

Article

Impacts of Prolonged Drought on Water-Dependent Tourism in Chile: An Integrated Hydro-Climatic and Economic Assessment

Carolina Rodríguez ^{1,2}, Jennyfer Serrano ³ and Eduardo Leiva ^{1,2,4,5,*} 

¹ Departamento de Química Inorgánica, Facultad de Química y de Farmacia, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, Macul 7820436, Santiago, Chile; cnrodriguez@uc.cl

² Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, Macul 7820436, Santiago, Chile

³ Escuela de Biotecnología, Universidad Mayor, Camino La Pirámide 5750, Huechuraba 8580745, Santiago, Chile; jennyfer.serrano@umayor.cl

⁴ Centro de Derecho y Gestión de Aguas, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, Macul 7820436, Santiago, Chile

⁵ Consorcio Tecnológico del Agua CoTH2O, CTI250001, Macul 7820436, Santiago, Chile

* Correspondence: ealeiva@uc.cl; Tel.: +56-2-2354-5792

Highlights

What are the main findings?

- Prolonged drought has significantly reduced snow cover and river streamflow in several tourism-relevant basins in Chile, with particularly strong effects in central Chile.
- Lower snow accumulation is strongly associated with shorter ski seasons, fewer skier-days, and reduced direct employment, while declining streamflow reduces rafting suitability in selected rivers.

What are the implications of the main findings?

- Water-dependent tourism in Chile is highly exposed to drought, but impacts vary according to geography, hydrological regime, and type of tourism activity.
- Improved tourism and environmental monitoring is needed to quantify economic impacts more accurately and support climate-resilient destination management.

Abstract

Prolonged drought in Chile has imposed increasing pressures on water-dependent tourism activities, although its effects have been assessed only fragmentarily and rarely linked to tourism-relevant indicators. This study provides an integrated hydro-climatic and economic assessment of drought impacts on two tourism categories especially sensitive to water availability: snow and mountain tourism, and tourism related to water bodies and watercourses. For this purpose, time series of snow cover, streamflow, precipitation, and water quality were analyzed for 2000–2024, complemented by sectoral statistics and indirect indicators of economic impact. Trend analyses used linear regression, the Mann–Kendall test, Sen’s slope, Pettitt change-point detection, and Spearman correlations between hydroclimatic variables and tourism proxies. Results show a significant decline in snow cover across most of northern and central Chile, with strong signals in basins critical for winter tourism and a common temporal break in 2009. Widespread streamflow reductions were also detected in rivers from central, southern, and Patagonian Chile, although with differing magnitude and timing. In contrast, water-quality changes were limited and spatially heterogeneous. In the ski sector, reduced snow accumulation was associated with shorter ski seasons, fewer skier-days, and lower direct employment. For rafting, declining streamflow was associated with reduced hydrological suitability, indicating less favorable



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potential operating conditions. Overall, drought affects tourism significantly but unevenly, depending on geography, hydrological regime, activity type, and data availability. The proposed integrated assessment helps identify differentiated drought-impact pathways and supports more climate-resilient tourism management.

Keywords: drought; water-dependent tourism; hydrological change; tourism vulnerability; Chilean tourism

1. Introduction

Chile's tourism sector has gained strong international visibility, particularly in adventure and nature-based segments. Between 2015 and 2025, Chile received the World Travel Awards for adventure tourism on 11 occasions [1]. Tourism also plays a relevant role in the national economy. In 2019, its direct contribution was approximately 3.3% of GDP (around CLP 6500 billion), and tourism-related industries employed 668,500 people (7.5% of total employment) [2]. Beyond direct employment, tourism can also generate indirect and induced employment through multiplier effects across accommodation, food services, transport, retail, and local supply chains. Tourism is also Chile's second-largest services export sector, accounting for 12.0% of total services exports in 2022 [2–4]. However, the recovery and expansion of tourism after the COVID-19 pandemic are occurring under increasing hydroclimatic stress. In particular, Chile has experienced more than a decade of precipitation deficits, declining snowpack storage, and reduced river flows, particularly in central and northern regions [5,6].

Drought is commonly defined as a prolonged absence or marked deficiency of precipitation; an abnormally dry period long enough for the lack of rainfall to cause severe hydrological imbalance [7]. However, relying on precipitation alone can provide a limited view of the phenomenon. Drought severity and impacts are also shaped by other components of the hydrological cycle, including evaporation and transpiration, as well as surface and groundwater storage dynamics, and by anthropogenic drivers that influence water availability and management [8,9]. Accordingly, drought is best understood as a complex, multidimensional process emerging from the interplay of climatic conditions and human decisions that affect natural and water systems.

The tourism sector is particularly sensitive to hydroclimatic change when tourism activities depend directly on natural resources and environmental conditions. Climate change and drought can affect tourism through multiple pathways, including reduced landscape attractiveness, shorter or less reliable seasons, lower water availability for recreational activities, and increased operational uncertainty for tourism providers [10]. These impacts are especially relevant for nature-based, mountain, and adventure tourism, where the quality, accessibility, and seasonal availability of environmental resources are central to the visitor's experience [11]. However, the magnitude and direction of these effects are rarely uniform, as they depend on the type of activity, local geography, infrastructure, adaptive capacity, and the availability of alternative destinations or activities [10,11].

Snow and mountain tourism has been one of the most widely studied examples of climate-sensitive tourism, as ski areas depend directly on snow reliability, snow accumulation, season length, and the elevation at which activities take place [11,12]. International evidence, particularly from mountain regions such as the European Alps and North America, shows that declining snow cover and warmer winter conditions tend to affect low-elevation destinations first, while higher-altitude areas may retain comparatively more favorable operating conditions for longer periods [11]. Therefore, reductions in snow cover do not translate automatically into equivalent tourism impacts across all destinations.

Rather, the consequences depend on the interaction between altitude, snowmaking capacity, infrastructure, market characteristics, and the ability of operators and destinations to adapt [13].

Tourism associated with rivers, lakes, and other water bodies is also vulnerable to drought, although it has received comparatively less attention than snow tourism. Activities such as rafting, kayaking, recreational fishing, bathing, boating, and scenic tourism depend not only on the presence of water, but also on flow magnitude, seasonality, safety conditions, and water quality [14]. In river-based recreation, both very low and very high flows may reduce suitability, since activities such as white-water rafting require hydrological conditions to remain within activity-specific ranges that ensure safety and recreational quality [15,16]. Nevertheless, long-term and activity-specific tourism statistics are often unavailable, particularly for small-scale or locally operated activities. In such contexts, hydrological indicators and suitability-based approaches provide useful indirect proxies to assess changes in recreational potential [15].

In Chile, the hydroclimatic dimension of drought has been extensively documented, particularly in relation to the central Chile megadrought, reduced precipitation, declining snow accumulation, streamflow reductions, and increasing pressure on water resources [6,17]. However, evidence on how these hydroclimatic changes affect tourism remains comparatively fragmented. Hydrological studies provide robust information on changes in snowpack, river discharge, and water availability [18,19], whereas tourism statistics and institutional datasets generally report services, attractions, employment, or visitation as sectoral indicators, without systematic linkage to basin-scale environmental conditions [4,20]. As a result, there is still limited evidence on how drought-related changes in snow cover, river discharge, and water quality translate into indicators that are operationally meaningful for tourism management.

This study addresses the following research question: How are drought-related hydroclimatic changes reflected in tourism-relevant indicators for snow/mountain tourism and tourism associated with water bodies and watercourses in Chile? To answer this question, the study develops an integrated assessment of drought-related pressures on water-dependent tourism, focusing on two groups of activities: snow and mountain tourism, and tourism associated with water bodies and watercourses. The analysis combines trends in snowpack, flow, precipitation, and water quality with sectoral statistics and indirect indicators of tourism performance or recreational suitability. The contribution of this study is to provide a national-scale synthesis of the spatially differentiated impacts of drought on water-dependent tourism in Chile.

1.1. Chile and Tourism

Chile has a broad and diverse tourism sector, encompassing a wide range of natural and cultural attractions across highly heterogeneous landscapes. In this context, the impacts of drought on tourism can be expressed through multiple pathways and across different tourism forms. However, a useful analytical approach is to focus on tourism segments that are directly linked to water, where this resource plays a central role in shaping the landscape, enabling recreational activities, or sustaining the overall visitor experience.

The National Tourism Service (SERNATUR) database identifies a total of 4881 tourism attractions nationwide, with the highest concentrations in Valparaíso (12%), the Metropolitan Region, which includes Santiago, the national capital, (10%), and O'Higgins (9%) [21]. These attractions are grouped into seven categories, two of which are particularly directly linked to activities sensitive to drought impacts: tourist routes and circuits and natural sites. These categories are further subdivided into ten attraction types, among which the

most prevalent are: (i) mountain attractions (17% relative share) and (ii) water bodies and watercourses (25%).

1.1.1. Snow and Mountain Tourism

Snow- and mountain-related attractions constitute a major component of Chile's tourism offer. Approximately 63.8% of continental Chile corresponds to mountainous areas, which include around 2900 volcanoes (90 active), 24,114 glaciers, 52 thermal springs of tourism interest, and 21 ski resorts. In this context, Production Development Corporation (CORFO) has promoted the National Mountain Tourism Plan, which includes more than 300 projects aimed at strengthening this tourism segment [22].

Figure 1A shows snow- and mountain-related tourism attractions by region. In northern Chile, attractions are dominated by volcanoes and hills, whereas from the Valparaíso Region southwards, snow-covered areas, high-mountain zones, and the Andes range become more frequent, reflecting a tourism offer more strongly associated with snow conditions [23]. Figure 1B presents registered tourism services linked to snow and mountain activities. Antofagasta stands out due to the high number of services related to mountain activities, hiking/trekking, and trail use. The Metropolitan Region also shows a high number of similar services, including ski resorts and horseback riding. La Araucanía likewise exhibits a relevant supply of mountain-related tourism services, particularly trekking/hiking and horseback riding.

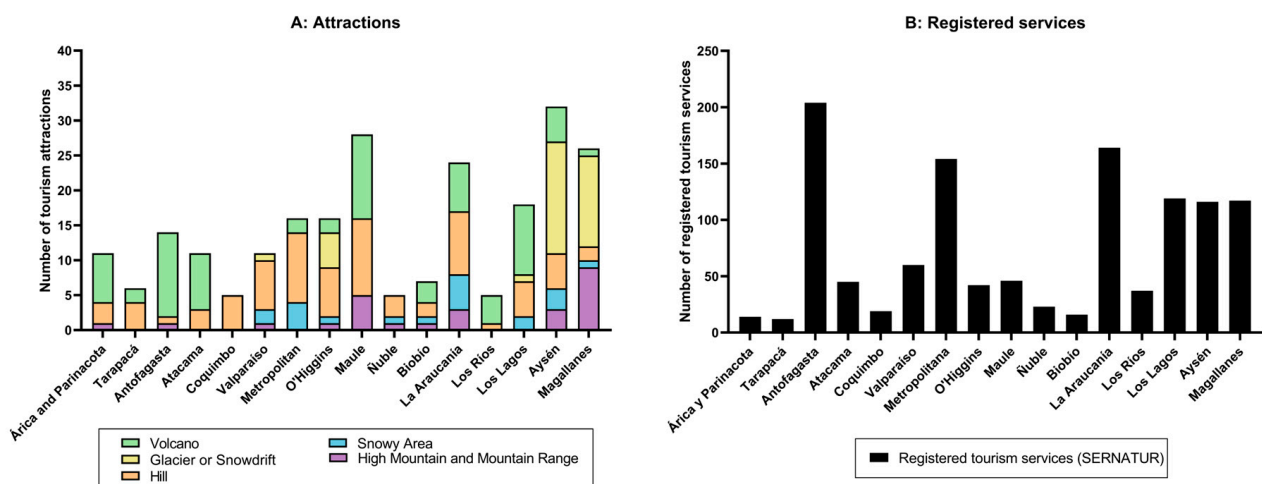


Figure 1. Snow- and mountain-related tourism attractions and registered tourism services by region. (A) Stacked bars show the number of tourism attractions associated with snow and mountain environments by attraction type. (B) Bars show the number of registered tourism services associated with snow- and mountain-related activities, according to SERNATUR.

1.1.2. Tourism Related to Water Bodies and Watercourses

Tourism attractions associated with water bodies and watercourses constitute a key pillar of nature-based tourism in Chile, given the abundance of rivers, lakes, wetlands, and coastal environments across the country. According to the 2024 State of the Environment Report, Chile comprises 101 basins including 1251 rivers, spanning more than 756,000 km² when considering both surface- and groundwater basins. A total of 368 lakes and 12,416 lagoons are also recorded nationwide, 71% of which are located in the southern and austral macrozones [24]. These ecosystems support activities such as recreational fishing, boating and navigation, rafting, wildlife observation, and scientific tourism.

Figure 2A presents tourism attractions associated with water bodies and watercourses. The following attraction types were considered: waterfalls, wetlands and high-Andean peatlands (bofedales), lakes and lagoons, rivers and streams, and other watercourse-related

attractions. The number of attractions is comparatively limited in northern and central Chile. In the Maule Region, and especially from La Araucanía southwards, a marked increase is observed, largely driven by lake/lagoons and rivers/streams. Figure 2B shows registered tourism services SERNATUR (2025) linked to water-based activities. Consistent with the attraction patterns, service supply increases substantially from La Araucanía southwards, particularly for rafting (white-water rafting) and nautical excursions.

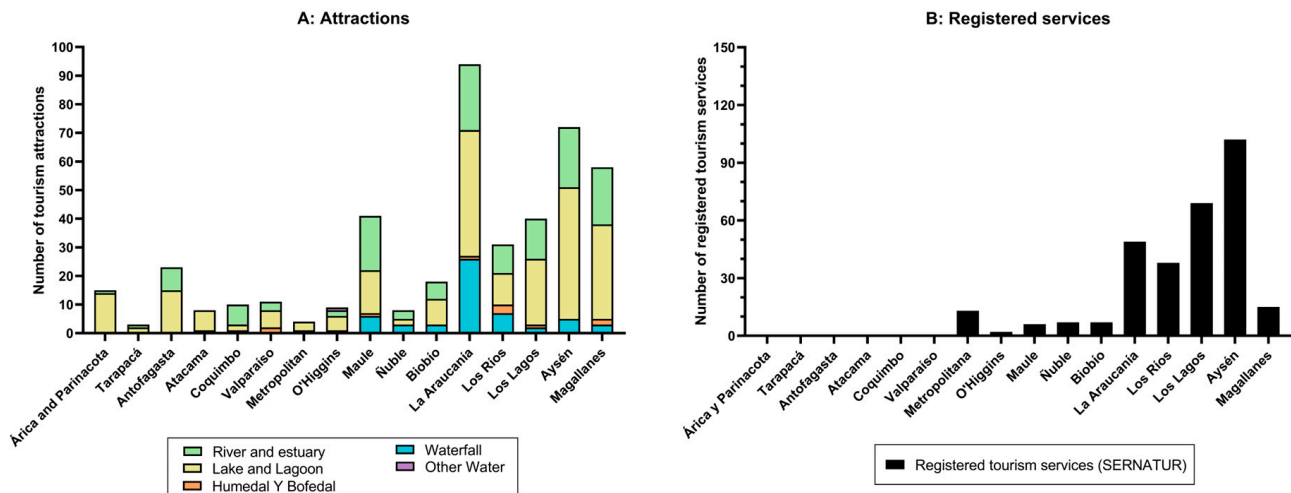


Figure 2. Tourism attractions and registered tourism services related to water bodies and watercourses by region. (A) Stacked bars show the number of tourism attractions associated with water bodies and watercourses by attraction type. (B) Bars show the number of registered tourism services associated with water-based tourism activities, according to SERNATUR.

2. Materials and Methods

The assessment of drought impacts on tourism was based on integrating multiple types of information: hydro-meteorological time series (snow cover, streamflow, and precipitation), water-quality data, and, complementarily, available sectoral statistics for specific tourism activities. The analysis period was generally bounded to 2000–2024, depending on the availability, continuity, and consistency of the records. Using these sources, we applied statistical procedures comparable across basins and tourism types, combining trend analyses, correlation analyses, and the construction of synthetic indicators of recreational suitability.

2.1. Selection of Case Studies

The study considered two broad tourism categories: (i) snow and mountain tourism and (ii) tourism related to water bodies and watercourses. For each category, basins and rivers were selected if they simultaneously met the following criteria:

1. Tourism relevance, as indicated by the presence of ski resorts, bathing areas, rafting activities, or other established attractions.
2. Availability of historical series for snow cover, streamflow, and/or water quality with sufficient length (≥ 20 years) to support trend and correlation analyses.
3. Geographical representativeness and coverage of different hydrological regimes (snowmelt-dominated, rain-snow mixed, and mixed regimes).

For snow and mountain tourism, the initial universe corresponded to the Chilean basins available in the Snow Observatory in the Andes of Argentina and Chile, which provides snow-cover information for the subtropical Andes between 27° S and 37° S from 2000 onward. These basins were cross-checked with the spatial distribution of snow- and mountain-related tourism attractions and services. Basins were retained when they had

both available snow-cover records and tourism relevance for mountain or snow-related activities. Based on this procedure, the selected basins were Copiapó, Elqui, Choapa, Aconcagua, Maipo, Mapocho, Cachapoal, Tinguiririca, Teno, Colorado, Maule, and Ñuble.

For tourism related to water bodies and watercourses, the selection was based on the spatial distribution of tourism attractions and services associated with waterfalls, wetlands and high-Andean peatlands, lakes and lagoons, rivers and streams, rafting, nautical activities, and other water-related attractions. These areas were then matched with available streamflow records from the National Hydrometric Network. Rivers were selected when they combined tourism relevance with sufficiently long and representative streamflow records for temporal analysis. Based on this procedure, the selected rivers were Maipo, Maule, Teno, Itata, Ñuble, Biobío, Laja, Toltén, Bueno, Calle Calle, Puelo, Aisén, Baker, Palena, Pascua, and Grande.

2.2. Data Sources and Preprocessing

The analysis was based on multiple environmental and tourism-related datasets, selected according to their temporal coverage, spatial relevance to the selected basins and tourism activities, and consistency across the study period. Table 1 summarizes the variables and data sources. In general, the study period was 2000–2024; however, shorter periods were used when data availability was limited.

Table 1. Data sources used in the hydroclimatic, water-quality, and tourism analyses.

Variable	Source	Dataset	Institution	Temporal Resolution	Period Used
Seasonal snow cover	Observatorio de Nieve en los Andes de Argentina y Chile [25]	Basin-scale historical snow-cover series derived from MODIS Terra/Aqua satellite imagery	IANIGLA-CONICET/CR2; online platform	Daily data aggregated seasonally	2000–2024
Streamflow	National Water Bank (Banco Nacional de Aguas, BNA), National Water Information System (Sistema Nacional de Información del Agua, SNIA) [26]	Mean monthly streamflow records from gauging stations	General Water Directorate (Dirección General de Aguas, DGA), Ministry of Public Works, Chile	Monthly	2000–2024, depending on station availability
Precipitation	National Water Bank (Banco Nacional de Aguas, BNA), National Water Information System (Sistema Nacional de Información del Agua, SNIA) [26]	Monthly accumulated precipitation records from rainfall stations	General Water Directorate (Dirección General de Aguas, DGA), Ministry of Public Works, Chile	Monthly	2000–2024, depending on station availability
Water quality	National Water Bank (Banco Nacional de Aguas, BNA), National Water Information System (Sistema Nacional de Información del Agua, SNIA) [26]	Physicochemical water-quality monitoring records	General Water Directorate (Dirección General de Aguas, DGA), Ministry of Public Works, Chile	Variable; annual series constructed from available records	2000–2024, depending on station and parameter availability
Ski-sector indicators	Chilean Ski Centers Association (Asociación de Centros de Ski de Chile, ACESKI) [27]	Annual report/news release on the 2024 ski season	ACESKI website	Annual	2015–2024

All time-series were checked to ensure temporal consistency (alignment of years and periods), removal of duplicates, and unit harmonization. When short gaps were present,

their potential influence on the analyses was assessed and, when necessary, years with insufficient information were excluded to avoid bias.

2.3. Trend Analysis of Snow Cover and Streamflow

To quantify long-term changes in snow cover and streamflow, we applied complementary parametric and non-parametric trend analyses commonly used in hydroclimatic studies, including simple linear regression, the Mann–Kendall test, and Sen’s slope estimator [28].

Simple linear regression was used to estimate the direction and magnitude of temporal change:

$$Y_t = \alpha + \beta t + \varepsilon_t$$

where Y_t is the variable of interest in year t , α is the intercept, β is the linear trend slope, and ε_t is the residual error. The slope β , its p -value, and the coefficient of determination R^2 were reported.

The Mann–Kendall test was used to identify monotonic trends without assuming normality. The test statistic was calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(Y_j - Y_i)$$

where

$$\text{sgn}(Y_j - Y_i) = \begin{cases} 1, & Y_j - Y_i > 0 \\ 0, & Y_j - Y_i = 0 \\ -1, & Y_j - Y_i < 0 \end{cases}$$

Sen’s slope was used as a robust estimate of trend magnitude and was calculated as the median of all pairwise slopes:

$$Q = \text{median}\left(\frac{Y_j - Y_i}{j - i}\right), j > i$$

Evidence of a trend was considered when at least one of the parametric or non-parametric approaches indicated statistical significance ($p < 0.05$) and the direction of change was consistent across methods.

2.4. Correlation Analysis Among Hydro-Meteorological Variables

Relationships among hydro-meteorological variables were assessed using Spearman’s rank correlation coefficient (ρ_s), a non-parametric measure of monotonic association. For paired observations X_i and Y_i , values were converted into ranks and the coefficient was calculated as:

$$\rho_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

where d_i is the difference between the ranks of each pair of observations and n is the number of paired observations. Statistical significance was evaluated using p -values with a threshold of $\alpha = 0.05$.

2.5. Water-Quality Analysis

The water-quality analysis focused on monitoring stations located in tourism-relevant rivers, particularly those associated with snow and mountain activities and with watercourse-based tourism. For each parameter (e.g., electrical conductivity, aluminum, arsenic, iron, among others), annual series were constructed from available records for 2000–2024. The same trend procedures used for snow cover and streamflow (simple linear

regression, Mann–Kendall, and Sen’s slope) were applied to identify parameters exhibiting significant increasing or decreasing trends and to assess whether observed changes could compromise resource quality from a tourism perspective.

2.6. Relative Hydrological Suitability Index for Rafting

Because systematic records of visits, trips, or revenues for rafting were not available, we developed a hydrology-based indicator as a proxy for river suitability for rafting. This approach is based on the premise that white-water rafting requires streamflow conditions to remain within activity-specific ranges that ensure both safety and recreational quality. Similar suitability-based approaches have been used to evaluate the relationship between river discharge and white-water recreation [15,16].

The rafting season was defined as September–May, encompassing the main months when rafting operates. Using historical monthly streamflow, operational ranges (not suitable, sub-optimal, optimal) were defined to reflect rafting conditions. These ranges were established based on the historical streamflow distribution and quartile thresholds.

A monthly score $S_{m,y}$ was assigned each month m in year y :

$$S_{m,y} = \begin{cases} 0, & \text{not suitable} \\ 0.5, & \text{sub-optimal} \\ 1, & \text{optimal} \end{cases}$$

The annual suitability score was then calculated as the mean monthly score during the rafting season:

$$A_y = \frac{1}{M} \sum_{m=1}^M S_{m,y}$$

where M is the number of months in the rafting season with available streamflow data. Finally, the index was normalized by the maximum annual score observed for each river:

$$RAI_y = \frac{A_y}{\max(A_y)}$$

where RAI_y ranges from 0 to 1. A value of 1 represents the year with the most favorable hydrological conditions observed for a given river, whereas lower values indicate fewer months with suitable flow conditions. The index should be interpreted as a relative measure of hydrological suitability, not as a direct estimate of visitor numbers, trips, or revenue.

2.7. Economic Impact Assessment

The economic assessment was conducted in a complementary manner for both tourism categories, acknowledging important data limitations.

For snow and mountain tourism, ACESKI reports were used, including average season length, accumulated snow, skier-days, and total direct employment. Spearman correlations were calculated between season length and each indicator, interpreting accumulated snow as a proxy for drought conditions (drier years associated with lower accumulation). This approach allowed us to quantify how variation in snow availability relates to season duration and, through it, to economic activity (skier-days) and employment in the sector.

For tourism related to water bodies and watercourses, given the lack of activity-specific economic statistics, the Relative Hydrological Suitability Index was interpreted as an indirect indicator of the potential operating conditions for rafting, rather than as a direct measure of tourism demand or revenue. Under the assumption that the number of commercial trips and related revenues depend partly on the number of months with

adequate flows, a sustained decline in the index was interpreted as an indirect indicator of less favorable hydrological conditions for rafting operations.

3. Results and Discussion

In the following sections, the main effects of drought on tourism in Chile are presented, covering ecosystem-level impacts, water-quality implications, and economic effects.

3.1. Impacts on Tourism Ecosystems

3.1.1. Snow and Mountain Tourism

Snow cover was analyzed over a 25-year window (2000–2024) using data from May to October, corresponding to the Andes snow accumulation and persistence cycle. This period overlaps with the core mountain tourism season and is informative for capturing the influence of dry years. Table 2 summarizes the trend statistics for each basin.

Table 2. Trend analysis results for seasonal snow cover (May–October; 2000–2024) across analyzed basins and sub-basins.

Basin	Slope (Linear)	p (Linear)	R ²	Z (Mann–Kendall)	p (Mann–Kendall)	Trend	Slope Sen
Copiapó River	−0.25	0.341	0.04	−0.90	0.370	No trend	−0.23
Elqui River	−0.75	0.031	0.19	−2.01	0.044	Decreasing	−0.82
Choapa River	−0.35	0.036	0.18	−2.35	0.018	Decreasing	−0.36
Aconcagua River	−0.71	0.003	0.31	−3.03	0.002	Decreasing	−0.70
Maipo River	−0.65	0.004	0.30	−2.79	0.005	Decreasing	−0.66
Mapocho River	−0.81	0.003	0.33	−2.93	0.003	Decreasing	−0.80
Cachapoal River	−0.49	0.006	0.28	−2.55	0.011	Decreasing	−0.45
Tinguiririca River	−0.36	0.036	0.17	−2.35	0.019	Decreasing	−0.36
Teno River	−0.33	0.106	0.11	−1.87	0.062	No trend	−0.45
Colorado River	−0.18	0.316	0.04	−1.14	0.254	No trend	−0.18
Maule River	−0.14	0.555	0.02	−0.65	0.513	No trend	−0.12
Ñuble River	0.66	0.042	0.17	1.72	0.085	No trend	0.71

The results show a generalized pattern of decline in the indicators analyzed for most river basins in northern and central Chile, with statistically significant trends identified by both linear regression and the Mann–Kendall test. The Elqui, Choapa, Aconcagua, Maipo, Mapocho, Cachapoal, and Tinguiririca basins exhibit consistent negative slopes (ranging from −0.35 to −0.81) and *p*-values below 0.05 in both methods, confirming robust decreasing trends. Among these, the Aconcagua, Maipo, and Mapocho basins stand out, as they display the highest coefficients of determination ($R^2 \approx 0.30\text{--}0.33$) and the most pronounced *Z* values (ranging from −2.79 to −3.03), indicating a persistent and systematic decline throughout the study period. In contrast, the Copiapó, Teno, Colorado, and Maule basins do not show sufficient statistical evidence to support the existence of a trend, despite exhibiting negative slopes, as their *p*-values exceed the significance threshold. Finally, the Ñuble basin is the only one showing a positive slope; however, both linear regression and the Mann–Kendall test indicate that this trend is not statistically significant, and therefore no sustained increase can be inferred. Figure 3 shows the spatial patterns associated with snow cover.

Figure 3 highlights a marked spatial concentration of snow-cover decline in north-central and central Chile. The strongest negative trends are observed in the Mapocho and Elqui basins, while Aconcagua and Maipo also exhibit substantial decreases; by contrast, basins in south-central Chile show weaker or non-significant changes. This pattern is particularly relevant for mountain tourism, as the most important ski area in the Metropolitan Region is located precisely in the central Andes, where ski infrastructure is concentrated around Santiago. Official tourism sources identify La Parva, El Colorado-Farellones, Valle Nevado, and Lagunillas as the main winter centers associated with the

Metropolitan Region, and both Valle Nevado and La Parva are located in the Andean sector of Lo Barnechea, directly linked to the high-mountain environment of the Mapocho-Maipo system [20,21]. Therefore, the spatial distribution shown in Figure 3 suggests that the most intense snow-cover losses are occurring in one of Chile's most relevant snow-tourism corridors, reinforcing the exposure of central Chilean ski destinations to ongoing reductions in snow accumulation and persistence.

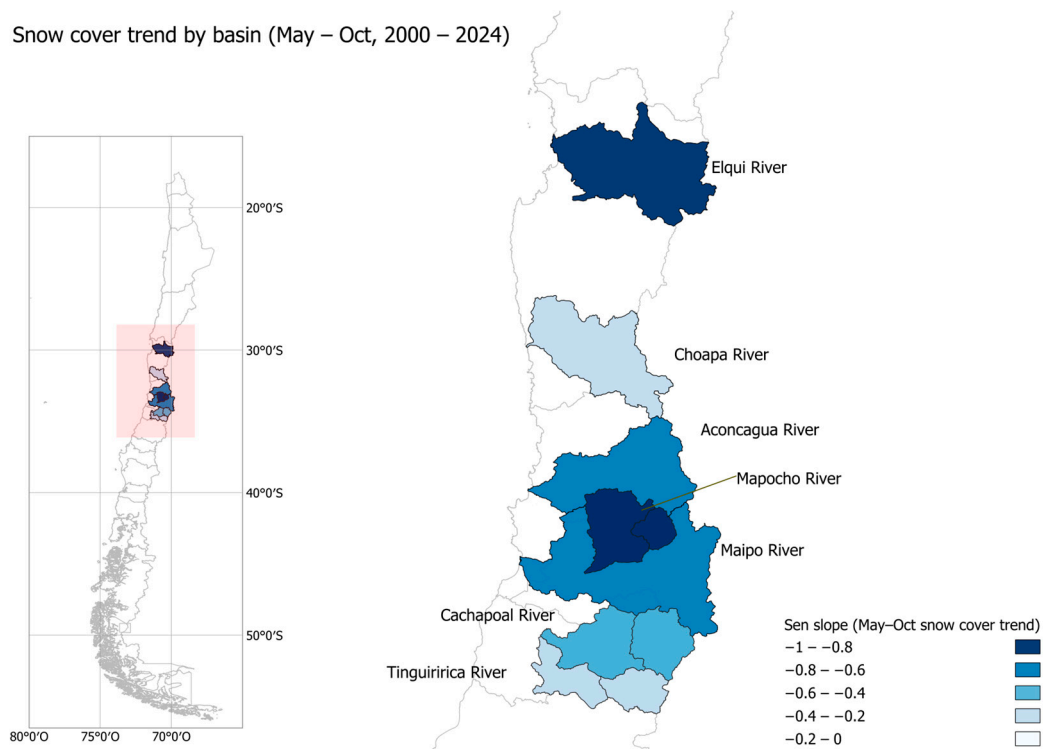


Figure 3. Spatial patterns of seasonal snow cover trends (May–October, 2000–2024) across Chilean basins.

The tourism implications of these snow-cover declines should also be interpreted in relation to altitude. International evidence indicates that low-elevation ski areas are generally more vulnerable to warming and reduced snow reliability, whereas higher-elevation areas may retain comparatively more favorable operating conditions for longer periods [11,12]. In the Chilean case, the main ski areas near Santiago are located in high-Andean sectors, which may partially buffer the immediate operational effects of declining snow cover. However, sustained reductions in seasonal snow cover may still affect season reliability, opening dates, snowmaking requirements, and operating costs, particularly in lower sectors of ski domains or in mountain destinations with less adaptive infrastructure [12,13]. Therefore, the tourism consequences of snow-cover decline are likely to be elevation-dependent rather than spatially uniform.

Additionally, a temporal break analysis was carried out; for this, Pettitt's change point analysis was applied to a subset of basins selected based on two criteria: a statistically significant declining trend in seasonal snow cover and their relevance for mountain tourism due to the presence of major ski destinations. Table 3 shows that all selected basins exhibit a common change point in 2009, suggesting a spatially coherent temporal shift rather than isolated basin-specific behavior. According to the Pettitt test, the break is statistically significant in the Aconcagua, Maipo, and Mapocho basins, whereas Cachapoal shows a weaker and non-significant signal under the conventional 0.05 threshold. In all cases, the post-break median is lower than the pre-break median, with reductions ranging from 6.8%

in Cachapoal to 22.6% in Maipo, indicating that snow-cover conditions after 2009 became systematically less favorable than in the preceding period.

Table 3. Pettitt change-point analysis of seasonal snow cover (May–October; 2000–2024) in selected basins.

Basin	Change-Point Year	Pettitt <i>p</i> -Value	Pre-Break Median	Post-Break Median	Post vs. Pre Change (%)
Aconcagua River	2009	0.014	71.18	60.21	−15.4
Maipo River	2009	0.016	55.39	42.88	−22.6
Mapocho River	2009	0.031	77.63	67.26	−13.4
Cachapoal River	2009	0.088	68.99	64.31	−6.8

Figure 4 illustrates this shift visually, showing that the annual May–October snow-cover series tends to cluster around higher values before 2009 and lower values afterward. The coincidence of the break year across basins is consistent with the onset of persistently drier conditions in central Chile associated with the megadrought period that began around 2010, reinforcing the interpretation of a regional transition toward a lower snow baseline [6]. From a tourism perspective, this result is especially relevant because the most important ski areas near Santiago are located precisely in the basins where the strongest and most significant changes are observed, particularly within the Maipo-Mapocho corridor. A sustained reduction in the typical snow-cover conditions during the accumulation and persistence season may therefore affect not only hydrological dynamics, but also the reliability and duration of the winter tourism season in one of Chile’s main snow-tourism regions.

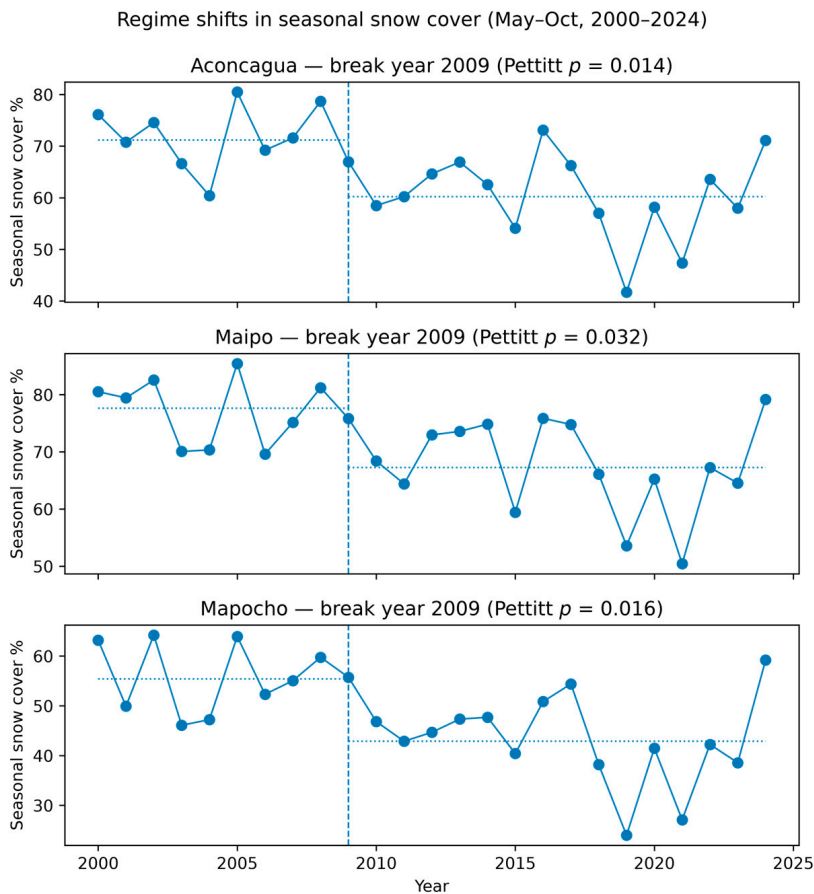


Figure 4. Pettitt change-point detection in seasonal snow cover (May–October) for selected basins.

Subsequently, a correlation analysis was conducted to examine the relationship between annual snow cover and hydroclimatic variables in the selected basins. In the

Aconcagua, Maipo, and Mapocho basins, annual snow cover showed positive and statistically significant correlations with both annual streamflow and annual accumulated precipitation (Spearman, $p < 0.01$). In particular, the snow-streamflow association was moderate to strong ($\rho = 0.629\text{--}0.674$), whereas the snow-precipitation association was strong ($\rho = 0.631\text{--}0.836$), suggesting that wetter years tend to exhibit greater snow cover and, in turn, higher streamflow. In the Cachapoal basin, a robust correlation analysis could not be performed due to the lack of sufficiently long records in high-mountain sectors or near the prioritized tourist attractions.

These results suggest that the observed snow-cover decline is not only a hydrological signal but also reflects broader climatic controls affecting the central Andes. Previous studies have linked the central Chile megadrought to persistent precipitation deficits and atmospheric circulation anomalies [6,17], while recent evidence has documented a rapid decline in extratropical Andean snow cover [19]. Therefore, the significant snow-cover reductions detected in the Aconcagua, Maipo, and Mapocho basins are consistent with regional climatic drying and reduced snow accumulation during the study period.

3.1.2. Tourism Related to Water Bodies and Watercourses

Monthly streamflow series were analyzed for the selected rivers over a 25-year period (2000–2024). For rivers whose gauging stations provided shorter records, the longest available period was used; the shortest case corresponded to the Calle Calle River, with analysis covering 2007–2023 (17 years). Temporal trends were assessed using simple linear regression (slope, significance, and R^2), complemented by the non-parametric Mann–Kendall test to detect monotonic trends, and Sen’s slope to provide a robust estimate of annual change. These results are presented in Table 4.

Table 4. Trend analysis results for river streamflow (2000–2024) across the analyzed rivers.

River	Slope (Linear)	p (Linear)	R^2	Z (Mann–Kendall)	p (Mann–Kendall)	Trend	Slope Sen
Maipo River	−3.87	4.86×10^{-4}	0.50	−3.30	9.77×10^{-4}	Decreasing	−3.76
Maule River	−3.24	1.37×10^{-3}	0.42	−3.57	3.60×10^{-4}	Decreasing	−1.57
Teno River	−2.62	1.53×10^{-6}	0.68	−4.62	3.80×10^{-6}	Decreasing	−2.58
Itata River	−2.57	6.75×10^{-3}	0.28	−2.16	3.09×10^{-2}	Decreasing	−2.42
Ñuble River	−1.23	8.19×10^{-2}	0.13	−1.33	1.82×10^{-1}	No trend	−1.08
Biobío River	−5.36	6.50×10^{-2}	0.14	−2.20	2.73×10^{-2}	Decreasing	−6.17
Laja River	−6.31	6.23×10^{-10}	0.87	−5.08	3.72×10^{-7}	Decreasing	−6.31
Toltén River	−0.82	8.42×10^{-1}	0.002	−1.16	2.43×10^{-1}	No trend	−4.10
Bueno River	−5.75	2.30×10^{-3}	0.41	−3.37	7.65×10^{-4}	Decreasing	−5.45
Calle Calle River	−4.65	4.38×10^{-1}	0.04	−0.83	4.09×10^{-1}	No trend	−5.37
Puelo River	−12.91	1.06×10^{-3}	0.44	−2.94	3.32×10^{-3}	Decreasing	−12.02
Aisén River	−8.10	1.21×10^{-3}	0.37	−3.52	4.37×10^{-4}	Decreasing	−9.70
Baker River	−7.29	1.84×10^{-3}	0.39	−2.77	5.68×10^{-3}	Decreasing	−7.66
Palena River	−9.02	1.57×10^{-3}	0.36	−3.13	1.76×10^{-3}	Decreasing	−9.99
Pascua River	−4.53	1.09×10^{-1}	0.12	−1.41	1.58×10^{-1}	No trend	−4.14
Grande River	0.25	2.49×10^{-1}	0.06	−0.85	3.96×10^{-1}	No trend	−0.28

Overall, results indicate a widespread decline in mean streamflow across most analyzed rivers in central and southern Chile, with statistically significant decreasing trends supported by both linear regression and the Mann–Kendall test. The Maule, Teno, Itata, Biobío, Laja, Bueno, Puelo, Aisén, Baker, and Palena rivers show negative slopes and $p < 0.05$ in both methods, confirming robust decreasing trends. Among these, the Laja River exhibits a particularly strong linear signal ($R^2 = 0.87$) and highly significant p -values, consistent with a pronounced and persistent decline. In contrast, the Ñuble, Toltén, Calle Calle, Pascua, and Grande rivers do not provide sufficient statistical evidence to assert a trend, despite negative slopes in several cases. The Grande River is the only case with a positive linear slope. However, neither linear regression nor Mann–Kendall supports

statistical significance, and thus a sustained increase cannot be concluded. Figure 5 shows the spatial patterns associated with river streamflow.

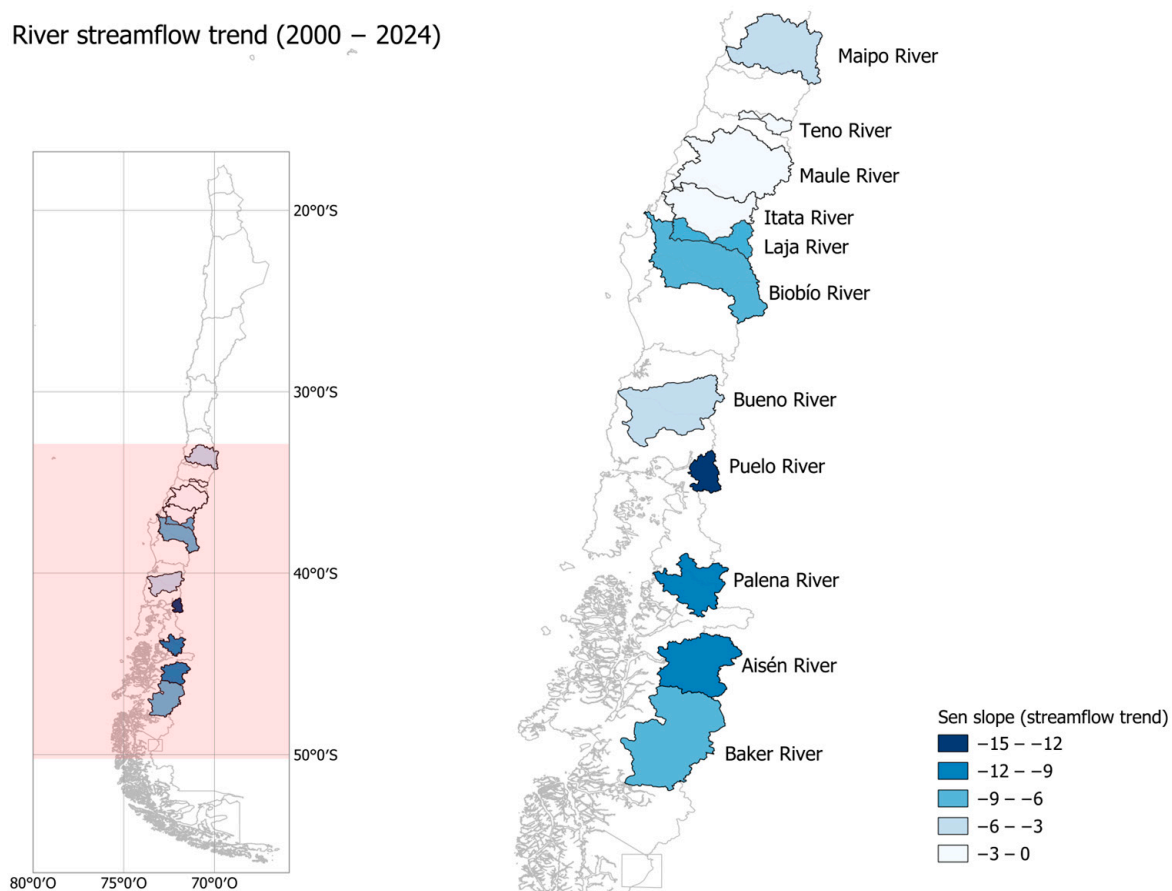


Figure 5. Spatial patterns of river streamflow trends (2000–2024) across Chilean basins.

Figure 5 shows that decreasing streamflow trends are spatially widespread across Chile, although their magnitude and statistical significance vary among basins. A first clear pattern is observed in central Chile, where rivers such as the Maipo, Maule, and Teno exhibit significant negative trends, indicating a sustained reduction in water availability in one of the country's most socioeconomically important regions [29]. This declining signal continues into south-central Chile, where the Itata, Biobío, and especially the Laja River also show marked decreases. Among these, the Laja River stands out as the most robust case, with the highest coefficient of determination ($R^2 = 0.87$) and highly significant results in both linear regression and the Mann–Kendall test, reflecting a strong and persistent decline over the study period.

A second relevant pattern is that negative trends are not restricted to central Chile, but also extend into southern and Patagonian rivers. Significant declines were detected in the Bueno, Puelo, Aisén, Baker, and Palena rivers, suggesting that streamflow reduction is geographically extensive rather than confined to the Mediterranean-climate zone [30,31]. In contrast, some rivers, including the Ñuble, Toltén, Calle Calle, and Pascua, show negative slopes but no statistically significant trend, pointing to greater interannual variability or less consistent long-term change.

The Pettitt change-point analysis identified statistically significant shifts in streamflow across all selected rivers, although the timing and magnitude of the break varied among basins (Table 5). In central Chile, both the Teno and Maule rivers exhibited a common change point in 2009, with marked reductions in post-break median streamflow of 55.1%

and 76.2%, respectively. These results indicate an abrupt transition toward substantially lower flow conditions after 2009, consistent with the strong declining trends previously detected in these rivers. The Biobío River showed an earlier break in 2006, with a median reduction of 35.9%, suggesting that hydrological changes in south-central Chile may have started slightly earlier in some basins. Overall, these results point to a broad shift toward reduced streamflow regimes, rather than gradual variation alone.

Table 5. Pettitt change-point analysis of streamflow (2000–2024) in selected basins.

Basin	Change-Point Year	Pettitt p -Value	Pre-Break Median	Post-Break Median	Post vs. Pre Change (%)
Teno River	2009	8.68×10^{-4}	68.00	30.55	−55.07
Maule River	2009	8.47×10^{-3}	43.77	10.42	−76.20
Biobío River	2006	1.95×10^{-2}	504.33	323.44	−35.87
Bueno River	2010	1.84×10^{-2}	358.40	309.07	−13.76
Palena River	2014	2.70×10^{-2}	845.79	735.85	−13.00
Aisén River	2012	2.70×10^{-2}	573.64	420.57	−26.68
Baker River	2015	2.80×10^{-2}	582.81	476.53	−18.24

Figure 6 further illustrates that this transition was not synchronous across the entire study area. While some rivers in central and south-central Chile experienced breaks around 2006–2009, southern and Patagonian rivers showed later change points, including 2010 in the Bueno River, 2012 in the Aisén River, and 2014–2015 in the Palena and Baker rivers. In all cases, post-break medians were lower than pre-break medians, confirming a systematic downward shift in typical streamflow conditions. From a tourism perspective, these results are particularly relevant because they indicate that rivers supporting water-based recreation and landscape attractions have experienced not only long-term declining trends, but also distinct regime shifts toward persistently lower flows.

Additionally, correlation analysis between streamflow and annual precipitation was conducted to assess whether the observed discharge declines could plausibly be linked to drier conditions rather than exclusively to anthropogenic regulation. Overall, most evaluated rivers showed positive and statistically significant associations, indicating that lower streamflow is, at least in part, related to reduced precipitation at the basin scale. The strongest relationships were found for the Teno and Biobío rivers, while the Maipo, Bueno, and Aisén rivers exhibited moderate but still significant correlations. In contrast, the Baker and Palena rivers did not show significant associations, suggesting that additional controls, such as glacier-influenced hydrology, local basin processes, or human interventions, may play a more important role in explaining streamflow variability. These results support the interpretation that precipitation deficits are a major driver of declining discharge in several priority basins, although the strength of this relationship is spatially heterogeneous and, in some cases, constrained by data limitations.

The spatial heterogeneity observed in streamflow trends also suggests that climatic forcing interacts with basin-specific controls. In central and south-central Chile, significant positive associations between precipitation and streamflow support the role of reduced precipitation as a major driver of declining discharge, consistent with previous evidence on the central Chile megadrought and increasing pressure on water resources [6,30]. In contrast, the weaker relationships observed in some Patagonian rivers indicate that glacier influence, natural storage, basin regulation, and local hydrological processes may modulate the response to climatic variability, as also suggested by studies documenting regional hydroclimatic anomalies and hydrological shifts in Patagonia [30,31].

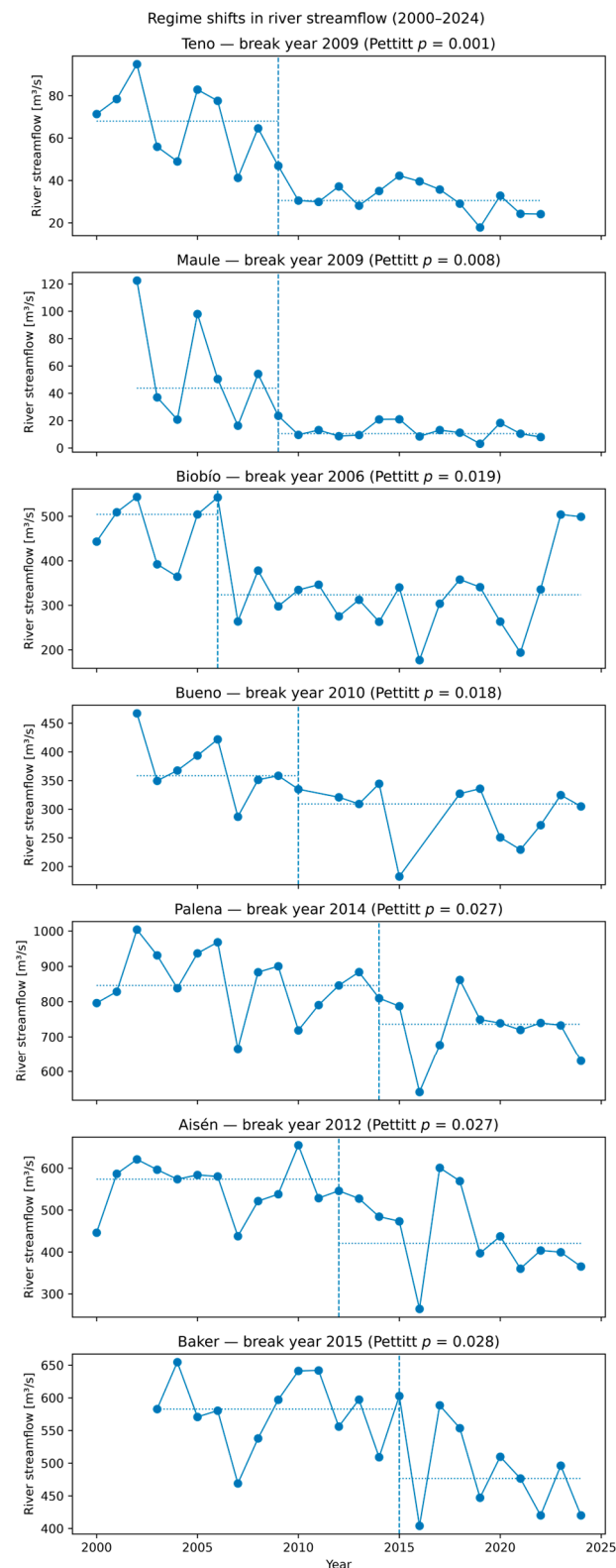


Figure 6. Pettitt change-point detection in river streamflow (2000–2024) for selected basins.

3.2. Impacts on Water Quality

Water-quality analyses were included to assess whether the hydrological changes identified in the selected basins were accompanied by detectable long-term deterioration in key physicochemical parameters. Overall, results indicate limited and spatially heterogeneous signals, with most parameters showing no statistically significant monotonic trends over the study period. Where significant trends were detected, these were generally

restricted to specific variables rather than reflecting generalized water-quality degradation. The most recurrent signal was an increase in electrical conductivity in some central basins, while several metals showed either stability or decreasing trends. Taken together, these results suggest that, despite the observed reductions in snow cover and streamflow, long-term drought-related effects on water quality were weak or not consistently detectable at the analyzed stations. Detailed results for each station and parameter are presented in Supplementary Materials (Tables S1–S8).

For snow- and mountain-tourism basins, most water-quality parameters remained stable over time. In the Aconcagua and Mapocho basins, the main signal was a significant increase in conductivity, suggesting possible salinization processes, whereas in the Maipo basin only arsenic showed a weak but significant increasing trend. In the Cachapoal basin, several metals exhibited decreasing trends, indicating changes that do not support a generalized drought-related deterioration in water quality.

For rivers associated with tourism related to water bodies and watercourses, results were similarly limited. The Teno River showed increasing conductivity and decreasing aluminum; the Biobío River, only a small increase in copper; and the Bueno River, slight increases in aluminum and arsenic. In contrast, the Aisén River showed no significant trends in any of the evaluated parameters. Overall, the detected changes were modest and site-specific, providing little evidence of widespread long-term water-quality degradation associated with declining streamflow.

3.3. Economic Impacts

One of the main limitations in estimating and assessing the economic impacts of drought on the tourism types analyzed is the limited availability of tourism visitation data. Information provided by SERNATUR generally lacks time series long enough to identify statistically robust trends or to establish correlations with drought indicators. This is further compounded by the effects of the pandemic and the subsequent recovery, which introduced abrupt fluctuations in recent records and complicate the interpretation of temporal trends. In addition, the available data do not provide the level of disaggregation required to directly link visitor flows to the specific tourist attractions selected in this study, thereby limiting the ability to assess impacts specifically associated with snow decline or the deterioration of water bodies and watercourses. Accordingly, the results of this analysis should be interpreted with caution in light of these constraints. The results for the tourism types evaluated are presented below.

3.3.1. Snow and Mountain Tourism

The Chilean Ski Centers Association (ACESKI) provides several reports containing relevant statistics on winter-season performance. However, it was not possible to access information prior to 2015, which limits the possibility of conducting long-term trend analyses. Figure 7 presents the information compiled on the average duration of the ski season in recent years.

The information reported by ACESKI constitutes a highly valuable source for estimating the economic impacts associated with mountain tourism, as it is provided directly by the ski centers themselves, which gives it a high degree of reliability. In the same report for the 2024 season, from which the data presented above were obtained, the number of skier-days, average accumulated snowfall (cm), and total employment generated were also reported. These indicators were analyzed and correlated with one another in order to explore possible relationships among snow availability, tourism activity, and employment generation in the sector.

For the purposes of this analysis, average accumulated snowfall was considered a drought-related indicator, such that years with lower snow accumulation were interpreted as relatively drier years. The first step of the analysis was to evaluate the correlation between accumulated snowfall and the average duration of the ski season. Spearman's correlation coefficient showed a strong and positive relationship between these two variables ($\rho = 0.887$; $p = 0.001$), indicating that, during the study period, a longer ski season was directly associated with greater snow accumulation. Figure 8a presents the correlation plot between these variables.

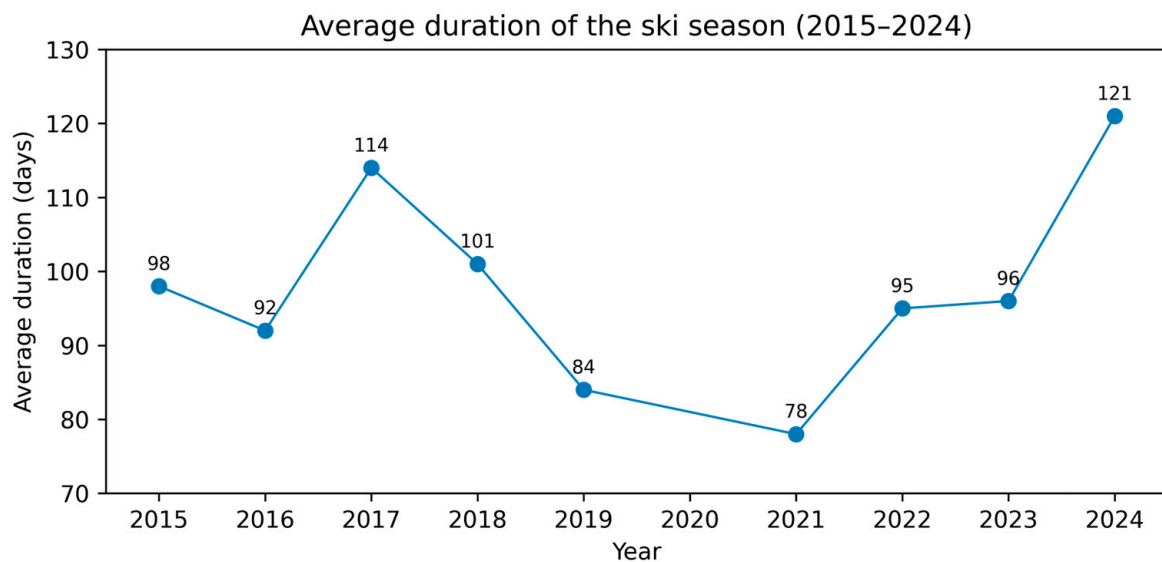


Figure 7. Average duration of the ski season (2015–2024).

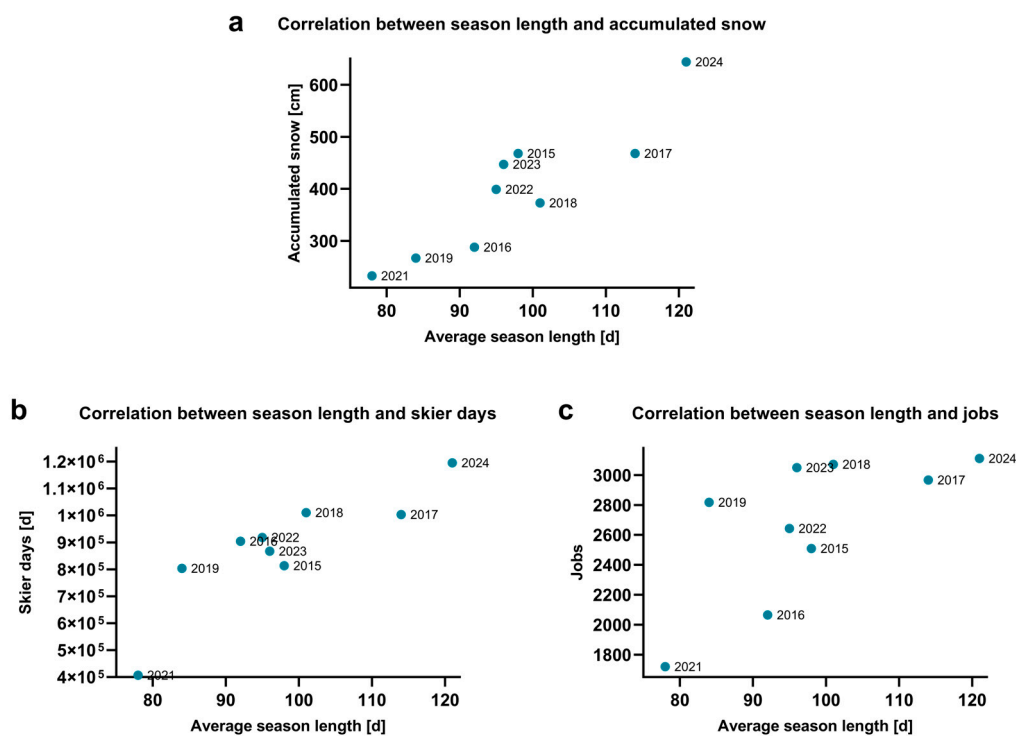


Figure 8. Correlation plots between: (a) average ski season duration and accumulated snowfall; (b) average ski season duration and skier-days; and (c) average ski season duration and total direct employment, based on ACESKI data.

Based on the above, drought can be understood to affect the ski sector through reductions in snow cover and snow accumulation, which are directly associated with a shorter ski season and, consequently, with relevant economic impacts on the sector. To further examine this relationship, the correlation analysis was repeated using average season duration against the other reported indicators: skier-days and number of jobs. The results show a strong positive relationship between season duration and skier-days ($\rho = 0.833$; $p = 0.005$), as well as between season duration and employment generation ($\rho = 0.767$; $p = 0.02$), as expected given the sector's dependence on snow availability. Figure 8b,c present the corresponding correlation plots.

Thus, by applying linear regression to the variables analyzed, it is possible to estimate the impact that an additional day (or a lost day) in the duration of the ski season may have on the other variables of interest. These values should be interpreted as approximations, since the number of visits and the level of employment in the tourism sector do not depend exclusively on season length, but also on other economic, infrastructural, and operational factors that are not addressed in this analysis. According to the regression results, one additional day in season duration is associated, on average, with approximately 13,849 additional visits and 25 jobs.

3.3.2. Tourism Related to Water Bodies and Watercourses

The assessment of drought impacts on tourism related to watercourses and water bodies, and particularly rafting as an activity directly associated with river flow, faces the fundamental limitation that there are no systematic public records on the number of visitors, trips, or revenues associated with this activity. Without this operational information, it is not possible to directly quantify annual variation in tourism demand. Given this, the approach used is based exclusively on available hydrological data, which constitute an objective, continuous, and reliable indicator of the conditions that enable or constrain white-water sports. This methodological restriction requires the use of an indirect approach that translates water availability into an indicator of recreational suitability.

To compensate for the absence of direct tourism data, a Relative Hydrological Suitability Index was constructed from historical monthly streamflow records. This index is based on the widely accepted assumption that rafting requires a relatively narrow flow range in order to provide a safe and attractive experience. Thus, the index classifies each month according to its hydrological suitability for rafting and then estimates, at the annual scale, a relative measure (0 to 1) of how favorable hydrological conditions were for rafting. Although indirect, this method is consistent with recreational valuation studies that use streamflow as a parameter representing the quality of the ecosystem service associated with the recreational use of water.

The analysis of relative recreational hydrological suitability reveals contrasting patterns among the basins evaluated. In the case of the Maipo River, a clearly decreasing and statistically significant trend is observed, both in the linear regression ($p < 0.001$) and in the non-parametric Mann–Kendall test ($p < 0.001$). This behavior reflects a sustained deterioration in hydrological conditions over the last 25 years, with a progressive reduction from high relative activity values (>0.80) during the 2000s to persistently low values (<0.45) from 2019 onward. The magnitude and consistency of this trend suggest that declining streamflow may indicate a cumulative reduction in hydrological suitability for rafting.

A similar pattern, although less intense, is observed in the Teno River, where a statistically significant decreasing trend is also detected ($p \approx 0.015$). As in the Maipo, the highest values are concentrated in the 2000s, whereas the last decade is marked by a sustained decline and the occurrence of critical years with index values below 0.50. Although the deterioration is less pronounced than in the Maipo, the results indicate an approximate

30–40% loss in the recreational suitability of the Teno River, consistent with the effects of drought on snowmelt-dominated rivers in central-southern Chile.

In contrast, the Biobío River does not show a significant trend in recreational activity over the analyzed period. Despite considerable interannual variability, alternating highly favorable years with poorer ones, the statistical results ($p \approx 0.65$ in the regression and $p \approx 0.68$ in Mann–Kendall) indicate that there is no systematic deterioration comparable to that observed in rivers of central Chile. This behavior suggests that the basin maintains greater hydrological resilience to drought processes, probably due to its mixed regime and the greater contribution of precipitation and natural storage.

In the case of the Bueno River, hydrological suitability for rafting shows a significantly decreasing trend over the analyzed period. After an initial decade with favorable conditions, reflected in relative activity values above 0.75 between 2002 and 2013, an abrupt drop is observed from 2014 onward to values close to 0.44, a level that remains persistently low for more than ten years. The statistical results confirm this sustained deterioration, with a significant negative slope in the linear regression ($p \approx 0.002$) and a Mann–Kendall test that also indicates a robust decreasing trend ($p \approx 0.0046$).

Finally, the Aisén River exhibits a slight negative trend, but it is not statistically significant ($p \approx 0.066$), indicating that, although several recent years show lower suitability values than those recorded during the 2000s, the deterioration signal is not sufficiently consistent to be considered a robust trend. Even so, the occasional decline in relative activity over the last ten years may reflect episodes of climatic variability or changes in the seasonality of streamflow.

Overall, these results show that the hydrological impact on recreational suitability is not spatially homogeneous at the national level. Rivers in central Chile, especially the Maipo and Teno, show significant deterioration associated with declining streamflow, indicating a substantial reduction in hydrological suitability for rafting. However, the results for the Bueno River show that this deterioration is not restricted solely to central Chile, as the basin experienced an abrupt and persistent decline in recreational suitability beginning in 2014. In contrast, southern rivers such as the Biobío and Aisén maintain comparatively more stable conditions, reflecting greater hydrological resilience to prolonged drought.

From a tourism-relevance perspective, these trends suggest that drought has affected not only water availability, but also the hydrological conditions that support rafting. The sustained reduction in recreational suitability suggests fewer periods with hydrologically favorable conditions for rafting. However, this should be interpreted as a hydrological suitability signal rather than as observed demand or revenue loss.

Taken together, the results suggest three differentiated drought-impact pathways for water-dependent tourism in Chile. First, reduced precipitation and declining snow cover affect snow and mountain tourism by reducing snow reliability and shortening the conditions that support ski-season operation. Second, declining streamflow affects the hydrological suitability of river-based activities by reducing the number of months with favorable conditions for rafting. Third, water-quality responses were more limited and spatially heterogeneous, suggesting that water quality is not yet a generalized limiting factor but remains a relevant monitoring dimension under prolonged drought. These pathways are not spatially uniform, as their magnitude depends on geography, hydrological regime, altitude, natural storage, infrastructure, and data availability.

4. Conclusions

The integrated analysis shows that prolonged drought in Chile has generated significant and differentiated impacts on water-dependent tourism activities. With regard to snow- and mountain-related tourism, snow cover exhibits a robust declining trend

across most of the country, with sustained annual reductions that are directly reflected in the duration of ski seasons. The consistency between declining snow accumulation, reduced streamflow, and the correlation with season duration confirms that the loss of snow cover constitutes a critical factor threatening the operational and economic stability of mountain resorts.

At the same time, rivers associated with tourism related to water bodies and water-courses show contrasting patterns. While basins in central Chile, such as the Maipo and Teno rivers, exhibit clearly decreasing hydrological trends that significantly reduce their suitability for activities such as rafting, other southern and Patagonian rivers, such as the Biobío and Aisén, maintain greater hydrological stability, reflecting higher resilience to climatic stress.

In terms of water quality, although most parameters do not show generalized significant deterioration, increasing trends in elements such as arsenic or iron are observed in certain basins, which could affect the perception and recreational use of the resource if these trends persist or intensify. Water quality does not yet appear to be a widespread limiting factor for tourism, but it does emerge as a dimension of vulnerability that should be monitored in the context of climate change and growing pressure on water systems.

From an economic perspective, the strongest evidence was observed for snow tourism, where accumulated snowfall, season duration, skier-days, and direct employment were positively associated. In river-based tourism, the systematic decline in hydrological suitability indicates fewer favorable conditions for rafting, although direct economic losses cannot be quantified with the available data.

Overall, this study contributes an integrated hydroclimatic and tourism-proxy assessment for evaluating drought impacts on water-dependent tourism in a data-limited context. The results show that drought impacts are heterogeneous and depend on geography, hydrological regime, activity type, altitude, and the availability of tourism-specific data. Future monitoring should prioritize activity-specific indicators, including ski-season operation by elevation range, skier-days, rafting trips, visitor numbers by destination, local revenues, employment, and environmental variables measured at tourism-relevant spatial and temporal scales. Strengthening the integration between environmental monitoring and tourism statistics would improve the quantification of impacts and support climate-resilient destination management.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cli14080156/s1>, Table S1. Trend analysis results for water-quality parameters (2000–2024) at the Blanco River station (Aconcagua River Basin). Table S2. Trend analysis results for water-quality parameters (2000–2024) at the Maipo River (Las Melosas station). Table S3. Trend analysis results for water-quality parameters (2000–2024) at the Mapocho River (Los Almendros station). Table S4. Trend analysis results for water-quality parameters (2000–2024) at the Coya River station (Cachapoal River Basin). Table S5. Trend analysis results for water-quality parameters (2000–2024) at the Teno River (Los Queños station). Table S6. Trend analysis results for water-quality parameters (2000–2024) at the Biobío River (Rucalhue station). Table S7. Trend analysis results for water-quality parameters (2000–2024) at the Bueno River (Puerto Lapi station). Table S8. Trend analysis results for water-quality parameters (2000–2024) at the Aisén River (Puerto Aisén station).

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