nevados have the same geological, geomorphological, and environmental features, their rarity increases. This yields a rarity scale based on the variables with values ranging from 0 to 10, with zero being very low and ten being very high (Fig. 5). The priority of Nevados for geoheritage was established by obtaining a numerical result by calculating the values of each variable and summarising them using a matrix.

Results and Discussion

The first result was related to the Nevados' interactions with the spatial analysis groups depicted in Fig. 5. The statistical validation indices demonstrate that, in this scale of analyses, a p value of 0.05% or better was found in more than 50% of Nevados (Table 2), representing an excellent statistical correlation value.

Table 2 Percentage of Nevados by level of geostatistical validation

p value	Geology (%)	Geomorphol gy (%)	Environmental (%)
0.001	21.78	16.57	17.73
0.01	20.29	18.62	20.25
0.05	15.42	20.33	31.44
Not significant	42.51	44.48	30.59

Correlation is an important component of regression analysis because it provides valuable information about potential relationships. In this case, the adjusted r^2 between the priority levels and the characteristics was greater than 0.9, indicating a very high correlation between the final score in the classes (Fig. 6); this demonstrates that the selected variables were successful in properly grouping the Nevados at each priority level. The index was unaffected by the inclusion of variables that could cause statistical noise in the results, such as the presence or absence of protected areas, which were not necessarily part of the physiographic characteristics.

The database could be consolidated based on these general statistical validations of the data and their respective statistical and spatial correlations. This was done to deepen the geospatial analysis in a GIS environment with the appropriate layer overlays and techniques capable of providing the necessary elements. These elements are necessary so the result of overlapping layers can generate the most reliable result in this scale of analysis. To subside the classified priority values, the Moran's index was applied to the grade matrix. In other words, when analysing the degrees of geospatial correlation between layers, the obtained values demonstrate that the spatial

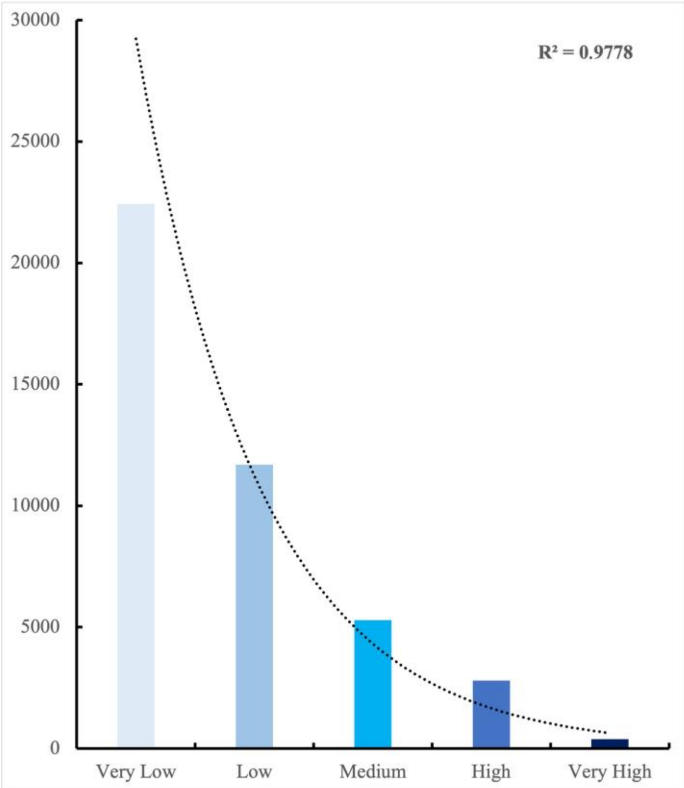


Fig. 6 Analysis of the regression line

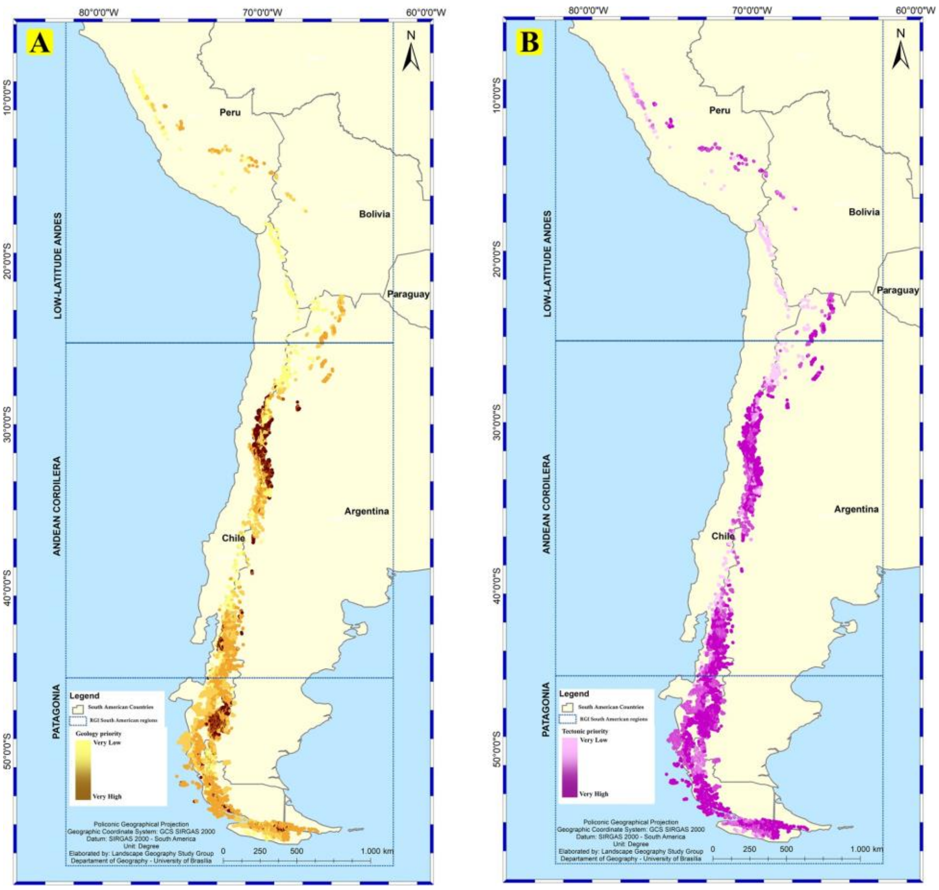


Fig. 7 Maps of structural variables. (A) Priority Nevados based on geological groups; (B) priority Nevados based on tectonic units

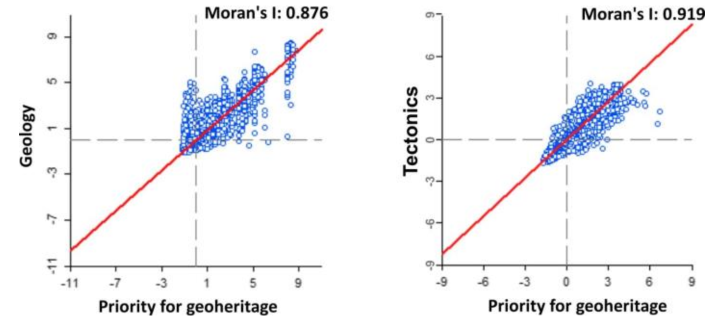
correlation aggregates the geological and geomorphological elements, which leads to a more reliable result. This index revealed consistent values for the geological grouping in which all available features (tectonics, structure, faults, lineaments, folds, geological age, lithology, and volcanism) were used (Fig. 7). The correlation maps reflect this index.

The proposed matrix overlay was applied to generate the first set of maps for South American structuring bases. These maps included both fundamental geological elements (origin and development) as well as elements that are currently required to comprehend this process.

At this stage, the Nevados were concentrated in the central and southern Andean Cordillera ranges, with a higher priority for geoheritage. Because the occurrences of the matrix elements were higher in these regions, the obtained result was consistent with the elements used. Nevados located in the tectonic units called “terranes accreted in the early Paleozoic” (Central Andean Cordillera) and “tectonic terranes accreted in the late Paleozoic” (Patagonia region) stood out in this partial result. This means that these tectonic units have a higher priority for geoheritage than others.

For all available elements, the partial results, which refer to the geological structure of the Nevados, were evaluated using a geospatial correlation with Moran’s index. Figure 8 shows a strong positive correlation between geological data and tectonic units, with Moran’s indices exceeding 0.8 for

Fig. 8 Moran's index (*I*) examples for geological elements



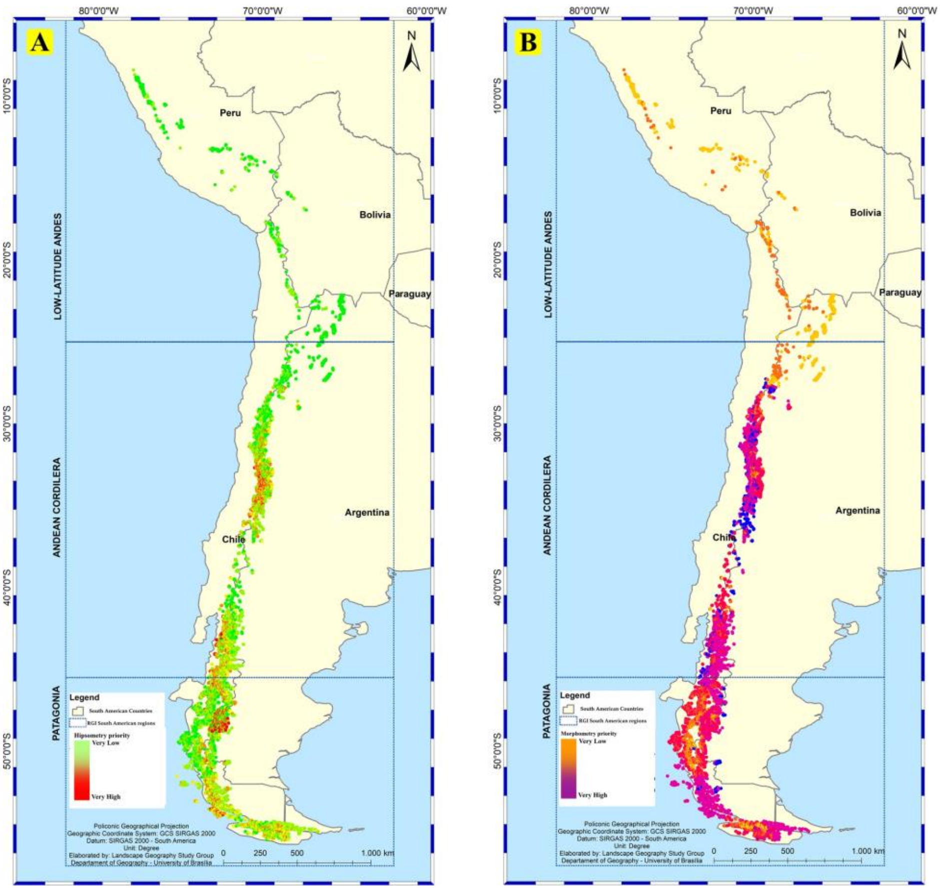


Fig. 9 Maps of geomorphological variables. (**A**) Priority Nevados based on hypsometry; (**B**) priority Nevados based on morphometry

the geology and exceeding 0.9 for tectonics. This correlation demonstrates that the geology and tectonics have a significant influence on the Nevados that can be prioritised for geoheritage.

The second set of characteristics was concerned with morphometric and geomorphological aspects. The Moran's index presented consistent values for all of the available characteristics (soils, morphometry, topography, slope orientation, altimetric amplitude, and dimensions of the Nevados) (Fig. 9), which is reflected in the spatial correlation maps (Fig. 10).

Additionally, the spatial distribution of the Nevados in the second set of variables examined was similar to that of the first set. That is, the Nevados were concentrated in the central and southern sections of the Andes Cordillera, particularly in Patagonia. Because of the climatic conditions and altitude of this section, the Nevados in Patagonia exhibit larger area dimensions and greater altimetric amplitudes. Applying the rarity value, this means that the Nevados in these areas have a lower geoheritage priority value.

All variables in the second grouping had Moran's index values greater than 0.5. According to the examples presented here, the hypsometry had a value of 0.535 and morphometry had a value of 0.837. The hypsometric index was most likely in the 0.5 range due to the influence of the smaller dimensions of Nevados in the Central and Northern Andes than those in Patagonia.

The third grouping of characteristics was related to natural resources protection and conservation, and all available characteristics were used (protected area, relevance to watershed, proximity to watercourses, and large watersheds). The "protected area" value was inserted in the matrix to highlight the geoconservation status of the Nevados in South America. Although it differed slightly from other characteristics in the correlation analyses due to the unique characteristics of each protected area, this grouping also demonstrated consistent Moran's index values (Fig. 12), as reflected in the spatial correlation maps (Fig. 11).

Among the environmental grouping elements, variables associated with hydrographic basin headwaters and the presence of protected areas stood out, indicating positive Moran's correlation indices, as shown in Fig. 12. In terms of the spatial distribution, the results in this grouping were more balanced: the northern Nevados gained prominence as a result of the inclusion of protected areas and their importance as the sources of headwaters to the world's largest hydrographic basin, the Amazon River basin.

Finally, the variables with statistically significant correlations were chosen. This set of partial results, generated based on the variables available in the scale analysis, led to a more complete and comprehensive approach for South American Nevados, which can now be recognised as important local, regional, and global geoheritage sites. The main results of this investigation are presented in Fig. 13, which shows the Nevados' priority level for geoheritage in a very objective manner.

Some aspects which deserve recognition could be identified according to this general classification. The first aspect was that the Nevados are important structures for geoheritage purposes not only in South America but also worldwide, as they are essential for water supply, human well-being, and can contain valuable information about the Earth's evolution. The second aspect is that these landscape icons are structures that serve as important environmental

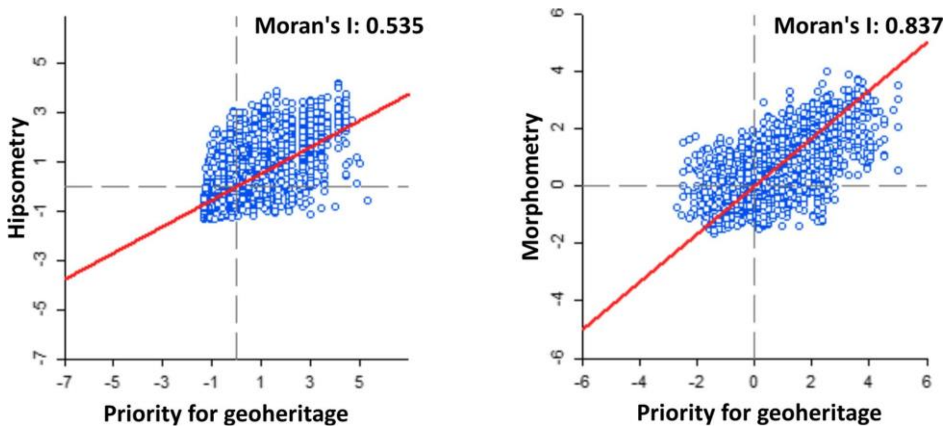


Fig. 10 Moran's index (*I*) examples for geomorphological elements

indicators, especially when considered in the context of climate change and landscape transformation. Another relevant aspect is directly related to local and regional water availability, since the Nevados are natural reservoirs of water, supplying numerous drainage and hydrographic systems through seasonal melting processes. Finally, the Nevados are essential for tourism (and can be important for geotourism) and the scientific community because they can preserve records of the Earth's evolution as well as being characterised by exceptional geobiodiversity.

Figure 14 depicts the distribution and some characteristics of Nevados in greater detail, using the location, topography, and area of the Nevados as elements. The spatial distribution of the Nevados was clearly not homogeneous, with very distinct local characteristics. Despite the fact that the Nevados in this section of the Andes were smaller than those in the south, their preservation in the low-altitude Andes is a high priority due to their role in water supply. Patagonia has larger and more numerous Nevados, but their rarity value was lower because they lacked those valuable geoheritage characteristics found in the north. However, more detailed research is required to demonstrate more variables and scientific, cultural, and scenic values for each Nevado.

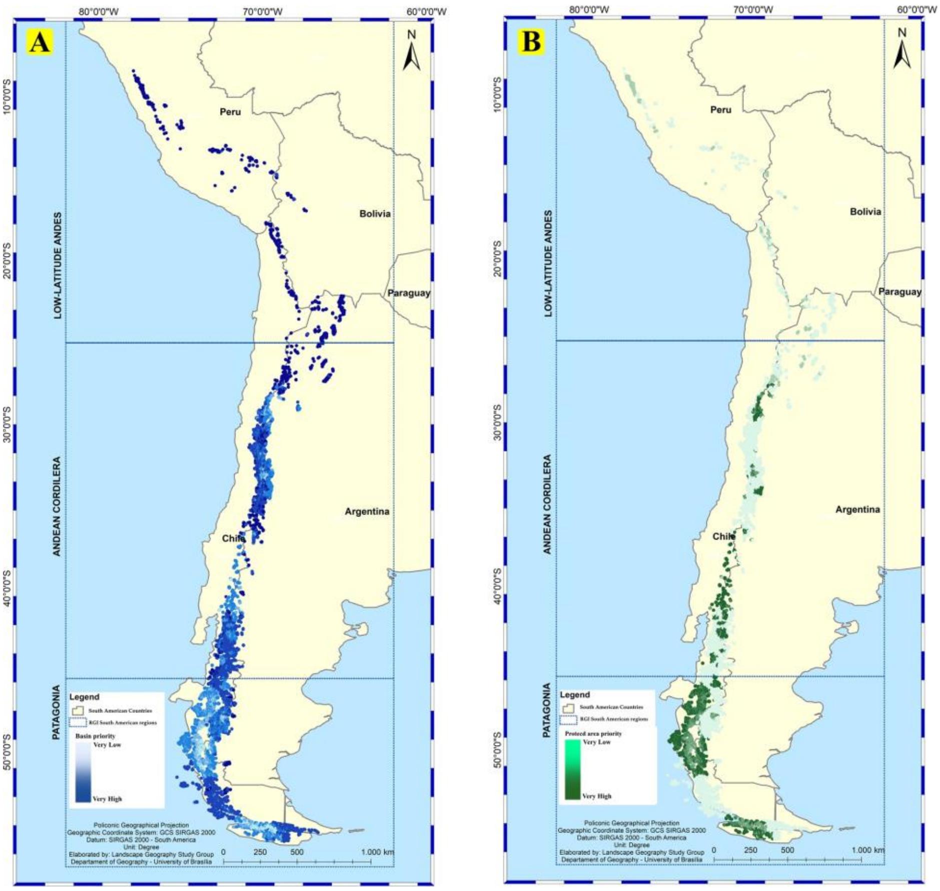


Fig. 11 Maps of environmental variables. (**A**) Priority Nevados based on hydrographic basins; (**B**) priority Nevados in terms of protected areas

The Andean Cordillera is unique in many ways, especially when it comes to geologic processes that occur only in this part of the world. Additionally, Nevados play a significant role in the hydrography of South America, providing the source of the headwaters of at least two major hydrographic basins and thus demonstrating the need for their geoconservation. The Andean Cordillera hosts Nevados that drain into the Pacific and Atlantic Oceans. Although Nevados can serve as a drainage divide, they can also function as a connector between hydrographic basins. This means that changes to a Nevado can affect two different basins at the same time, albeit at different levels and in different ways.

Nevados can therefore be considered elements of geoheritage because they have important features and functions that must be preserved for future generations as well as for the current generation's well-being. The Andean Cordillera is home to some of the greatest geobiodiversity in the world, and the latter must be protected. Consequently, extensive research into South American Nevados, particularly those of the Andean Mountain Range, as well as other Nevados around the world, is critical. The protection of Nevados would result in the protection of headwaters, preservation of the Earth's past, and action against climate change.

Future research in this region could help public policies supporting the geoconservation of the Nevados of the Andean Cordillera, which are under significant stress due to anthropogenic processes. The method applied here could also be used to conduct research on other Nevados to better understand their geodiversity.

Conclusions

This investigation presents a novel approach for classifying South American Nevados as priority areas for geoheritage identification and indication. Considering their unique characteristics and a geoconservation approach, Nevados should be added to the list of areas of interest for geoheritage.

Studies that demand indications of areas at various scales to indicate the relevance for geoheritage of a site should include a spectrum of scales, from microzones (with high levels of detailing) to macrozones (Brocx and Semeniuk 2007). In this research, we sought to agglutinate and integrate regional and local scales, which contributes to geoheritage science, especially when considering that this approach was applied for the first time to this theme. This study provides insights for future research areas that require delving into the finest scales, to better understand the Nevados at a local scale.

Methodology adaptations developed and applied by Pessoa et al. (2019) and Steinke (2021) were used to indicate priority areas for geoheritage. This allowed us to objectively classify Nevados according to a priority range capable of supporting the territory management and the scientific dissemination of geoheritage at all social levels, as recommended by Fuertes-Gutiérrez and Fernández-Martínez (2010).

It is worth noting that the Andes have a great number of important Nevados. They are distributed from north to south and represent key geoheritage sites. Although they are occasionally located in different countries, they are all connected by water resources. This creates a complex network with intertwined variables and contexts, which calls for attention in cross-border public policies. Assuming that Nevados are an indicator of

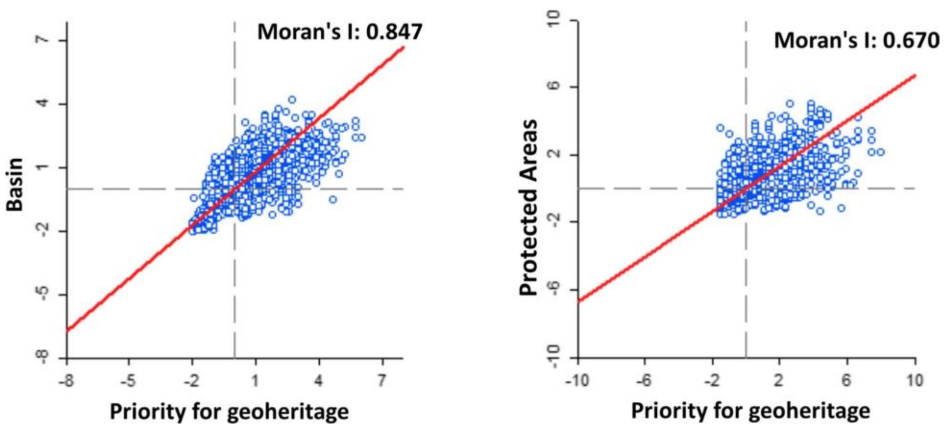


Fig. 12 Moran's index (*I*) examples for environmental elements

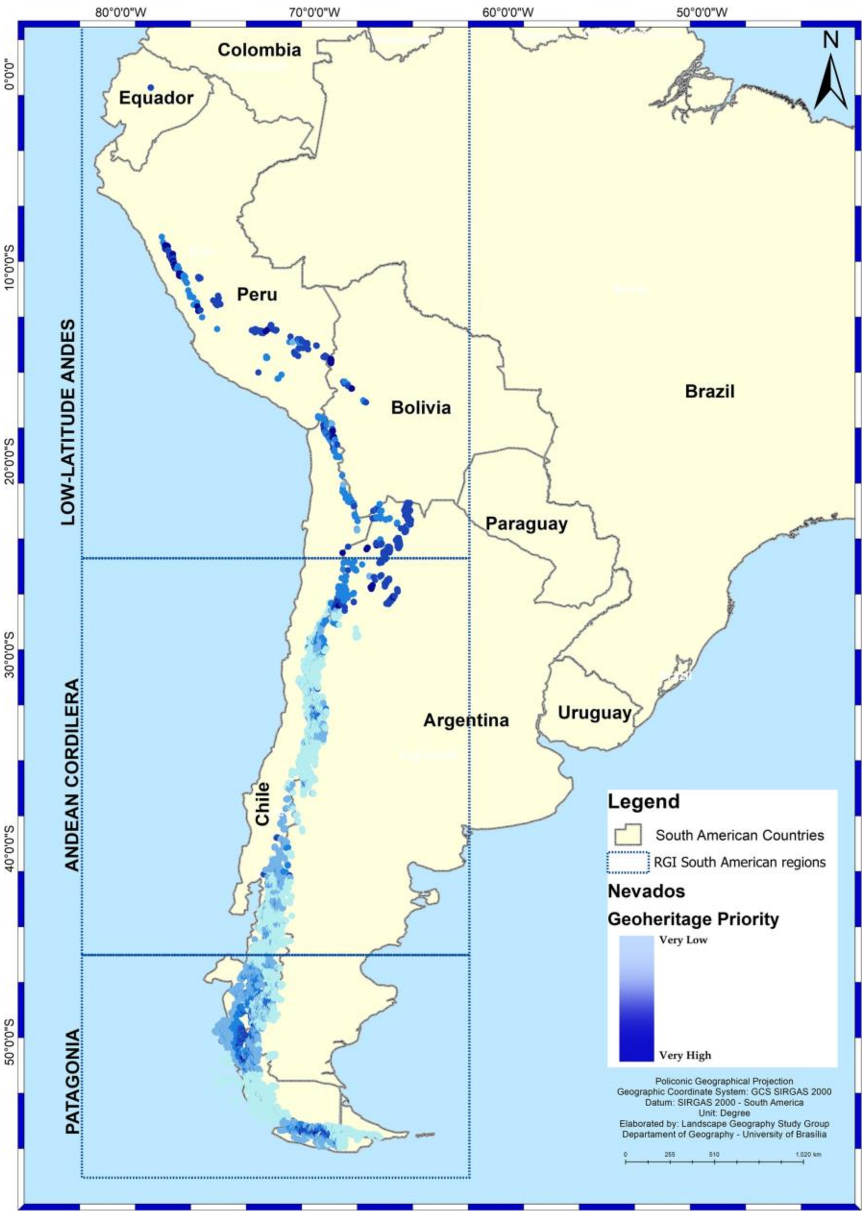


Fig. 13 Priority Nevados for geoheritage in South America

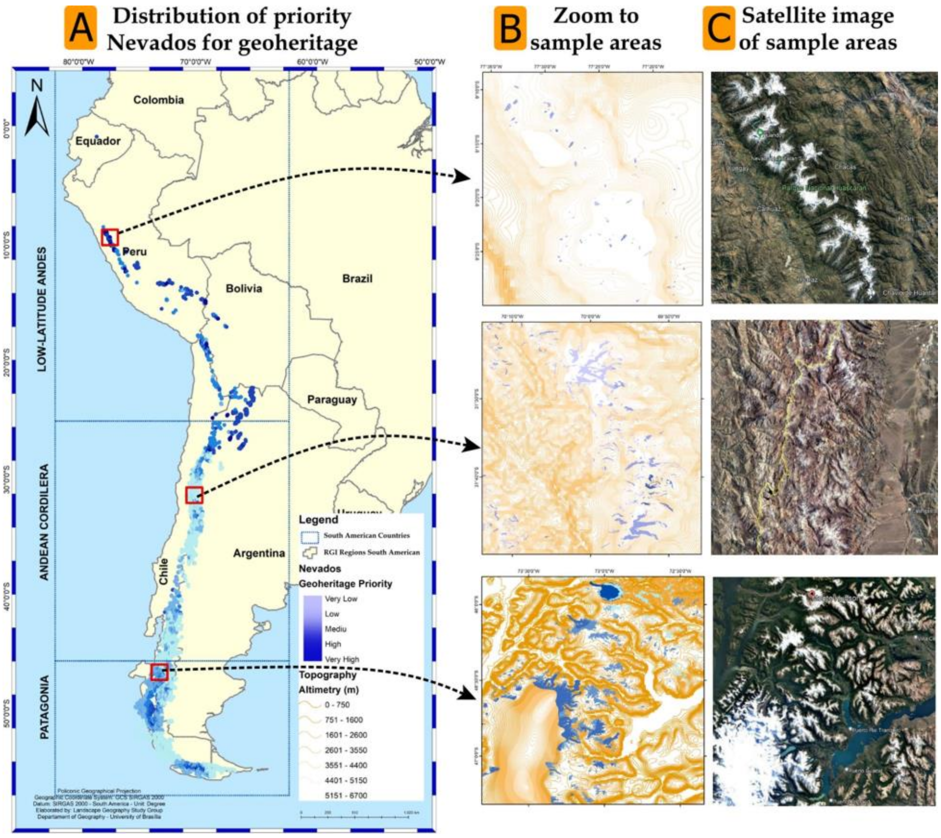


Fig. 14 Detailed cartogram of South American Nevados. (**A**) General results; (**B**) details of three specific areas with snow and contours; (**C**) 2022 satellite image (available on Google Earth)

environmental change, public policies aimed at combating climate change should consider Nevados essential water suppliers.

Using the elements that comprise the foundations of geoheritage, this innovative approach provides a necessary and substantial opportunity for inter-governmental discussions about the cooperative or shared management of natural resources. The results presented in this research meet the basic requirements for the adequate protection of geoheritage elements in the territory of the South American Andes, especially in terms of geoconservation aspects.

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Declarations

Ethical Approval This research does not contain any studies with human participants or animals performed by any of the authors.

Conflict of Interest The authors declare no competing interests.

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CONSIDERAÇÕES

Um aspecto crítico para compreender a importância dos nevados para o Geopatrimônio, em especial para a América do Sul, é compreender o conceito de nevado e a sua diferenciação frente a outro conceito similar – os glaciares de montanha. E, para isso, é necessário adentrar em conceitos importantes sobre glaciares em geral. Isto porque, de acordo com Meier (2020), os glaciares de montanha são todos aqueles que possuem gelo perene que não sejam mantos de gelo. Isto é, todas as geleiras menores que 50.000 km² podem ser classificadas como glaciares ou geleiras de montanha.

Ainda em concordância com Meier (2020), os glaciares de montanha são demarcados por um canal e, a depender do formato do canal e em que nível o glaciar preenche este canal, determina seu tipo. Dentro disso, são definidos seis tipos de glaciares de montanha: glaciares de vale, glaciares de círculo, glaciares suspensos, glaciares regenerados, glaciares de piemonte e glaciares costeiros (BENN & EVANS, 2014). A partir desses tipos de glaciares, ainda é possível existir várias outras subclassificações. Eles ainda podem ser diferenciados como polar, subpolar ou temperado e definidos a partir da superfície: neve-seca, percolação e saturação (MEIER, 2020).

Um glaciar se forma a partir da precipitação de neve e sua acumulação, necessariamente transformando-se, com a passagem do tempo, em gelo glaciar. O primeiro passo, portanto, é o acúmulo de neve contínuo, possibilitando a compressão das camadas inferiores. No entanto, os mecanismos responsáveis por essa transformação complexa dependem de inúmeros fatores, principalmente da temperatura (CUFFEY & PATERSON, 2010).

A neve precipitada e acumulada pode sofrer compressão do peso devido ao acúmulo de camadas de gelo, forçando a recristalização dos flocos de neve e, consequentemente, comprimindo o espaço de ar entre os grãos de neve e, assim, aumentando a densidade. Após certa passagem de tempo, a neve transforma-se em *firn* e, a medida em que a densidade aumenta, forma-se gelo glaciar (CUFFEY & PATTERSON, 2010; NATIONAL SNOW AND ICE DATA CENTER, 2023).

No campo da glaciologia, ainda assim, os nevados não são considerados uma categoria dos glaciares. Por sua acumulação ser baseada, principalmente, em neve – ou seja, uma etapa anterior à formação do que pode ser considerado um glaciar -, os nevados não podem ser considerados uma geleira, sendo uma etapa anterior à formação dessas estruturas glaciais. Nesse sentido, a preocupação com a geoconservação dos Nevados deve ser redobrada, visto que estes são formações desconsideradas por muito tempo nas Ciências da Terra.

Nesse contexto, os nevados são formações cobertas principalmente por neve, podendo também conter gelo. Eles são encontrados em áreas elevadas das montanhas e desempenham um papel importante no armazenamento de água e no abastecimento de nascentes de diferentes bacias de drenagem. Devido a essas características, os nevados, mesmo estando localizados no topo das montanhas e sendo potenciais divisores de drenagem, também atuam como conectores entre diferentes bacias de drenagem. Isso ocorre porque, após o derretimento, a água proveniente de um mesmo nevado pode fluir para duas bacias distintas. Em outras palavras, eventos que ocorrem em um ponto focal podem ter impacto em bacias hidrográficas diferentes.

Dessa forma, ao considerar e explorar a potencialidade dos Nevados como Geopatrimônio, é possível garantir não apenas a segurança hídrica de milhares de pessoas, mas também utilizar essas formações para propósitos educacionais, científicos, turísticos, estéticos, entre outros. Ao pensar sobre a herança do Geopatrimônio, a sustentabilidade dos Nevados se torna cada vez mais crítica devido às intensas taxas de derretimento que são observadas em um cenário de aquecimento global (ROUNCE et al., 2023).

A geoconservação dos Nevados torna-se crucial para garantir existência dos glaciares, visto que o acúmulo de neve é uma etapa imprescindível para a formação de gelo glaciar. Diante das taxas cada vez mais preocupantes e crescentes da temperatura global, bem como da ocorrência cada vez mais frequente de fenômenos extremos, é crucial que a ciência do Geopatrimônio se preocupe com o impacto nos geossítios e adote medidas de geoconservação capazes de mitigar os efeitos das mudanças climáticas. No caso dos Nevados como geossítios, a preocupação principal é a segurança hídrica: a perda dessas formações pode ter consequências graves para diversas populações e ecossistemas.

Nesta pesquisa, a abordagem metodológica preocupou-se em analisar os Nevados sob uma perspectiva geossistêmica. Para isso, foram utilizados métodos baseados em uma análise matricial, integrando dados geoambientais e geoespaciais. A construção da matriz considerou elementos específicos relacionados aos nevados, com o objetivo de identificar os nevados prioritários para o Geopatrimônio. As variáveis foram agrupadas de acordo com suas características, sendo possível identificar três grupos: o grupo estrutural, o grupo geomorfológico e o grupo ambiental.

No grupo estrutural, a variável relacionada ao tectonismo descreve a movimentação das placas tectônicas na área do Nevado, envolvendo colisões, surgimento de cadeias de montanhas e falhas geológicas. A variável vulcanismo indica a atividade vulcânica no Nevado, refletindo erupções passadas ou atuais de magma e materiais vulcânicos. Já a variável litologia descreve a composição e tipos de rochas presentes, incluindo granito, basalto, calcário, entre outros, e sua distribuição na área. Por fim, a variável geologia aborda a estrutura geológica, como camadas rochosas, falhas e dobras, sendo pontuada de acordo com a complexidade e interesse dessa estrutura. Quanto maior a ocorrência de tectonismo, vulcanismo, a diversidade litológica e as estruturas geológicas, mais alta será a pontuação, indicando maior proximidade com o valor 10 na área do Nevado.

No grupo geomorfológico, a variável amplitude refere-se à variação vertical das elevações no terreno, indicando a diferença entre as altitudes máxima e mínima no Nevado. A topografia descreve a configuração do terreno do Nevado. A morfometria, representada pelo índice de rugosidade do relevo (Ri), avalia a rugosidade do terreno. Quanto maior o valor de Ri, mais acidentado é o relevo, e quanto mais próximo da pontuação 10, portanto, maior é a rugosidade do Nevado. A área refere-se à extensão territorial do Nevado analisado. A declividade representa a inclinação do terreno, indicando a variação vertical em relação à distância horizontal percorrida. Por fim, o sombreamento do relevo refere-se à sombra projetada no relevo do Nevado, fornecendo informações sobre a exposição solar e os detalhes da topografia. Quanto mais próximo de 10 cada variável mencionada se aproxima, maior é a prioridade dada ao Nevado, evidenciando sua importância em termos de amplitude, topografia, morfometria, área, declividade e sombreamento do relevo.

No grupo ambiental, a variável água está relacionada à presença e disponibilidade de recursos hídricos no Nevado. Quanto maior a quantidade de características hidrológicas, mais próxima a pontuação estará de 10. A variável bacia hidrográfica avalia a contribuição do Nevado para as nascentes dos rios, refletindo sua importância para a regulação do fluxo de água. Quanto maior a contribuição do Nevado, mais próxima a pontuação estará de 10. A presença de áreas protegidas, como parques nacionais ou reservas, é considerada na variável áreas protegidas, refletindo uma maior conservação ambiental. Quanto maior a presença dessas áreas, maior será a pontuação. A variável vegetação considera a presença de vegetação nativa no Nevado, sendo que quanto maior a presença de vegetação nativa, mais próxima a pontuação estará de 10.

A matriz de análise desempenhou um papel fundamental na identificação dos Nevados prioritários para o Geopatrimônio, proporcionando uma quantificação da importância desses locais em relação aos elementos geoespaciais considerados. Por meio da atribuição de pontuações e da avaliação da raridade dos nevados, foi possível utilizar a matriz como base para a definição das áreas prioritárias.

A matriz construída permitiu uma visualização organizada e comparativa das pontuações atribuídas, possibilitando a identificação dos Nevados prioritários para o geopatrimônio. Essas áreas se destacaram ao apresentar as pontuações mais altas, indicando características estruturais, geomorfológicas e ambientais relevantes, com potencial científico, educativo e histórico-cultural.

E, além disso, com a utilização de ferramentas de geoprocessamento e análise estatística, foi possível identificar as interações entre as variáveis e analisar os padrões espaciais resultantes. A técnica estatística do Índice de Moran foi empregada para avaliar a autocorrelação espacial das variáveis, fornecendo uma visão mais aprofundada da distribuição dos Nevados.

Os resultados desta pesquisa têm implicações significativas para o Geopatrimônio. Os resultados demonstraram a aplicabilidade de uma abordagem metodológica geossistêmica na análise e priorização dos Nevados da América do Sul, localizados na Cordilheira dos Andes, com base em suas características geológicas, geomorfológicas e ambientais.

É importante destacar que, entre os resultados, os Nevados da Cordilheira dos Andes demonstraram que possuem um geossistema único e sem comparação em qualquer outra região do mundo, especialmente no que se refere aos recursos hídricos. Esses Nevados são responsáveis por prover bacias hidrográficas importantes para todo o globo, como a Bacia Amazônica.

Essa evidenciação ressalta a relevância dos Nevados andinos não apenas em termos de Geopatrimônio, mas também como um recurso vital para a sustentabilidade ambiental e o equilíbrio dos ecos e geossistemas. A preservação e valorização desses Nevados são fundamentais não apenas para a conservação da geodiversidade, mas também para a manutenção dos recursos hídricos essenciais para a biodiversidade e o funcionamento dos ecossistemas em nível local, regional e global.

O estudo fornece uma base inicial, porém sólida, para a formulação de políticas públicas de geoconservação, de segurança hídrica e proteção dos Nevados prioritários. A compreensão e reconhecimento das características e valores dos Nevados como elementos do Geopatrimônio, portanto, torna-se fundamental para a sua preservação e ação contra a ameaça de extinção.

Além da criação de áreas protegidas, como os geoparques, é imprescindível que haja uma conscientização ampla por parte dos tomadores de decisão em diferentes setores da sociedade sobre os riscos que as mudanças climáticas representam para a segurança hídrica. A proteção ambiental dessas áreas desempenha um papel crucial na garantia do abastecimento de água para diversas regiões e seu equilíbrio está intrinsecamente ligado ao equilíbrio térmico global.

A conscientização deve estender-se não apenas aos governos, mas também a outros setores da sociedade, incluindo o setor privado, organizações não governamentais e a população em geral. A disseminação do conhecimento sobre os Nevados, os riscos que enfrentam e sua conexão com a segurança hídrica global pode mobilizar ações efetivas e engajamento para proteger e preservar essas áreas.

Para mitigar os impactos consequentes das mudanças climáticas, é crucial que os tomadores de decisão adotem ações imediatas. Isso inclui a redução das emissões de gases de efeito estufa para limitar o aquecimento global e o estabelecimento de medidas de conservação para proteger as estruturas relacionadas à criosfera.

Um próximo passo para obter uma compreensão mais aprofundada sobre os Nevados, seria a realização de estudos em escala de detalhe, focando em áreas específicas dos Nevados sul-americanos. Isso permitiria uma análise mais aprofundada das características geológicas, geomorfológicas e ambientais de cada Nevado individualmente, levando em consideração fatores locais que podem influenciar sua importância como Geopatrimônio, principalmente valores atrelados à cultura.

Os estudos em escala de detalhe são importantes por tornarem possível a investigação as singularidades de cada Nevado, incluindo seus processos erosivos, padrões de drenagem, fauna e flora, cultura, ameaças, entre vários outros. Essas informações são necessárias para compreender o contexto ambiental de cada Nevado, fornecendo dados valiosos para a sua geoconservação e valorização. A escala de detalhe permite que conhecimento seja adquirido sobre a geodiversidade local, permitindo melhores medidas voltadas à geoconservação.

Como pontuado anteriormente, as mudanças climáticas têm o potencial de causar impactos significativos nos Nevados, incluindo o derretimento da neve, impedindo a formação de geleiras e alterando os regimes de precipitação e gerando aumento da ocorrência de eventos extremos, como secas e tempestades. Essas alterações podem afetar tanto as características físicas dos Nevados quanto os ecossistemas associados a eles.

Por causa disso, é essencial novas investigações mais a fundo as implicações das mudanças climáticas nos Nevados e o que isso pode significar para o Geopatrimônio. Compreender como essas estruturas estão respondendo às alterações climáticas e como isso afeta sua geoconservação e valor como patrimônio natural é de extrema importância em futuras pesquisas.

É importante ressaltar que os esforços sobre o conhecimento dos Nevados não devem ser restringidos apenas aos Nevados da América do Sul. A abordagem metodológicaaplicada nesta pesquisa possui um potencial significativo e pode ser adaptada e aplicada em diversas partes do mundo. Isso permitiria aos pesquisadores entender e identificar Nevados prioritários para a geoconservação em diferentes regiões. Esses estudos complementares e aprofundados são essenciais para garantir o avanço do campo do Geopatrimônio, fortalecer as bases científicas para a geoconservação e proteção ambiental, promovendo, assim, uma maior conscientização sobre a importância dos geossítios para as gerações presentes e futuras.

Por fim, é imperioso reconhecer que a proteção dos Nevados não apenas salvaguarda os recursos hídricos e os registros geológicos, mas também possui implicações socioeconômicas e ambientais com reverberações em escala regional. Esses geossítios desempenham um papel crucial no abastecimento de água, no equilíbrio ecológico e na resiliência dos ecossistemas e do geossistema. Além disso, os Nevados são importantes atrativos turísticos e podem contribuir para o desenvolvimento sustentável de comunidades locais.

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