

# Riparian forests: a temporal analysis of their ecological status in urban river systems of the Andean Patagonia, Chubut, Argentina

Gabriela Papazian <sup>1,\*</sup>, Adriana M Kutschker<sup>1</sup>, Adriana E Rovere<sup>2</sup>

<sup>1</sup>Facultad de Ciencias Naturales y Ciencias de la Salud, Universidad Nacional de la Patagonia San Juan Bosco, Sarmiento 849, Esquel, Chubut, 9200, Argentina

<sup>2</sup>INIBIOMA (CONICET, Universidad Nacional del Comahue), Pje. Gutiérrez 1415, San Carlos de Bariloche, Río Negro, 8400, Argentina

\*Corresponding author. Facultad de Ciencias Naturales y Ciencias de la Salud, Universidad Nacional de la Patagonia San Juan Bosco, Sede Esquel, Chubut, Argentina. E-mail: gabipapazian@gmail.com

## Abstract

Streams and rivers are ecosystems strongly impacted by changes associated with urbanization, which cause ecological degradation of their banks and the deterioration in water quality. Assessing the ecological state of riverbanks and proposing measures to mitigate their degradation are priorities. This study aimed to evaluate the quality of riparian forests in three urban river systems with different population densities and to analyze changes over a temporal scale. The pre-urban, urban and post-urban sections of the rivers were analyzed. The Quality Index of Riparian Forests for Andean Patagonian rivers (QBRp) was used. This index assesses four riverbank attributes: vegetation cover, vegetation structure, cover quality and degree of naturalness of the river channel. In all cases, pre-urban sections showed the highest QBRp values, indicating good quality riverbanks. The application of the index at different times allowed the identification of temporal changes in the ecological quality of the riverbanks, both in general and regarding individual components. A general trend of stability or improvement in the ecological quality of the riverbanks was recorded in peri-urban sections; meanwhile, urban and one post-urban sections displayed a decrease in quality, a condition related to modifications in the structure and quality of vegetation and the loss of the river channel naturalness. Urban areas with medium-high population density were associated with poor quality riverbanks. The QBRp index enables the assessment of how urbanization affects diverse aspects of riparian quality over time and supports the development of concrete actions for the effective management of these riparian environments.

**Key words:** urban stream; ecological quality; QBRp index; degradation

## Introduction

Riparian environments constitute a transition zone or interface that enables direct contact and interaction between terrestrial and aquatic ecosystems (Ward 1989). They are systems whose dynamics connect them longitudinally, laterally and vertically through hydrological, geomorphological and ecological processes, establishing relationships that generate biological complexity and habitat heterogeneity (Gregory et al. 1991, Naiman et al. 2005, Doering et al. 2012). Due to the ecological importance of these riparian ecosystems, they constitute key elements for conserving biodiversity and maintaining the health of river systems.

Riparian forests are part of a very diverse plant community in terms of their physiognomy and structure. In a broad sense, they correspond to the wooded mass that grows on the banks of rivers or their floodplains, providing ecological, social benefits, and substantial ecosystem services (Naiman and Décamps 1997). They play a crucial role in the hydrological and biogeochemical cycles of the aquatic ecosystem, in the regulation of water quality and temperature, nutrient filtering, stabilization of watercourse margins and the attenuation of floods, as well as in the provision of essential habitats for numerous species, serving as critical

corridors for wildlife movement (Tabacchi et al. 1998, Bertoldi et al. 2011, Gurnell et al. 2012).

Human beings have historically occupied river spaces, and they constitute favorable areas for urban settlement and the development of productive activities, which have defined their current physiognomy and state of conservation. At a global level, these changes in land use have led to the degradation of the banks of rivers and streams, reducing their capacity to provide the multiple ecosystem functions that are characteristic of them (Naiman and Turner 2000, Burton and Samuelson 2008, Tonkin et al. 2018). River spaces in Patagonia have also greatly influenced the organization of urban and suburban centers. Based on the analysis of the different processes of settlement, occupation and development of economic activities since pre-Hispanic times, it has been established that one of the axes of progressive settlement, beyond the extensive maritime coastline, corresponds to the flood terraces of the rivers and valley bottoms (Cepparo de Grosso 1997, Bondel 2009).

The world population is largely urban, and the streams and rivers immersed in the landscape of this matrix are especially sensitive and deeply impacted by the changes associated with the urbanization of watersheds (Bernhardt and Palmer 2007).

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The term “urban stream syndrome” describes the ecological degradation of streams that drain urban lands (Walsh et al. 2005). Among the impacts, we can mention: the alteration of drainage density, changes driven by soil compaction and impermeability, and the consequent acceleration of surface runoff (Walsh et al. 2005); channel modifications and the increase in sediments due to bank erosion (e.g. after channeling or defense works to prevent flooding in periods of high discharge) (Trimble 1997); and the discharge of wastewater and pollutants into the river (Paul and Meyer 2001). These activities and disturbances also entail other types of potential impacts, such as the loss of substrate, the removal of trunks or roots that allow for greater bank stability, and the disruption of the sequence of pools and rapids, which alters both the physicochemical processes of ecosystems and their biological associations (Brookes 1988, Paul and Meyer 2001, Meyer et al. 2005, Roy et al. 2005). Furthermore, the urbanization of river spaces impacts ecosystems through the replacement of vegetation with urban infrastructure (buildings, roads, services) and indirectly through alterations in the composition and structure of vegetation due to environmental fragmentation and degradation, thus reducing habitat quality for certain native species and increasing colonization by exotic species (McKinney 2002, Pennington et al. 2010).

At the same time, due to the complexity of interactions between the components of a riparian ecosystem and the processes at the watershed scale, it is unlikely that management practices applied exclusively to forested riverbanks for protect rivers from the advance of urbanization are effective and self-sustainable, unless watershed-level processes are incorporated into the analysis (Booth 2005). It has been postulated that although riparian forests may not be sufficient to protect rivers in urbanized watersheds, at the reach scale, these forested riparian areas can still provide the essential functions of shading, bank stability and contributing organic matter to the river system (Roy et al. 2005).

In this sense, some indices evaluate the quality of riparian forests at the scale of the river reach, and they constitute a useful tool for qualifying the ecological status of rivers. One of these indices is the QBR (Qualitat del Bosc de Ribera) proposed by Munné et al. (1998) to evaluate the quality of riparian forests in Spanish rivers. The application of this index has been widely extended and adapted to American rivers, as well as those of México (Rodríguez-Téllez et al. 2012), Costa Rica (Araya-Yannarella and Fernández-Hernández 2017), Colombia (Posada-Posada and Arroyave-Maya 2015), Ecuador and Perú (Acosta et al. 2009), Chile (Fernández et al. 2009, Palma et al. 2009, Peredo et al. 2012, Peredo-Parada et al. 2012, Carrasco et al. 2014), and Argentina (Kutschker et al. 2009, 2020, Gualdoni et al. 2011, Miserendino et al. 2011, 2016, Sirombra and Mesa 2012, Fernández et al. 2016).

Previous studies in the Patagonian region have evaluated the quality of riparian forests as a measure of the ecological health of aquatic environments at a given time (Kutschker et al. 2009, 2020, Papazian, 2009, Miserendino et al. 2011, 2016). The uniqueness of the present work lies in the temporal analysis of the ecological quality of riparian forests in urban river systems and the fact that they were evaluated for over a decade. Likewise, the study highlights the usefulness of using the QBRp index as a management and monitoring tool for tracking and controlling the ecological state of riparian areas in the face of new interventions or changes in land use, as well as for monitoring restoration activities in the riparian environment. The objective of this study was to assess the quality of riparian forests and analyze their variation over time in three urban river systems in northwestern Chubut. In this context, the following working hypotheses were

formulated: (i) in mountain rivers that traverse urbanized areas, the ecological quality of the riparian zones is at its lowest in urban sections, recovering quality downstream; (ii) the deterioration of riparian forest quality in urban stretches is directly related to population density; (iii) the QBRp index detects temporal changes in the attributes of the natural state of riparian areas, validating its suitability as a monitoring tool in urban fluvial systems.

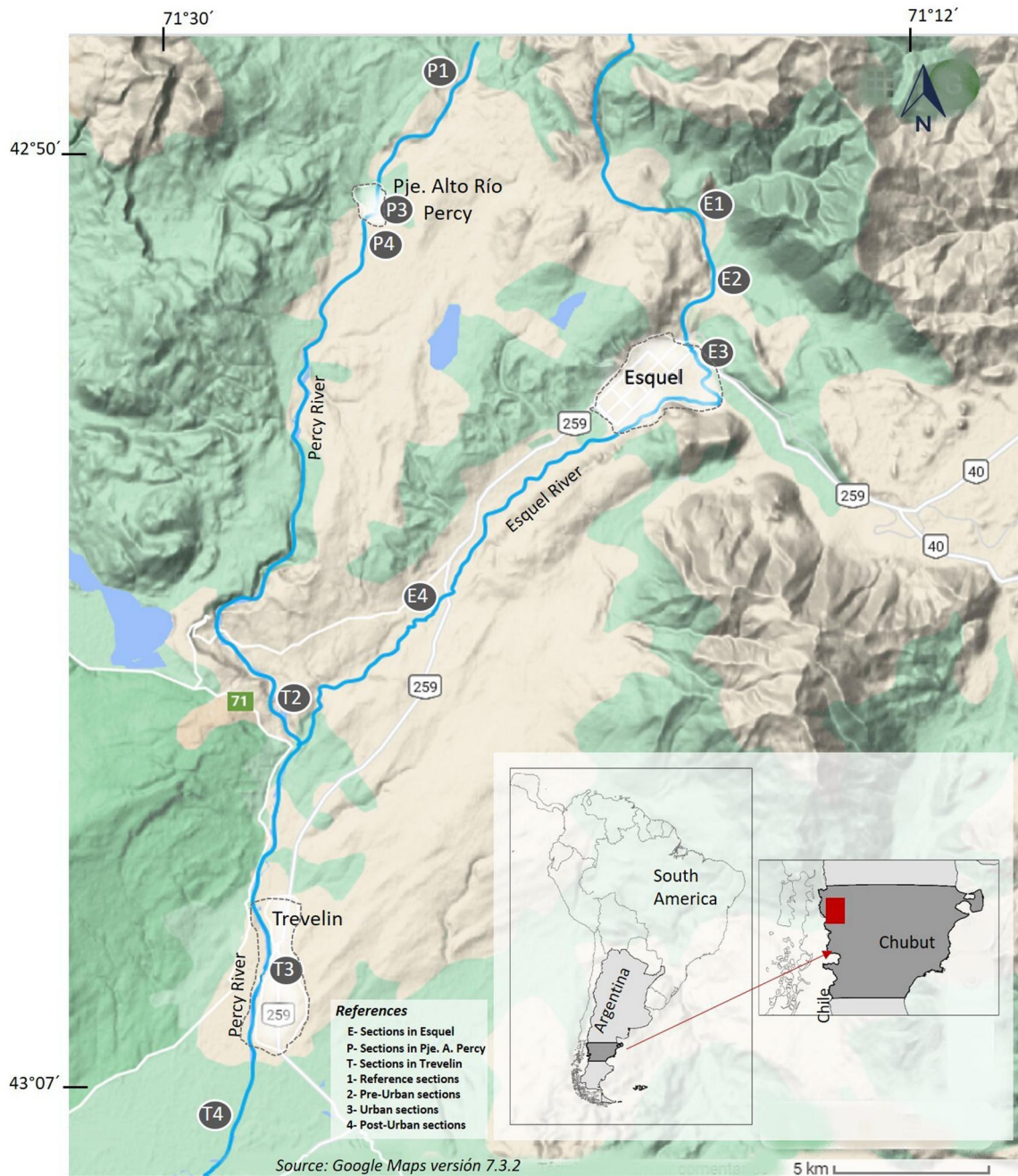
## Materials and methods

### Study area

The urban and peri-urban riversides of the Percy and Esquel rivers were studied in and around the towns of Esquel (42°54'S–71°18'W) and Trevelin (43°05'S–71°28'W) respectively, as well as those of the Percy river, which runs through the rural settlement of Paraje Alto Río Percy (42°51'S–71°26'W). The three locations are in the northwest of the province of Chubut, Argentina (Fig. 1).

The Esquel-Percy river system is part of the Futaleufú-Yelcho basin, which has an area of ~7630 km<sup>2</sup> and drains into the Pacific Ocean (SSRH 2002). The Esquel-Percy sub-basin has a permanent regime with an average discharge of 12 m<sup>3</sup>/s, flowing primarily from north to south, with its headwaters at 2100 m a.s.l. near the Cordón Leleque and the western flank of the Cordón Esquel. The Percy River runs for ~80 km and crosses the entire 16 de Octubre Valley. Upstream from the town of Trevelin, it receives the Esquel River, one of its main tributaries, which has a length of ~35 km. The basin is characterized by a cold-temperate climate (Paruelo et al. 1998), with an average annual temperature of 12.5°C and average temperatures in winter that range between 1°C and 3°C and between 14°C and 16°C in summer (SSRH 2002), which shows marked seasonality throughout the year. Rainfall and snowfall are concentrated in the winter season, presenting an annual average that exceeds 2500 mm in the western limit of the basin and 500 mm in the eastern sector (Paruelo et al. 1998). A hydrological regime is thus established with two maximum pulses in the year, one resulting from heavy winter precipitation and another caused by the melting of ice and snow in the mountains (Coronato and del Valle 1988).

The study area is located in the ecotone between the Subantarctic forest and the Patagonian steppe, with transition forest being the characteristic vegetation unit. The predominant native species are ñire (*Nothofagus antarctica*), radial (*Lomatia hirsuta*), mountain cypress (*Austrocedrus chilensis*), maitén (*Maytenus boaria*), notro (*Embothrium coccineum*), and a shrubby and herbaceous understory represented by chacay de la cordillera (*Discaria chacaye*) and chacay (*Ochetophila trinervis*), laura (*Schinus patagonicus*), calafate (*Berberis* spp.), bacaris (*Baccharis* spp.), and several species of *Acaena* spp. (Ezcurra and Brion 2005). The middle and lower riparian reaches of the sub-basin are characterized by the presence of exotic willows, mainly *Salix fragilis*, *S. alba* and their hybrid *Salix x fragilis*, which in some cases is the dominant species (Miserendino et al. 2016, Orellana Ibáñez et al. 2021). For more than 100 years, land use in the Esquel-Percy system has been primarily associated with the planting of pastures and forage, extensive cattle and sheep farming, and more recently, with horticultural production and urban expansion along the riverbanks. The Esquel River runs through the city of the same name, which is the most densely populated urban center in northwest Chubut (32 758 inhabitants—28 inhabitants/km<sup>2</sup>, INDEC 2010). Interruptions in its urban section include lateral containment works (canalization) and transverse structures across the channel (sediment retention dams). In the post-urban sections and



**Figure 1.** Location of the urban and peri-urban segments in the Esquel-Percy river system in the northwest of Chubut, Patagonia, Argentina.

downstream to its mouth, agricultural and livestock activities predominate.

In its upper basin, the Percy River crosses the Alto Río Percy Rural Area, which is part of the municipal district of Esquel. It is home to around a hundred families permanently and receives many visitors and tourists during the summer due to its use as a recreational area. Halfway along its course, the Percy River receives the waters of the Esquel River, and further downstream, some 10 km before it joins the Corinto River, it passes through a large part of the town of Trevelin (7908 inhabitants—6.4 inhabitants/km<sup>2</sup>). The area around the Percy River is intensively used for agricultural and livestock activities, aggregate extraction, channel diversions and the construction of irrigation canals or ditches. The river also functions as a recipient of treated water

from the local sewer waste treatment plants in the towns of Trevelin and Esquel (Miserendino et al. 2016, Acheritobere et al. 2017).

### Sampling design

Sampling was carried out during the dry season between 2015 and 2016, from December to March. For each river, riparian segments were selected, including urban, peri-urban and reference sections, each measuring 100 m in length along both banks and with an average width equivalent to three times the width of the channel (Fig. 1). Reference sections were selected based on floristic, environmental, and ecological characteristics to represent a riparian ecosystem in good conservation status, with no alterations to the natural morphology of the channel or banks. For the

selection of other sections, three criteria were established: (i) zoning determined by the land use plans of both municipalities, which designate urban areas as those intended for intensive human settlements subject to various activities and uses. Pre- and post-urban sections correspond to areas classified as “subrural” or “suburban”, located near urban centers, with intensive productive use and isolated housing. (ii) Accessibility to the sections, related both to permissions from landowners and to the natural morphology of the banks. (iii) The possibility of obtaining comparable results with previous studies conducted in the basin, to detect temporal changes in riparian quality. In total, 10 segments were studied, in which physical and ecological variables were measured. These included the width and depth of the wetted channel, the width of the dry channel (equivalent to the annual active floodplain), and the percentage of substrate devoid of vegetation (SD) and the morphological type of the riverbanks (that depends on the shape and slope of the riparian environment).

The riparian tree and shrub vegetation was characterized in each section, for which two randomly located transects were established on each bank, each 50 m in length, perpendicular to the river channel. In each transect, four plots of 5 × 5 m were arranged, equidistant from each other, covering a total sampling area of 400 m<sup>2</sup> per section. In each of these plots, species richness (S) (as the number of species in the community) and species composition were determined, using for identification the Patagonian Flora collection (Correa 1978–1999) and the Catalog of Vascular Plants of the Southern Cone (Zuloaga et al. 2008), indicating their origin and habit.

The Riparian Forest Quality Index for Patagonian rivers (QBRp) was used to evaluate the quality of riparian forests (Kutschker et al. 2009), modified from Munné et al. (1998, 2003). This index is calculated using a field sheet that includes information to be completed and scores for four sections (Supplementary Appendix I). Each section evaluates the components and attributes of the riparian corridor in relation to the total vegetation cover (A1), the structure of vegetation (A2), the quality of the vegetation cover (A3) and the degree of naturalness of the river channel (A4). The first component (A1) is an assessment of the degree of coverage of riparian areas, including any type of tree, shrub, or helophyte, and excluding annual plants because their coverage could vary too much depending on the year and hydrological conditions. Additionally, this section assesses the percentage of connectivity between the riparian environment and adjacent terrestrial ecosystems. The second component (A2) assessment is made of the structural complexity of the riparian environment and the initial score depends on the total percentage of cover due to trees, and may be increased by the presence of shrubs and other vegetation of lower height that makes up the understory. The presence of helophytes or other vegetation in the channel also increases the score. When assessing coverage quality (A3), we assume that the number of tree species present in a stream reach will vary depending on riparian morphology. This component positively values the richness of native tree and shrub species that should ideally be recorded in the analyzed stretch, which depends on the morphological type of the banks and the lotic order (see page 2 of Supplementary Appendix I). The morphological type depends on the shape and slope of the riparian environment, the presence or absence of islands in the riverbed, and the percentage of hard substrate. Thus, three morphological types are defined: very closed riverbanks with little possibility of hosting continuous vegetation, generally found in headwater areas (Type 1); riverbanks with intermediate potential for the development of vegetation, with the presence of

gallery forests (Type 2); and extensive riverbanks with large riparian habitats and numerous tree species, characteristic of lower reaches of the watershed (Type 3) (Munné et al. 2003). The presence of exotic species, either in isolation or forming communities, negatively affects the index value. In the degree of naturalness of the river channel (A4), the assessment includes modifications made by humans in the alluvial terraces or the fluvial channel, including river channelization. Each of these components is assessed on a scale ranging from 0 to 25. Their sum corresponds to the QBRp index value, which is categorized into five quality ranges: >90: natural state, undisturbed riparian forest; 90–71: good quality, slightly disturbed forest; 70–51: intermediate quality, beginning of important alteration; 50–26: poor quality, strong alteration; ≤25: extremely poor quality, extreme degradation. The values obtained per index component were recorded in a field spreadsheet for each segment studied.

### Changes in the quality of riparian forest over a temporal scale

To detect possible changes in the quality of riparian forests, data from studies conducted in different years within the basin were selected, using the QBRp index as an indicator of riparian quality. The data corresponded to the years 2007 and 2008 (Papazian and Kutschker 2008), 2009 (Papazian 2009), and 2011 (Miserendino et al. 2016), and were compared with those obtained in 2016. Although the index has a degree of subjectivity that can introduce errors such as method assumptions and observer bias (Munné et al. 2003), it is important to highlight that the same researchers conducted all past and current measurements.

To analyze the changes over time in the ecological state of the riverbanks depending on the urbanizations that each river crosses, the population density of adjacent areas was estimated. To do this, the number of households within 1 km<sup>2</sup> of each sampling site was counted for the years 2008 and 2016, using satellite imagery obtained from Google Earth Pro version 7.3.2. This value was then multiplied by the average number of inhabitants per household provided by the National Census of Population, Households and Housing (INDEC 2010), which is 3.2 inhabitants/household for Esquel and Paraje Alto Río Percy and 2.85 inhabitants/household for Trevelin. Subsequently, population density was classified according to four categories: uninhabited, low density (1–1000 inhabitants), medium density (1001–2000 inhabitants), and high density (>2000 inhabitants).

### Statistical analysis

To verify whether environmental and ecological data (altitude, wet and dry channel widths, channel depth, bare soil, species richness, total and by-component QBRp, and population density) followed a normal distribution, the modified Shapiro-Wilks test was employed using InfoStat software version 2008. To evaluate the relationship between variables, the Spearman correlation coefficient (rs) was calculated, selected due to its robustness in the absence of assumptions about data distribution. Regression coefficient calculations were conducted to analyze the relationship between the QBRp index and each of its attributes, as well as variations in population density for each section.

### Results

In the Esquel and Percy rivers, the depth of the channel decreased from the headwaters towards the reaches with the highest stream orders, with the lowest depth values recorded in the urban sections of Esquel and Trevelin. Furthermore, an inverse

relationship was observed with the wet and dry channel width variables, which generally present the highest values in the middle and lower reaches of the sub-basin—in this case, corresponding to the segments running through the town of Trevelin, which presented the highest values for both variables (Table 1). Likewise, the banks of the Percy River presented the highest percentage of substrate devoid of vegetation (SD), varying between 40% and 45%, except for the post-urban section, where the percentage of bare soil was 21%. The banks of the Esquel River presented lower SD values, varying between 15% in the pre-urban section and 33% in the urban section. The morphology of the riverbanks varied mainly between riverbanks with intermediate potential to support vegetation with the presence of gallery forests (Type 2) and extensive riverbanks with large riparian habitats (Type 3). A Type 1 morphology was recorded in the urban section of Esquel, a product of the lateral containment works (canalization) that artificially transformed the riverbanks into very closed morphologies with low to no probability of vegetation establishment.

Along the Esquel-Percy riverbank system, a total of 24 species of woody plants with arboreal and shrubby habits were recorded, with 21 species identified in the Esquel River and 16 in the Percy River, with the exotic willow (*Salix* spp.) being the species present in all of the studied sections.

In the Esquel River, 81% of the recorded species were native, with the antarctic beech (*ñire*; *Nothofagus antarctica*) and the maitén (*Maytenus boaria*) being the native tree species on the riverbanks of the pre-urban sections. Regarding growth habit, 81% were shrubs, the most frequent being the chacay trinervis (*Ochetophila trinervis*), present in the pre-urban and post-urban sections. The sections with the highest species richness were the reference and pre-urban sections, with 18 and 13 species respectively, of which 89% and 69% were native. Two exotic shrub species were recorded in the pre-urban sections, *Rosa rubiginosa* and *R. canina* (both commonly known as rosehip). Only the exotic willow (*Salix* spp.) was recorded in the urban section, with the shrub layer absent.

In the Percy River, 75% of the species were native, with the *ñire* and the maitén being the only trees, the first present in the pre-urban section of Paraje Alto Río Percy and the second in the pre-urban section of Trevelin. The highest species richness was found in the pre-urban sites, with 8 species recorded in Paraje Alto Río Percy and 9 in Trevelin, of which 75% and 89%, respectively, were native. The lowest species richness was observed in the urban and post-urban sections of Trevelin, with 1 and 2 species recorded, respectively: the willow and the black poplar (*Populus nigra*), both exotic tree species, with the shrub layer absent. Shrub species represented 75% of the total vegetation, with

the exotic shrubs rosehip (*Rosa rubiginosa*) and Scotch broom (*Cytisus scoparius*) recorded in the pre-urban and urban sections of Paraje Alto Río Percy. The most common shrub species in this river were mamuel choique (*Adesmia volckmanii*), chacay de la cordillera (*Discaria chacaye*), and chacay trinervis (*Ochetophila trinervis*), all of them native and present in all sections of the rural area.

The quality of the riverbanks varied between good, with slightly disturbed forests, in the headwater sections of the Esquel River (90 points) and middle sections of the Percy River basin, and poor, with substantial alteration of the forest in the urban sections of the Esquel (25.5 points), and the urban and post-urban sections of the Percy. The pre- and post-urban sections were generally of intermediate quality, except for the post-urban section in the city of Trevelin, which proved to be of poor quality, presenting the lowest values along the river (Table 2).

In the case of the Esquel River, the main difference between the values of the peri-urban sections was related to vegetation cover. In the post-urban section, non-native tree species, including exotic willows (*Salix* spp.) formed a large community along the riverbank, which decreased the component's score (Table 2). In the pre-urban sector, the value increased due to the presence of native tree species (although in a lower-than-optimal number) and the isolated distribution of a few willow individuals. The urban section had a low score in the four index components and was mainly differentiated from the rest due to alterations in the naturalness of the river channel, which was subject to permanent modifications. In addition, it had a low percentage of vegetation cover and limited connectivity between the riverbank forest and its surroundings (A1), as well as poor cover quality (A3) due to the absence of native tree and shrub species and the presence of isolated alien species.

In the Percy River, the sections running through Paraje Alto Río Percy varied between good and intermediate quality, with the quality of the cover being the main cause of the decrease in value in the urban section due to the absence of native tree species and the presence of exotic species forming communities. The quality differed in the lower reaches of the river, with the pre-urban section proving to be of intermediate quality and the urban and post-urban sections of poor quality, with low values in all components of the index (Table 2).

Population density values were clearly differentiated between both rivers' urban and peri-urban sectors. Differences were found between the population densities of the urban sections of both locations, with 2819.2 inhabitants/km<sup>2</sup> (high density) in Esquel and 937.65 inhabitants/km<sup>2</sup> (medium density) in Trevelin. Regarding the peri-urban sections, two sections of the Esquel

**Table 1.** Physical-environmental variables of the urban and peri-urban sections of the Esquel-Percy river system.<sup>a</sup>

| Locality       | River  | Section | Altitude (m s.l.) | Distance to the headwater (km) | Morphological type | Strahler stream order | Depth (m) | Wet channel width (m) | Dry channel width (m) |
|----------------|--------|---------|-------------------|--------------------------------|--------------------|-----------------------|-----------|-----------------------|-----------------------|
| Esquel         | Esquel | REF     | 723               | 7.40                           | 3                  | 2                     | 0.36      | 2.59                  | 4.11                  |
|                |        | PRE     | 661               | 9.50                           | 2                  | 3                     | 0.27      | 5.60                  | 10.50                 |
|                |        | URB     | 581               | 13.30                          | 1                  | 3                     | 0.16      | 4.95                  | 11                    |
|                |        | POST    | 495               | 26.30                          | 3                  | 3                     | 0.19      | 7.67                  | 12.73                 |
| Alto Río Percy | Percy  | REF/PRE | 773               | 32.94                          | 2                  | 3                     | 0.58      | 13.30                 | 28                    |
|                |        | URB     | 720               | 40.02                          | 2                  | 3                     | 0.24      | 9.50                  | 22.50                 |
|                |        | POST    | 708               | 41.20                          | 2                  | 3                     | 0.29      | 13.90                 | 23.40                 |
| Trevelin       |        | PRE     | 430               | 64.48                          | 2                  | 4                     | 0.19      | 19                    | 31.10                 |
|                |        | URB     | 369               | 74.46                          | 2                  | 4                     | 0.17      | 6.15                  | 44.50                 |
|                |        | POST    | 361               | 76.47                          | 3                  | 4                     | 0.20      | 14                    | 35                    |

<sup>a</sup> Morphological type. 1: Closed riverbanks; 2: Riverbanks with intermediate potential to support vegetation; 3: Extensive riverbanks.

River and the pre-urban section of Paraje Alto Río Percy were recorded as being unpopulated. In contrast, the rest of the sections of the Percy River presented a low population density (between 8 and 22.4 inhabitants/km<sup>2</sup>), indicating the rurality of these riverside areas, which lie in the vicinity of urban areas. According to preliminary data reported by (INDEC 2022), the region experienced a population growth of ~10–15% since the last census, with the highest growth trend observed in the town of Trevelin, which according to the latest data has ~9000 inhabitants.

The Shapiro-Wilks normality test revealed that the data for river depth, population density, and the naturalness of the river channel (A4) did not exhibit a normal distribution ( $P < .05$ ). The Spearman's correlation coefficient ( $r_s$ ) revealed a strong positive correlation ( $r_s > 0.9$ ,  $P\text{-value} \leq .0002$ ) between the QBRp index and the degree of coverage (A1), structure (A2), and quality (A3) of the vegetation. Similarly, species richness showed a positive correlation ( $r_s > 0.85$ ,  $P\text{-value} \leq .001$ ) with the structure (A2) and quality (A3) of the vegetation, as well as with the QBRp index. Additionally, population density showed a negative correlation, though less significant, with species richness, depth, vegetation cover, and the QBRp index, but no significant correlation with other index components or soil devoid of vegetation (Table 3).

**Table 2.** Total values and by component of the QBRp index in the urban and peri-urban sections of the Esquel-Percy riverbank system.<sup>a</sup>

| River                       | Section | A1 | A2 | A3   | A4 | QBRp | Quality range |
|-----------------------------|---------|----|----|------|----|------|---------------|
| Esquel                      | REF     | 22 | 23 | 20   | 25 | 90   | GOOD          |
|                             | PRE     | 15 | 17 | 12.5 | 25 | 69.5 | INTERMEDIATE  |
|                             | URB     | 5  | 8  | 2.5  | 10 | 25.5 | BAD           |
|                             | POST    | 17 | 13 | 2.5  | 25 | 57.5 | INTERMEDIATE  |
| Percy (Pje. Alto Río Percy) | REF/PRE | 20 | 15 | 15   | 25 | 75   | GOOD          |
|                             | URB     | 13 | 15 | 5    | 25 | 58   | INTERMEDIATE  |
|                             | POST    | 20 | 19 | 7.5  | 25 | 71.5 | GOOD          |
| Percy (Trevelin)            | PRE     | 17 | 15 | 12.5 | 25 | 69.5 | INTERMEDIATE  |
|                             | URB     | 10 | 13 | 5    | 15 | 43   | BAD           |
|                             | POST    | 13 | 10 | 0    | 15 | 38   | BAD           |

<sup>a</sup> A1: Degree of riparian cover; A2: Cover structure; A3: Cover quality; A4: Naturalness of the river channel.

## Changes in the quality of riparian forests over a temporal scale

The temporal changes in the quality of riparian forests of the studied reaches showed a general trend of stability or improvement in quality, especially in the pre-urban and post-urban reaches (Fig. 2a and b). Some particularities were observed in the urban sections where the quality remained unchanged over time, with intermediate quality in Paraje Alto Río Percy and poor quality in Esquel and Trevelin.

Population density varied notably in urban sections between 2008 and 2016, with an increase of 9% in the town of Esquel and 75% in Trevelin. Riparian quality and population density showed significant covariance ( $R^2 = 0.78$  and  $P < .002$ ) for the year 2016, but not for the year 2008 ( $R^2 = 0.27$  and  $P > .1$ ). The general trend indicates that urban sections have increased their population density and have lost ecological quality in their riparian zones (Table 4). The index components most affected by population density were the degree of vegetation cover ( $R^2 = 0.67$  and  $P = .003$ ) and the degree of naturalness of the river channel ( $R^2 = 0.66$  and  $P = 0.004$ ).

The variation in the values of the different components of the QBRp index in a historical/temporal context revealed the main ecological and morphological factors that led to changes in riverbank quality over time (Figure 3a–i).

The quality of the peri-urban sections of the Esquel River generally remained within the intermediate quality category, although with different QBRp values. In the case of the pre-urban section, the quality went from intermediate (2008) to very good (2011) and subsequently returned to intermediate quality, but with QBRp values higher than those obtained in 2008 (Fig. 2a). This decrease is reflected in the degree of cover (A1) and the quality (A3) of the riparian vegetation (Fig. 3a). Regarding the urban section, it was observed that there had been a decrease in QBRp values in all four components, but the changes were mainly in the structure of the cover (A2) (Fig. 3b).

In the Percy River, the quality ranged between intermediate and good, with slightly disturbed forest, except for in the urban and post-urban sections of Trevelin. In the particular case of the post-urban section of the town of Trevelin, there was a significant deterioration in quality, going from intermediate to poor in

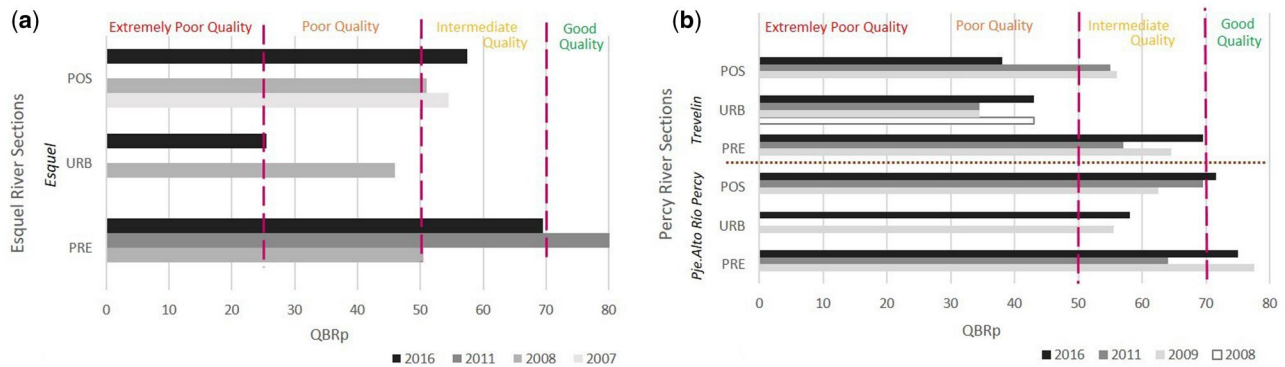
**Table 3.** Spearman correlation analysis for each pair of variables analyzed.<sup>a</sup>

|                           | Altitude | Wet channel | Dry channel | Depth  | Richness | Vegetation cover | Vegetation structure | Vegetation quality | Population density | Channel naturalness | S.D. | QBRp |
|---------------------------|----------|-------------|-------------|--------|----------|------------------|----------------------|--------------------|--------------------|---------------------|------|------|
| Altitude                  | 1        |             |             |        |          |                  |                      |                    |                    |                     |      |      |
| Wet channel               | −0.30    | 1           |             |        |          |                  |                      |                    |                    |                     |      |      |
| Dry channel               | −0.55    | 0.71        | 1           |        |          |                  |                      |                    |                    |                     |      |      |
| Depth                     | 0.77**   | 0.06        | −0.26       | 1      |          |                  |                      |                    |                    |                     |      |      |
| Richness                  | 0.55     | −0.01       | −0.43       | 0.74   | 1        |                  |                      |                    |                    |                     |      |      |
| Vegetation cover (A1)     | 0.59     | 0.12        | −0.27       | 0.79** | 0.76**   | 1                |                      |                    |                    |                     |      |      |
| Vegetation structure (A2) | 0.65     | −0.09       | −0.40       | 0.77** | 0.86*    | 0.75**           | 1                    |                    |                    |                     |      |      |
| Vegetation quality (A3)   | 0.68     | −0.15       | −0.30       | 0.69   | 0.85*    | 0.72**           | 0.83**               | 1                  |                    |                     |      |      |
| Channel naturalness (A4)  | 0.58     | 0.18        | −0.31       | 0.68   | 0.77**   | 0.78             | 0.79**               | 0.65               | 1                  |                     |      |      |
| QBRp                      | 0.74**   | 0.01        | −0.30       | 0.86*  | 0.87*    | 0.91*            | 0.91*                | 0.91*              | 0.81**             | 1                   |      |      |
| S.D.                      | 0.08     | 0.57        | 0.54        | −0.03  | −0.11    | 0.16             | 0.07                 | 0.17               | 0.15               | 0.19                | 1    |      |
| Population density        | −0.40    | 0.06        | 0.35        | −0.72  | −0.75    | −0.71            | −0.52                | −0.57              | −0.65              | −0.66               | 0.41 | 1    |

<sup>a</sup> Different asterisks indicate significant differences.

\*  $P \leq 0.001$ .

\*\*  $P \leq 0.02$ .



**Figure 2.** Riparian quality index (QBRp) of the urban and peri-urban sections of the Esquel (a) and Percy (b) rivers in different study years.

**Table 4.** Changes in population density and ecological quality of riparian zones in 2008 and 2016.<sup>a</sup>

| River  | Section | Population density*<br>(inh./km <sup>2</sup> ) | Population density**<br>(inh./km <sup>2</sup> ) | Variation of the<br>QBRp index | Changes in<br>quality ranges |
|--------|---------|------------------------------------------------|-------------------------------------------------|--------------------------------|------------------------------|
| Esquel | REF     | 0                                              | 0                                               | ↑                              | Intermediate / Good          |
|        | PRE     | 0                                              | 0                                               | ↑                              | Bad / Intermediate           |
|        | URB     | 2582.4                                         | 2819.2                                          | ↓                              | Bad / Bad                    |
|        | POST    | 0                                              | 8                                               | ↑                              | Intermediate / Intermediate  |
| Percy  | REF/PRE | 0                                              | 0                                               | ↓                              | Good / Good                  |
|        | URB     | 48                                             | 48                                              | ↑                              | Intermediate / Intermediate  |
|        | POST    | 23.5                                           | 22.4                                            | ↑                              | Intermediate / Good          |
|        | PRE     | 11.4                                           | 19.9                                            | ↑                              | Intermediate / Intermediate  |
|        | URB     | 535.8                                          | 937.6                                           | ↓                              | Bad / Bad                    |
|        | POST    | 11.4                                           | 11.4                                            | ↓                              | Intermediate / Bad           |

<sup>a</sup> Estimated for the years \*2008 and \*\*2016.

five years (2011 to 2016) (Fig. 2b). Although a decrease in quality was observed in all components, the main deterioration is reflected in the quality of the cover (A3), which obtained the minimum possible value (Fig. 3i).

## Discussion

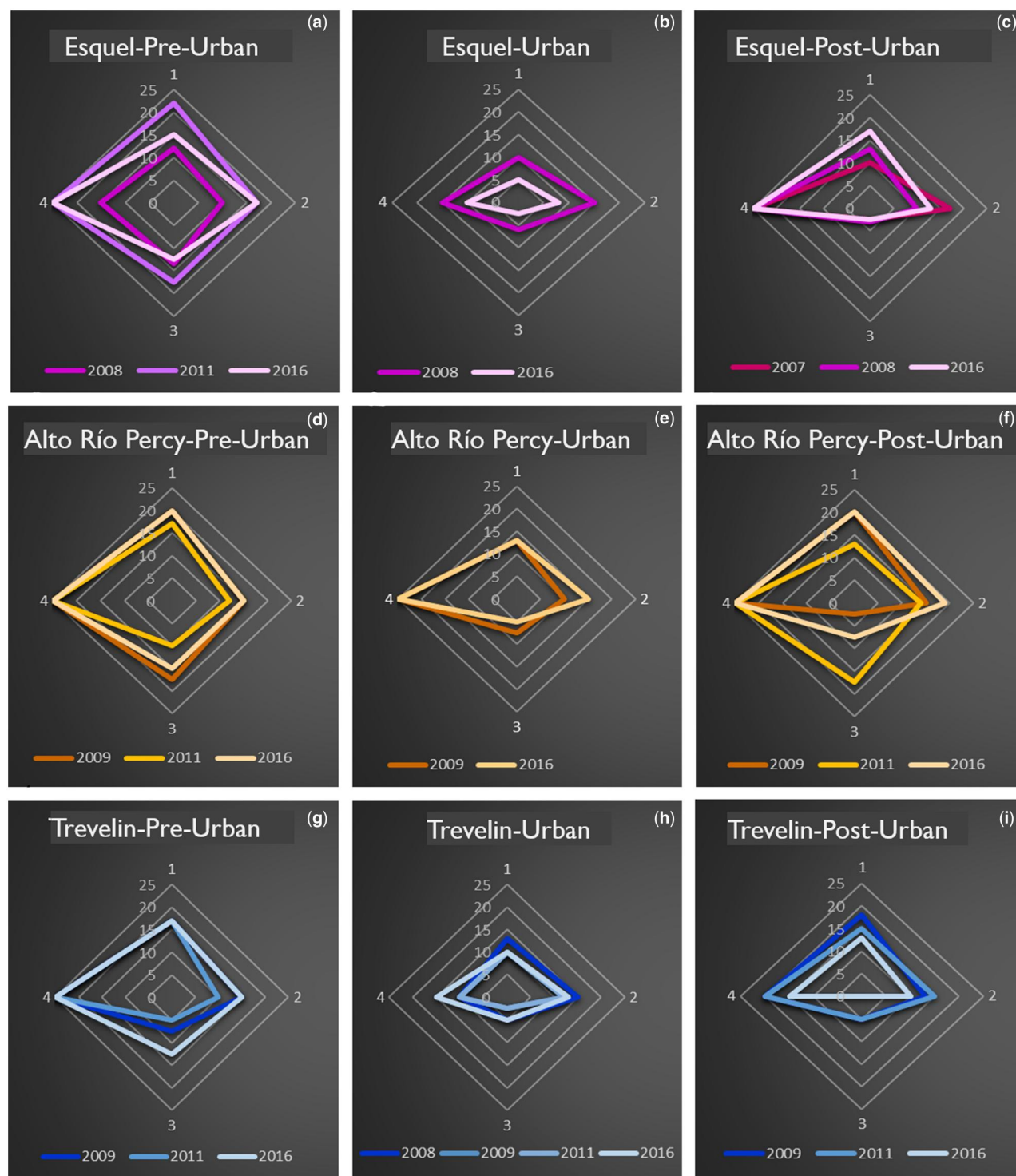
### The quality of riparian forests responds to many variables

The riparian environments of urban and peri-urban areas are not only subject to the dynamics of the river system of which they are part; but their structure and functioning are affected by disturbances of natural origin and anthropogenic interventions. Among them are variables such as depth, speed of runoff waters and width of the channel and they are usually affected by direct anthropogenic actions such as rectification, canalization, material extraction and channel dredging (Gregory 2006), with

ecological consequences throughout the fluvial environment and in the associated biological communities.

In the rivers of the Esquel-Percy fluvial system, the quality of the riparian forests did not reach optimal values indicative of very good ecological status, nor were there sections in poor condition with extreme degradation. Several authors have indicated that the degradation of riverbanks is more intense in the lower reaches of the rivers compared to the headwaters due to increased anthropogenic pressures in those areas (Sirombra and Mesa 2012, Valero et al. 2014, Kutschker et al. 2020). This is partially consistent with the findings of this study, as it particularly applies to mountain rivers where topography limits urban expansion, displacing urbanization processes to the middle and lower sections of the rivers.

The quality of riparian forests in the pre-urban sections of the different localities varied between intermediate and good, in all cases maintaining the naturalness of the river channel, but with



**Figure 3.** Changes in the values of the components (0–25) of the QBRp index in the urban and peri-urban sections studied in the three locations in different years of study: (a–c) Esquel; (d–f) Paraje Alto Río Percy; (g–i) Trevelin. Ref: A1-Degree of vegetation cover, A2-Structure of the vegetation, A3-Quality of the vegetation cover, A4-Naturalness of the river channel.

a decrease in vegetation cover, modification of the structure and species composition, with a greater presence of exotics, mainly willow, arranged in isolation or forming communities. As expected, a better quality of riparian vegetation was recorded in pre-urban sections, which are not subjected to high intensity anthropic interventions, compared to urban sections. This has been verified in other works, with similar results

(Miserendino et al. 2011, Rodríguez-Tellez et al. 2016, Kutschker et al. 2020, Theodosiou and Panajiotidis 2023).

### Quality of riparian forests in the Esquel-Percy fluvial system

The urban sections recorded the lowest values in riparian forest quality, with low scores in the different attributes evaluated by

the index, but in general, with a very marked decrease in the naturalness of the river channel and the quality of riparian vegetation represented by the absence of native species and high frequency of exotics. Although a recovery in the ecological quality of the riverbanks downstream of the urbanized areas was observed, mainly due to an increase in vegetation cover and complexity, and to the recovery of the naturalness of the river channel, this was not a general rule. In one of the rivers, the deterioration of the ecological quality continued, due to a simplification of the vertical structure of the riparian vegetation and the dominant presence of willow (*Salix* sp.), an exotic species that extends along the riverbank, and that conditions not only the development of other vegetation strata, but also modifies other ecological and morphological properties of the aquatic ecosystems (Serra et al. 2012). In relation to other environmental and ecological variables considered in the study, depth and species richness were positively correlated with the values of the QBRp index, but not with the soil devoid of vegetation. Regarding depth, this study found that urban sections are the shallowest. This aligns with what Conesa García and Pérez Cutillas (2014) propose, suggesting that there is a tendency towards incision of the riverbed in response to interventions in the watercourse; however, there are medium or lower river sections that, when channeled or straightened, lead to clogging of the riverbed, resulting in a consequent modification of its depth.

The urban sections, with medium and high population density, presented a poor ecological quality of their riverbanks. The impacts generated by urban development alter the riparian ecosystems, often dramatically and permanently. These impacts include, among others, the replacement of vegetation by impervious surfaces, modification of infiltration, aquifer recharge, and alteration of hydrological dynamics in general (Walsh et al. 2005, Pennington et al. 2010, Macfarlane et al. 2018).

Although the site with low population density presented an intermediate quality in the urban section, it was lower than the associated peri-urban stretches. In this case, the urbanization is located closer to the headwaters of the river and presents a rural-type urban development, with a low stable population density, although it is a recreational area that is frequently visited during the summer season. The deterioration in the ecological quality of these urban sections was related to the decrease in vegetation cover, the loss of vegetation strata and species richness, as well as due to modifications of the terraces adjacent to the riverbed with reduction of the fluvial channel and in extreme cases by the complete canalization of some sections. All of these impacts of urbanization have been widely noted in other studies that have addressed the study of riparian communities in urban areas (Trimble 1997, McKinney 2002, Pennington et al. 2010). From the analysis of the variation in population density in the years 2008 and 2016, it can be concluded that the greatest changes in the value of the QBRp index were recorded in the urban sections of medium-high density, which was not necessarily associated with a change in the riparian quality, which maintained their poor condition, with a strong alteration of the riverbanks.

### Temporal analysis of riparian Forest quality

In the pre-urban sections, there was no general trend in the evolution over time of the ecological riparian quality in the Esquel-Percy river system. Those sites with different land uses, whether recreational, sporting or drinking water supply, showed many changes in the quality of their riverbanks. In this sense, the implementation of works to improve and maintain the water supply

system periodically led to the ecological quality of these sections being affected in its different components, which was reflected in the fluctuation of the QBRp index values. In sites more inaccessible to settlers or visitors, with little variation in population density and low pressure from agricultural and livestock use, there were no major variations over time in the quality of their riparian zones.

At the urban section level, the quality of riparian forests has been decreasing over time, considering the various aspects evaluated by the index. In urbanized areas with medium-high population density, the index attributes most affected over time were the naturalness of the river channel due to urban expansion and the consequent increase in interventions in riparian areas. Among the most impactful interventions recorded were the extraction of aggregates in the lower basin, inadequate willow control (*Salix* spp.), as well as the straightening and total channelization of the river, which directly affects both the ecological conditions and the biological communities of the riparian zones (Allan 2004). In urban sections with low population density, an increase in the complexity of the vegetation structure was observed, with greater representation of native tree and shrub species. The management of willow in that sector, which is the most visited during the summer season, may have contributed to the regeneration of native vegetation.

The post-urban sections have generally recovered over time some quality in terms of vegetation cover, but they have lost vegetation strata, with the other components of the index remaining more or less unchanged. In those cases, where a decrease in the quality of vegetation cover has been observed, it was due to the dominance of exotic trees forming more or less continuous communities along the riparian areas. In the post-urban section where a decrease in ecological quality was recorded, there was a decline in the assessment of all components of the QBRp index over time, but particularly in the quality and complexity of the vegetation cover. In these sections, the species forms continuous communities that alter the riparian landscape and becomes an engineering species capable of producing profound bio geomorphological transformations (Serra et al. 2012, Gurnell 2014).

### QBRp index, ecological status and interventions

Considering that the riparian environment is a naturally dynamic system that undergoes constant change, the simple and rapid application of an index like QBRp with easily measurable attributes makes it a valuable tool for the evaluation and monitoring of riparian ecological quality. This index allows the detection of changes associated with both natural events and those derived from different land uses, identifying aspects of the riverbanks that are being affected or modified in relation to reference conditions. The QBRp value analyzed for the Esquel-Percy fluvial system enabled us to assess the ecological status of each section. Additionally, the examination of each component of the QBRp provided a specific diagnosis of the fluvial system, which can guide necessary interventions for restoring the fluvial channel, as well as for improving the coverage, structure, and composition of the vegetation. This study also facilitated the evaluation of ecological quality at sites that can serve as reference areas to ecological restoration.

The use of QBRp index contributes to the design and implementation of specific actions for the management and restoration of riparian environments, aimed at recovering ecosystem values and enhancing the social and economic values of urban river spaces (Walsh et al. 2005, Santasusagna Riu and Tort Donada 2018, Kutschker et al. 2020). In this regard, some general

guidelines are proposed, aimed at the recovery or protection of the riparian corridor through an integrated approach: (i) plan and design urban development in riverside cities that incorporates the river and its banks to ensure social and environmental sustainability, (ii) manage and regulate different land uses so that they are compatible with the conservation of river ecosystems, (iii) limit livestock access to the river in areas under grazing to promote natural vegetation regeneration, thereby restoring cover and vertical structure, (iv) implement revegetation or bioengineering techniques to control erosion and mitigate other interventions in the fluvial system (straightening, channelization, dredging) as alternatives to hard engineering techniques, (v) prioritize the use of native species for revegetating the banks and control the spread of invasive exotic species to improve the quality and structure of riparian vegetation.

This work presents the first results derived from applying the QBRp index in urban river systems from Andean Patagonia, analyzed in a temporal context. The processes of increasing urbanization require this type of tool that provides precise and quickly accessible information for the recovery of the ecological values and functionality of riparian environments. Urban planning and development in riverside cities must incorporate the river and its banks to achieve a socially and environmentally sustainable urban design.

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## Author contributions

Gabriela Papazian (Conceptualization-Equal, Formal analysis-Equal, Investigation-Equal, Methodology-Equal, Writing—original draft-Equal), Adriana Mabel Kutschker (Conceptualization-Equal, Investigation-Equal, Methodology-Equal, Writing—original draft-Equal), and Adriana Edit Rovere (Supervision-Equal, Writing—review & editing-Equal).

## Supplementary data

Supplementary data are available at JUECOL online.

Conflict of interest: None declared.

## Data availability

Data is available upon reasonable request to the corresponding author.

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