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A new method to evaluate the vulnerability of watersheds facing several stressors: A case study in mediterranean Chile

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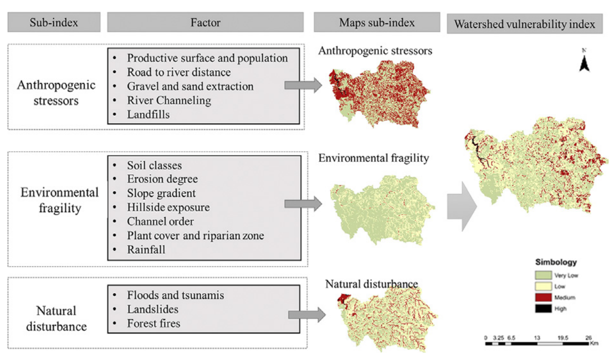
HIGHLIGHTS

- The watershed vulnerability index, is composed by anthropogenic stressors, environmental fragility and natural disturbances.
- Among the multiple stressors, forest fires, productive surfaces and population had the greatest impact on watershed vulnerability.
- The lower section of the watershed accumulates the impacts of multiple stressors, decreasing the health of the ecosystem.
- This new index is transferable to other mediterranean river watersheds.

GRAPHICAL ABSTRACT



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ABSTRACT

Freshwater systems are subjected to multiple anthropogenic stressors and natural disturbances that act as debilitating agents and modifiers of river systems, causing cumulative and synergistic effects that deteriorate their health and result in watershed vulnerability. This study proposes an easy-to-apply spatial method of watershed vulnerability evaluation using Geographic Information Systems (GIS) in the Andalién River watershed, located in the Chilean mediterranean. A watershed vulnerability index (WVI) based on three sub-indices – anthropogenic stressors, environmental fragility and natural disturbances – was developed. To determine the index grouping weights, expert surveys were carried out using the Delphi method. We subsequently normalized and integrated the factors of each sub-index with relative weights. The ranges of each thematic layer were re-classified to establish vulnerability scores. The watershed was divided into three sections: headwaters zone, transfer zone and depositional zone. The watershed vulnerability index showed that 41% of the watershed had very low vulnerability and 42% had medium vulnerability, while only 1% – in the depositional zone – had high vulnerability. A one-way ANOVA was carried out to analyze the vulnerability differences among the three sections of the watershed; it showed significant differences (F (2, 16) = 8.15: $p < 0.05$). The a posteriori test showed differences between the headwaters and depositional zones (Tukey test, $p = 0.005$) and between the transfer and depositional zones (Tukey test, $p = 0.014$). To validate the WVI, water quality was measured at 16 stations in the watershed; there was a significant correlation between vulnerability level and NO_2^- levels ($r = 0.8$; $p = 0.87$; $\alpha = 0.05$) and pH ($r = 0.8$; $p = 0.80$; $\alpha = 0.05$). The WVI showed the cumulative effects of multiple stressors in the depositional

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zone of the watershed. This is the first study to evaluate and validate non-regulated watershed vulnerability with GIS using multiple anthropogenic and natural stressors.

1. Introduction

River systems are essential for humans, as they provide a number of ecosystem services to society (Barber and Gleason, 2018; Grizzetti et al., 2016). The deviation of an ecosystem from its natural reference condition is a function of its vulnerability and the intensity of the stress factors that affect it (Rasmussen et al., 2012; Tolkkinen et al., 2016). These systems may change slowly due to continuous, growing pressures (usually anthropogenic stressors) or rapidly due to events outside the normal range of the system (disturbances) (Harik et al., 2017; Grantham et al., 2010). Rapport and Maffil (2011) defined natural disturbances (e.g., floods, tsunamis) as periodic perturbations that are potentially beneficial to ecosystems; however, when these perturbations are extreme the ecosystems are transformed, decreasing their biodiversity. This transformation sets the stage for recovery (Mitchell et al., 2013; Rapport, 1983). Natural disturbances are rarely more than temporary setbacks, since ecosystems recover rapidly, generating spaces for adaptation (Turner and Dale, 1998). In contrast, anthropogenic stressors are debilitating rather than revitalizing agents, since the stressed ecosystems do not recover and may continue to degrade.

The concept of vulnerability has been studied and applied to different disciplines in recent years, including a wide variety of content evaluation methods (Tran et al., 2012). This concept is defined as the fragility or environmental sensitivity of an ecosystem to degradation, in accord with its intrinsic and extrinsic characteristics (Vegas et al., 2011), as a result of anthropogenic stressors or natural disturbances (Fuertes-Gutiérrez and Fernández-Martínez, 2010; Shabbir and Ahmad, 2016; Turner et al., 2003). However, recent studies have focused on numerous vulnerability factors, diverging from the traditional evaluation, which is centered on only one stress factor, and focusing on several multidisciplinary aspects. These aspects include the synergistic effect of various types of stressors and the mechanisms that improve or limit the capacity of the system to adapt and recover amid various cumulative stressors (Milano et al., 2012), which are often synergistic with serious impacts on water quality and biodiversity (Clark and Dickson, 2003; Pistocchi et al., 2017; Tran et al., 2012). One tool to spatialize these multiple stressors in watershed is Geographic Information Systems (GIS). GIS have the ability to quantitatively integrate raster images and relational databases, which can be useful when working in regions with significant anthropogenic pressures and natural disturbances, such as mediterranean regions (Liu and Yang, 2015; Pistocchi et al., 2017).

Mediterranean regions have been recognized for their sensitivity to the high number of economic activities and population centers that have developed in them, as well as their and great biological diversity (Babel et al., 2011; Grantham et al., 2010). They are among the 25 Global Biodiversity Hotspots (Myers et al., 2000), with endemism rates from 23% in Chile to 75% in Australia. The coasts of mediterranean regions are fragile areas (Harik et al., 2017); in 2001 there were 187 million people living on them, and the projection for 2050 suggests that the total population in these ecoregions will reach 269.7 million, leading to an increase in irrigated areas, canals and dams and valleys with water shortages. This will generate strong competition for water and thus an increase in river system threat levels.

During the last few decades the mediterranean coast of south-central Chile (36°–38°S) has undergone complex, erratic processes of landscape change as a result of high levels of human intervention and natural disturbances, mainly urban and industrial growth, alterations to landscape connectivity, native forest removal (Echeverría et al., 2007; Lara et al., 2009; Little and Lara, 2010; Nahuelhual et al., 2012; Pizarro et al., 2006), forest fires, river flooding and flooding due to tsunamis and mass removals (Altamirano et al., 2013; Rojas et al., 2015; Úbeda and Sarricolea, 2016).

In spite of the numerous types of transformations and impacts on Chilean mediterranean ecosystems, human interventions and natural disturbances have not been sufficiently quantified with integrated methods that allow a simple, easy-to-apply evaluation of watershed vulnerability using high-resolution spatial datasets (Grantham et al., 2010; Kuehne et al., 2017; Stefanidis and Stathis, 2013). An understanding of the vulnerability index of watersheds degraded as a result of various anthropogenic and natural processes would allow sectors with higher degrees of fragility or sensibility to environmental degradation, with the resulting loss of river ecosystem health, to be strategically detected (Fu-Liu and Shu, 2000; Segurado et al., 2018).

It is necessary to generate spatial methods that both indicate the state of watersheds according to their intrinsic characteristics and quantify the different types of stressors in order to understand the degree of watershed vulnerability. Thus, the objective of this study is to develop a validated spatial method to determine watershed vulnerability amid multiple anthropogenic stressors and natural disturbances. We used three physical and environmental indicators to develop the watershed vulnerability index (WVI): the anthropogenic stressors sub-index (ASS), environmental fragility sub-index (EFS) and natural disturbances sub-index (NDS).

2. Materials and methods

2.1. Case study: Andalién River watershed

The watershed of the Andalién River is a coastal watershed located in south-central Chile (36.8°S). It has a surface area of 775 km^2 and is the site of the second-largest urban agglomeration in Chile, the Concepción Metropolitan Area (Rojas et al., 2017) (Fig. 1). It is a 5th order (Strahler) watershed, with a rainwater regime and a prevailing climate that is transitional between warm mediterranean and cold-humid, with a significant marine influence (Di Castri and Hajek, 1976). Its major tributary is the Nonguén Stream sub-watershed, which has a surface area of 44 km^2 and 3rd order in the drainage system (Rojas et al., 2015). The Nonguén Natural Reserve (NNR), with a surface area of 30 km^2, is located in the headwaters. It was created in 2009 to preserve and protect the land and endangered species, as the NNR is the last continuous coastal deciduous forest ecosystem in the Concepción area. To protect its water production as well, in 2017 the National Forest Corporation (CONAF) started the application process to change the NNR to a national park. Although the headwaters of the sub-watershed are located on the outskirts of Concepción, they are characterized by high flora and fauna endemism (Bocaz-Torres et al., 2013) and the conservation status of their water ecosystems (Correa-Araneda and Salazar, 2014). Urban areas are concentrated in the depositional zone of the watershed, where 90% of the population resides. The water is used for recreation, irrigation and domestic consumption, but there are no dams or reservoirs in the watershed. The Andalién River has an average annual flow of 12.5 ± 6.6 m^3 s^{-1}, with maximums of up to 643 m^3 s^{-1} during floods (Rojas et al., 2017).

2.2. Information sources for the watershed vulnerability index (WVI)

To construct the index we used the definition of Füssel (2007). We identified and selected the system of interest, the stressors and the study period. Then we developed the WVI, expressed as a function of the indicators (Fig. 2). The construction of the thematic layers of each

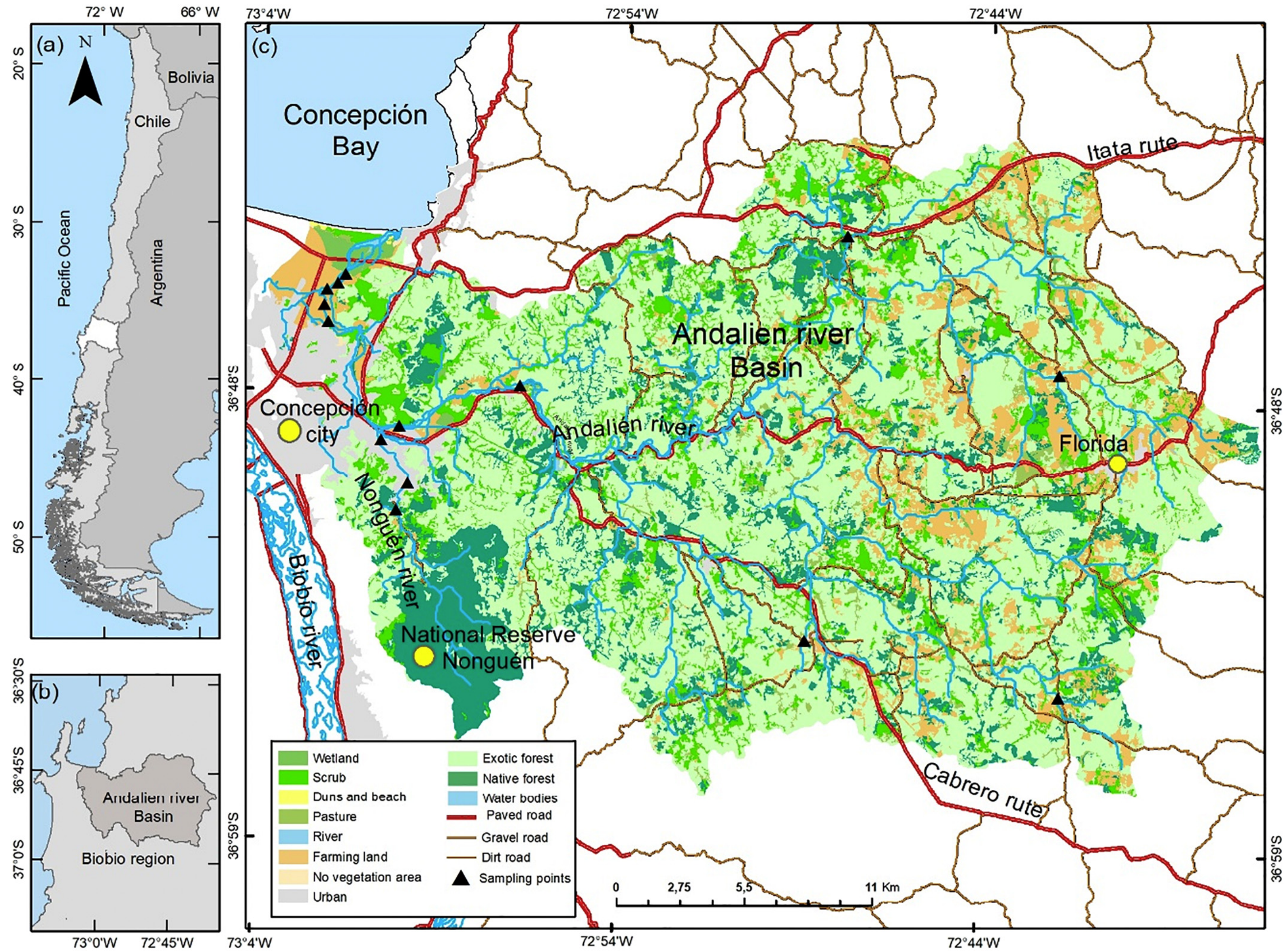

Fig. 1. Location of the Andalién River watershed, Chile. (a, b) show the geographical context in South America the region; (c) presents the watershed with land use and land cover; the red lines indicate the main roads in the watershed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

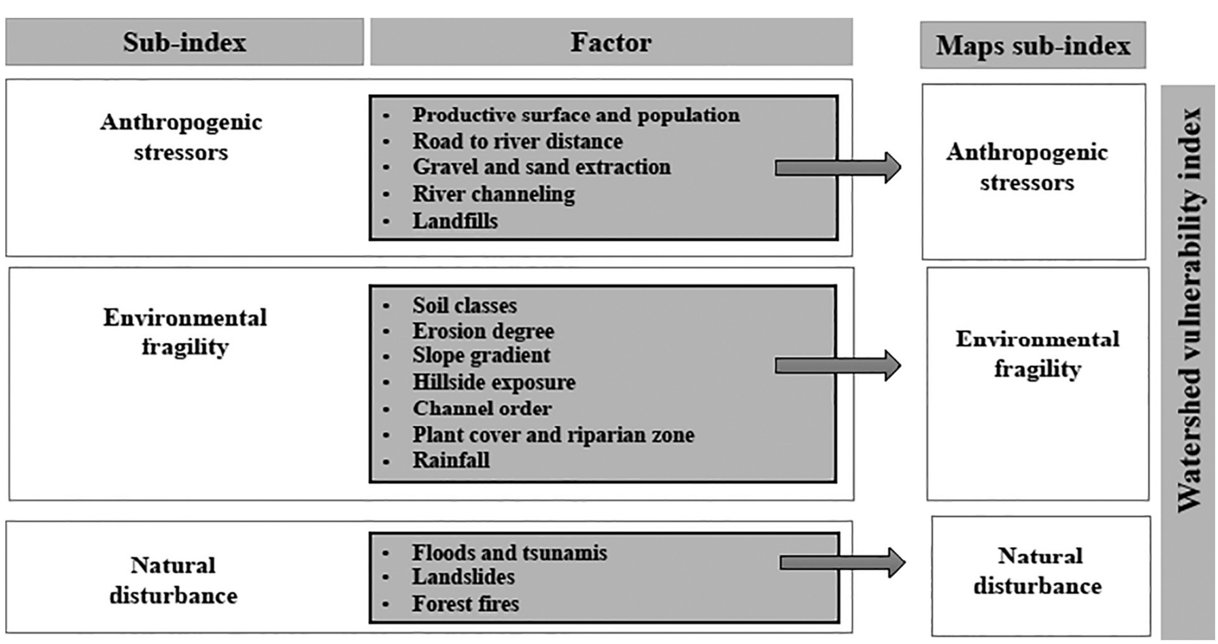

Fig. 2. Chart of the WVI structure.

factor was based on a literature review, field evaluations, visual analysis using Google Earth Pro (7.3.1.4507), public databases, expert consultation and surveys. For the analysis of relief and slopes we used a Digital Elevation Model (DEM) generated using a 30 × 30 m Advanced Spaceborne Thermal Emission Raster and Reflection Radiometer (ASTER) image. This information was digitized and standardized in ArcGIS 10.1 software ESRI (Environmental Systems Research Institute), 2010. The cell output format of each variable was 150 × 150 m. The WVI is a spatial index without a temporal component.

2.3. Multi-criteria evaluation for the development of the WVI

To determine the index grouping weights, we carried out surveys aimed at scientific experts, scholars, government scientists, students (MSc or PhD) and private sector environmental consultants with experience in research into various aspects of freshwater mediterranean watersheds. Forty-two experts were contacted via email (August–September 2018) and were informed about the purpose of the survey via the Delphi method (Okoli and Pawlowski, 2004). We sent 42 sent surveys and received 26 completed surveys. The agreement of the experts was evaluated through Kendall concordance analysis ($W = 0.6$; $\alpha = 0.05$) (Rojas et al., 2017). All statistical analyses were performed in SPSS (IBM Corp. Released 2013). For the comparative integrated evaluation of the different factors of each sub-index, we normalized the data (Molero et al., 2007); then we defined the relative weights (W) of each factor, assigning an order based on the importance of the factors:

$$W = \frac{O_f}{\sum O_f} \quad (1)$$

where W: Weight based on order; O_f: Order as a function of the factors; $\sum O_f$: Sum of all the order values calculated for each factor. The ranges of each thematic layer were re-classified to establish vulnerability scores on the following scale: 1) Very low, 2) Low, 3) Medium, 4) High. We also included the exclusion category "does not apply."

2.4. Integrated maps and construction of the WVI

To construct the WVI we integrated the thematic layers of each sub-index using ArcGis 10.1 software. We introduced each layer in raster format; these layers were integrated using Raster Calculator with the following expression:

$$WVI = (F_1 \times W_1) + (F_2 \times W_2) + \ldots (F_n \times W_n) \quad (2)$$

WVI is the watershed vulnerability index, F_n are the reclassified vulnerability factors (vulnerability scores) and W_n (relative weight) is the relative score by weight of influence.

The sub-indices were weighted as follows: anthropogenic stressors, $W = 50$; natural disturbances, $W = 30$ and environmental fragility, $W = 17$. The results were reclassified into four classes or levels of watershed vulnerability. Levels 1 and 2 represent very low and low watershed vulnerability, respectively, associated with sectors with low fragility and minor impacts resulting from anthropogenic stressors and natural disturbances; such sectors have territorial components that need to be conserved. Level 3 represents medium vulnerability; level-3 sectors are affected by a wide range of anthropogenic stressors and natural disturbances, with medium environmental fragility and a need for conservation. Level 4 includes sectors with major impacts resulting from anthropogenic stressors and natural disturbances, as well as high environmental fragility; these areas require restoration, mitigation and environmental management measures.

2.5. Anthropogenic stressors sub-index

We considered anthropogenic stress factors to be any possible source of pollution, damage or destruction resulting from human activities in river ecosystems (Harik et al., 2017). We identified and classified five specific stressors, which were used to construct this sub-index (Fig. 2) (Table 1).

2.5.1. Productive surface and population

This factor groups forestry plantations, agriculture and the population (in terms of number of inhabitants), which generally extend to

Table 1
Reclassification of the factors to determine vulnerability according to ranges and weights for each anthropogenic stressors sub-index.

Thematic Layers	Vulnerabiliy	Watershed Area (%)	Range		Weight (%)	Reference
Productive surface (SP) and population (P)	Very low	31	SP (%/ha) ≤20	P (h) <25	64	Mardones and Vidal, 2001; Fierro et al., 2016; Blanchard and Lerch, 2000.
	Low	11	21–40	100–25		
	Medium	16	41–59	100–200		
	High	42	≥60	>200		
Road to river distance (m)	Does not apply	–	Does not apply		07	Bouahim et al., 2015.
	Very low	–	> 2500			
	Low	–	2500–1500			
	Medium	16	1500–500			
	High	84	<500			
Gravel and sand extraction	Does not apply	99	Does not apply		11	Mooney and Pickles, 2005.
	Very low	–	No extraction			
	Low	0.02	Permanent extraction outside of bed			
	Medium	0.07	Point extraction in the bed			
	High	0.35	Constant extraction in the bed			
River Channeling	Does not apply	99	Does not apply		14	PAS, 2016[a].
	Very low	–	Free flowing			
	Low	–	Semi-channeled			
	Medium	–	Channeling with course change			
	High	1	Channeling with lining			
Landfills	Does not apply	97.25	Does not apply		04	Zafar and Alappat, 2004
	Very low	–	No garbage dumps or sanitary fills			
	Low	–	Sanitary fill away from the channel			
	Medium	1.85	Sanitary fill near the channel			
	High	0.90	Garbage dump near channel			

[a] Sector environment permission. Elaboration by authors.

the riverbanks and wetlands, causing fragmentation and alteration of landscape connectivity and significant impacts on the hydrology and geomorphology of river systems (Doyle et al., 2000; Grantham et al., 2010). The population sizes of urban and rural zones were obtained from census information from the National Statistics Institute (INE, 2002) and the Planning Directorate of the Ministry of Public Works (DIRPLAN, 2008). The population numbers were re-classified using the parameters of Mardones and Vidal (2001). We also incorporated extensive production covers such as forestry and agricultural plantations obtained from the CONAF (2008) Vegetation Catalog. Using the results of Fierro et al. (2016) and Blanchard and Lerch (2000), we reclassified forestry and farmland uses.

2.5.2. Road-to-river distance

Roads are strips that interfere with hydrodynamics and lead to sediment deposition and contaminant intrusion (Chiogna et al., 2016; Yunker et al., 1999). To determine the distances from roads to rivers we used the National Road Network Database from the Ministry of Public Works (MOP, 2017) and the National Water Network Database from the General Water Directorate (DGA-MOP, 2017), employing an MDT ASTER (30×30 m). To obtain the distances in the rest of the watershed we used Euclidean distance (Table 1).

2.5.3. Gravel and sand extraction

These activities lower the riverbed, modifying the channel profile; they also alter the transport of fine sediment in both the river and the adjacent coastal zones. We identified and reclassified the zones of influence according to the degree and frequency of intervention. We estimated and spatialized the area affected by gravel and sand extraction according to Mooney and Pickles (2005), in accord with the surface flow direction (Table 1).

2.5.4. River channeling

Channeling changes the transmission of gradations that produce adjustments in both the geometry of the channel and the equilibrium gradient (Huang et al., 2014), causing rivers to lose hydraulic efficiency. We considered all types of interventions in the river system for flood control, bank erosion management and channel relocation for the construction of infrastructure projects. To determine the level of channel intervention, we classified the interventions according to the Guide for Environmental Sector Authorization for Regularization of Natural Channel Defenses, published by the Environmental Assessment Service (PAS, 2012) (Table 1).

2.5.5. Landfills

These are complex chemical matrices that include organic matter, inorganic salts, trace organic pollutants and heavy metals. The concentration and composition of the leachate is dependent on the characteristics of the waste deposit and is affected by environmental conditions, landfill function and decomposition process dynamics (Moody and Townsend, 2017; Yao, 2017). We identified the zones of influence of the garbage dump and sanitary landfill in the study area according to the direction of the river surface flow (Table 1).

2.6. Environmental fragility sub-index

Naveas (1979) estimated the fragility of the natural ecosystems of Chile, expressing the concept as the susceptibility of an environment to deterioration as a result of disequilibrium among its geomorphological, climate and vegetation variables. We used seven specific factors to construct this index (Fig. 2) (Table 2).

2.6.1. Soil classes

The environmental fragility of soil classes is a result of the alteration of soil properties due to human activities, mainly associated with inappropriate agricultural practices (Zalidis et al., 2002). Ross (1994) indicated that soil classes are determined as a function of their texture, structure, consistency, degree of cohesion and horizon depth/thickness. The methodology developed by CIREN (2009) was used to determine soil type fragility. We estimated the clay range (A) in the soil according to the composition of the texture classes (Jaque, 1996) using the following formula:

$$A = \frac{Sand\% + Silt\%}{Clay\%} \quad (3)$$

Based on the classification of the pedon depth (CIREN, 1997, 1999) and the clay range, a tabular data matrix for every variety of soil was generated and subsequently classified in accord with the vulnerability ranges (Tables A1 and A2).

2.6.2. Erosion degree

This factor is the detachment and movement of soil or rocks due to the action of water, wind, ice or gravity. It is related to geo-ecological factors (e.g., lithology, topography and climate) and soil uses. We used the classification based on the specifications from CIREN (2010) agrological studies, with a scale of 1:50000, and CONAF technical bulletins (Table 2).

2.6.3. Slope gradient

This factor influences processes and water balances due to precipitation events (Wu et al., 2018), altering the surface flow of runoff and the intrusion of organic and inorganic material, nutrients and fine sediments into the river system (Kosmas et al., 2000). To calculate the slope in degrees we used the DEM layer with the Slope tool in ArcGIS 10.1, reclassified according to De Pedraza (1996) (Table 2).

2.6.4. Hillside exposure

This factor is determinant in vegetation distribution and soil development. Hydrologically, it is a factor in the mechanisms of seasonal control of runoff generation and soil humidity, directly influencing hydrological and erosion processes (Ruiz et al., 2010). Exposure was calculated from DEM using the Aspect tool in ArcGIS 10.1, resulting in eight categories (directions) (Table 2).

2.6.5. Channel order

Anthropogenic alteration of the river headwaters could cumulatively affect the ecological function of the river system downstream. Therefore, we analyzed the river network using the Strahler method incorporated into ArcGIS 10.1 (Strahler, 1957), reclassifying it into four categories (Table 2).

2.6.6. Plant cover and riparian zones

The effect of plant cover and riparian zones on the health of the ecosystem is related to the diversity, richness and width of the riparian plant community (Elliott and Vose, 2016). We determined the level and type of plant cover using CONAF (2008) covers. Then we determined the width of the riparian buffer zones (RZ) according to the analysis and classification of river order based on Garlapati et al. (2010). The width of the riparian zones was overlaid with vegetation density and type according to Munné et al. (2003). Fragility was classified into four categories (Table 2).

2.6.7. Rainfall

Rainfall plays a key role in the water cycle, since it affects water storage and quality (Shehane et al., 2005). We obtained a national 1×1-km raster from Clim-Global Climate Data, corresponding to average rainfall time series from 1970 to 2000, reclassified at watershed level according to Rojas (2015).

Table 2
Reclassification of the factors to estimate vulnerability using ranges and weights for the environmental fragility sub-index.

Thematic Layers	Vulnerability	Watershed Area (%)	Range		Weight (%)	Reference
Soil classes (Association)	Very low	28.78	San Esteban		11	CIREN, 1999[a]
	Low	2.78	Curanipe			
	Medium	67.24	Constitución - Cauquenes			
	High	1.20	Sandy series			
Erosion degree	Does not apply	3.41	–		15	De Pedraza, 1996; CIREN, 2010[a]
	Very low	10.60	Slight			
	Low	55.76	Moderate			
	Medium	27.32	Serious			
	High	2.92	Very serious			
Slope gradient	Very low	0.36	>25°		16	De Pedraza, 1996; Kosmas et al., 2000.
	Low	26.39	10.1°–24.9°			
	Medium	39.83	5°–10°			
	High	33.43	<4.9°			
Hillside exposure	Very low	11.17	S		5	CIREN, 2010[a].
	Low	48.45	E–SE–SW			
	Medium	12.85	NE			
	High	27.52	N–NW			
Channel order	Does not apply	81.55	–		17	Freeman et al., 2007; Elliott and Vose, 2016.
	Very low	13.60	1–2			
	Low	3.28	3–4			
	Medium	1.56	5–6			
	High	0.00	>7			
Plant cover and riparian zone	Very low	15.68	Plant Cover (%)	Type of Vegetation	28	Munné et al., 2003; You et al., 2015.
			>80	Native forest, wetland		
	Low	46.34	50–80	Shrublands, grasslands.		
	Medium	26.73	49–10	Forest plantation, Agriculture		
	High	11.25	<10	No vegetation		
Rainfall (mm)	Very low	5.46	>1500		8	Rojas, 2015; INE, 2016[b]
	Low	90.61	1499–1200			
	Medium	3.92	1199–900			
	High	0.00	<899			

[a] Natural resources information center.
[b] National Statistics Institute. Elaboration by authors.

2.7. Natural disturbances sub-index

Natural disturbances have been defined as any relatively discreet or one-time event that interrupts an ecosystem or its physical surroundings. They result from a wide range of physical and biological activities that vary in size, frequency and intensity (Mitchell et al., 2013; Rapport, 1983). We used three types of natural disturbances (Fig. 2) (Table 3).

2.7.1. Floods and tsunamis

Floods are increases in water flow from the river system, while tsunami flooding produces an intrusion of salt water into the river system (Watanabe et al., 2014). We deemed floods to have medium impacts on river systems and tsunamis to have high impacts. To develop this factor we used the National Service of Geology and Mining 2006 Flood Coverage Map (SERNAGEOMIN, 2010). For tsunamis we used the Chilean Navy Hydrographic and Oceanographic Service Flood Coverage Map (SHOA, 2013) (Table 3).

2.7.2. Landslides

Landslides are the movement of the surface material of a slope to a point of equilibrium due to the direct action of gravity. A landslide may produce debris flows and floods, with long-term consequences for river systems (Geertsema et al., 2009, Mardones and Vidal, 2001), including contamination due to an excess of sediment and suspended solids (Persichillo et al., 2017, 2018). Landslides were reclassified according to the parameters of the 2016 Regional Energy Plan (PER, 2016) (Table 3).

Table 3
Reclassification of the factors to determine vulnerability according to ranges and weight for the natural disturbances sub-index.
Source: Elaboration by authors.

Thematic Layers	Vulnerability	Watershed Area (%)	Range	Rating	Weight (%)	Reference
Floods and Tsunamis	Does not apply	82.9	Does not apply	–	36	Espada et al., 2017; Rojas et al., 2015
	Very low	0.0		1		
	Low	15.0		2		
	Medium	1.1	Floods	3		
	High	1.0	Tsunami flooding	4		
Landslides	Very low	0.3		1	20	Guerra et al., 2017
	Low	43.3		2		
	Medium	54.8		3		
	High	1.6		4		
Forest fires	Very low	0.3		1	44	Temporetti, 2006; Castillo et al., 2013
	Low	43.2		2		
	Medium	54.7		3		
	High	1.6		4		

2.7.3. Forest fires

Forest fires have mostly anthropogenic causes; only 2% have been classified as natural (Alcañiz et al., 2018). They are a dominant factor in mediterranean watersheds (Pausas et al., 2008); they may alter soils and vegetation and modify hydrological characteristics (Temporetti, 2006). To determine these areas we used a model of susceptibility according to altitude, slope, orientation and vegetation (PER, 2016); the model was validated using information from CONAF (2008) on forest fire events in the 2002–2007 period (Table 3).

2.8. Validation of the WVI

Multiple stressors cause nutrient intrusion and disruption in the chemical parameters of water (Vargas et al., 2013) at the expense of water quality and river system health, which are essential for maintaining coastal ecosystems, and causing eutrophication of river and coastal ecosystems. To validate the WVI we used pH, dissolved oxygen, total dissolved solids, salinity, turbidity, temperature and conductivity, as well as nitrate (NO_3^-) and nitrite (NO_2^-) concentrations, since they are highly soluble and have low retention in soils (Temporetti, 2006). In addition, they are not limiting elements in rivers and thus are good indicators to evaluate the state of water quality in a watershed system (Nikolaidis et al., 2014). The watershed was divided into the three main sections – the headwaters, transfer and depositional zones – according to Schumm (1977) and the slope gradient.

2.8.1. Water sampling and physicochemical parameters

We sampled 16 stations along the Andalién River (Fig. 1). The water samples collected in the stream were always sampled at low tide. We sampled during the austral summer and winter of 2017. River surface samples were collected from the central channel and placed into 15 mL HDPE bottles in triplicate for analysis of nitrate (NO_3^-) and nitrite (NO_2^-); the samples were filtered through 0.45-μm GF/F glass-fiber filters and frozen at −20 °C until analysis in the laboratory. Standard colorimetric techniques were used to determine nutrients (Grasshoff et al., 1983). We also measured in situ pH, dissolved oxygen, total dissolved solids, salinity, turbidity, temperature and conductivity using a multiparameter meter (Hannah model HI 9829).

2.8.2. Statistical analysis of the validation

To associate the ranges of NO_3^-, NO_2^-, pH, dissolved oxygen, total dissolved solids, salinity, turbidity, temperature and conductivity with watershed vulnerability, we estimated quartiles for each parameter. This allowed each parameter to be classified into four quality categories (very low, low, medium and high) in order to correlate the categories with the watershed vulnerability classes. We determined the mean area of influence for each of the 16 sampling points. Then we estimated the number of pixels in this area of influence and the type of mean watershed vulnerability.

To estimate the importance of the chemical factors to watershed vulnerability and then validate the index, we calculated a matrix of Spearman correlations among the seasonal concentrations of NO_3^-. NO_2^-, pH, DO, TDS, salinity, turbidity, temperature, conductivity and watershed vulnerability. The significance level was set at 0.05 using Bonferroni correction. We assumed that $r \geq 0.6$ indicated a strong correlation, values from 0.4 to 0.6 indicated a moderate correlation and values below 0.4 indicated a weak correlation (Nowak and Schneider, 2017). To determine if watershed vulnerability is significantly different throughout the watershed, we performed a one-way ANOVA using the zoning of the watershed as a fixed factor with three groups, with watershed vulnerability as the response variable. The ANOVA assumptions were evaluated with a Levine test for homogeneity of variances and a Shapiro-Wilk test for the normality of residuals. A Tukey a posteriori test was used to evaluate the significant differences in the factor. The significance level was set at 0.05 for the tests of ANOVA assumptions and the a posteriori test.

3. Results and discussion

3.1. Anthropogenic stressors sub-index (ASS)

These stressors were distributed heterogeneously in the Andalién River watershed; those with the greatest mean impact for this sub-index were productive surface and population, while those with the lowest were landfills and river-to-road distance (Table 1, Fig. 3). The areas with very low (41%), low (17%) and medium (42%) anthropogenic stressor impacts were found in the transfer zone and headwaters of the watershed, while the highest impact (1%) was in the depositional zone. A number of authors agree that cumulative impacts converge in the depositional zones of rivers (Grizzetti et al., 2016). It is worth mentioning that in the wetland and national reserve the impacts were low and very low (Fig. 3), forming patches of biodiversity; however, only the Nonguén Stream sub-watershed, where the reserve is located, has conservation measures in place.

3.1.1. Productive surfaces and population

Areas with high potential for anthropogenic stress were found mainly in the headwaters and depositional zones of the watershed (Fig. 3), associated with productive surfaces and population (Table 1, Fig. 4). The Andalién River watershed was historically subjected to highly dynamic landscape processes linked to a 67% reduction in the native forest between 1975 and 2000, an annual loss of 4.5% (Echeverria et al., 2006). We estimated that aquatic macroinvertebrate diversity and water quality have decreased by >60% (Table 1), while agriculture, plantations and urbanization have increased at annual rates of 1.1%, 2.7% and 3.2%, respectively (Schulz et al., 2010). Some authors state that in the last 50 years urban development has been rapid and uncontrolled in the area around the Andalién River and on filled-in wetlands (Araya-Muñoz et al., 2017; Rojas et al., 2013; Rojas et al., 2017; Vidal and Romero, 2010). Smith and Romero (2009) indicated that wetlands in the urban zone lost 40% of their surface area between 1975 and 2004, significantly affecting biodiversity conservation (Pauchard et al., 2006) and homogenizing the biological and physical landscape (Torres et al., 2015). López-Doval et al. (2013) showed that there is a correlation between pollution and population, industries and agriculture due to the increase in the transport of sediments and nutrients in river systems, degradation of flood flows (Deng and Xu, 2018) and hydrogeomorphological modifications (Chin, 2006).

3.1.2. River-to-road distance

Eighty-four percent of the watershed has a high potential for anthropogenic stress due to the high proximity of the river system to roads (e.g., distance <500 m) (Table 1, Fig. 4). Since 2004 there has been increasing road infrastructure development, causing temporary diversions, constructions of river embankments and stream cleaning in the river system (Moraga, 2018). These road projects do not include riparian buffer zones; hence, the infrastructure surrounds the watercourses, mainly in the depositional and transfer zones of the watershed, with direct implications for the river system (Moraga, 2018). Several studies concluded that these projects are associated with direct and indirect negative effects on the biotic integrity of terrestrial and aquatic ecosystems (Delgado et al., 2004). They also influence biological and ecological processes in rivers (Barber et al., 2014; Green et al., 2008), increasing the concentration of polycyclic aromatic hydrocarbons due to runoff and deposition of atmospheric oligoelements (Pb, Cd, NO_x, SO_x) (Chiogna et al., 2016; Foraster et al., 2011), altering the nitrogen cycle (Green et al., 2008) and favoring the propagation of introduced species (Forman and Deblinger, 2000).

3.1.3. Gravel and sand extraction

Of the total surface area of the watershed, 0.3% has a high potential for anthropogenic stress due to the constant extraction of gravel and sand (Table 1, Fig. 4), which affects the depositional and transfer

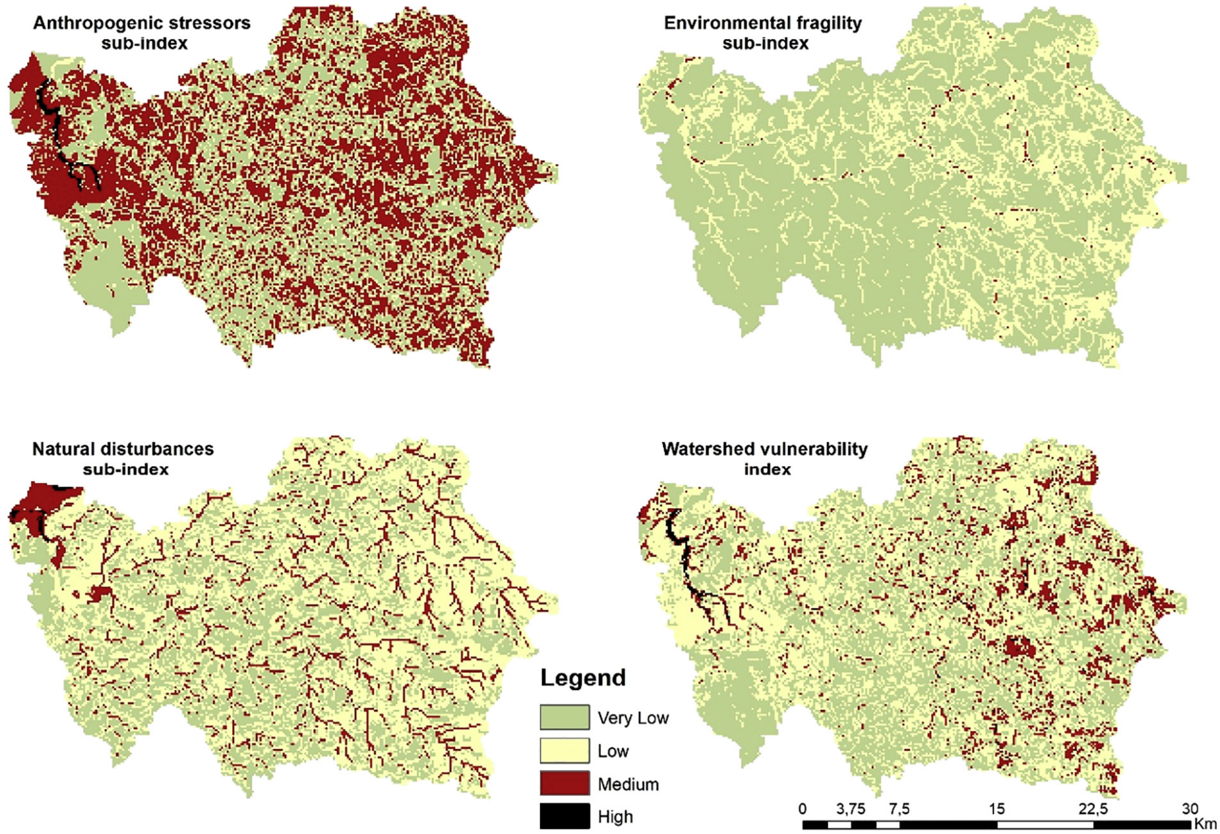

Fig. 3. Maps of the anthropogenic stressors sub-index, environmental fragility sub-index, natural disturbances sub-index and watershed vulnerability index (WVI). Made by the authors.

zones and generates great pressure on rivers and floodplains (Kori and Mathada, 2012). During the Andalién River channeling process, sand and gravel was extracted to fill other areas at risk of flooding, decreasing native fish habitats (Ortiz-Sandoval et al., 2009). This kind of activity decreases about 1.5 m from the river bed, affecting the aggregate transport rate up to 5 km from the extraction point (Smith and Fernald, 2006; Whol et al., 2015). Gravel extraction can alter stream ecology through the loss of habitat heterogeneity (Lau et al., 2006). The abundance of some fish can decrease when spawning sites are altered by a higher amount of fine sediments (Boudaghpour and Hashemi, 2008; Wyzga et al., 2009); abundance and richness of benthic invertebrates can also decrease, as breathing is restricted due to high turbidity (Mori et al., 2011).

Extractions may also alter the transport of fine sediment to coastal zones, disturbing management areas in estuaries and adjacent oceanic zones (Erskine, 1990). The interface of estuary and river zones is highly vulnerable to extractions, since they can extend the saline limit upstream, resulting in complex impacts on tide dynamics in the river and thus on community structure (Erskine, 1990).

3.1.4. River channeling

One percent of the study area has high vulnerability to this anthropogenic stressor, which is classified as a high-impact stressor. However, the main watercourse is channelized only in the transference and depositional zones, while Nonguén Stream is channelized in the depositional zone (Table 1, Fig. 4). The channelized area in the depositional zone of the study area has increased since 2006 after a large flood in the watershed (Rojas et al., 2017). In the Nonguén Stream depositional zone the channeling was more complex, with channel widening and compacting, lining of the streambed with concrete and rocks and changing of the channel course (Moraga, 2018). According to Rambaud et al. (2009), different types of channeling have different degrees of impact on a river system. Smiley and Dibble (2008) indicated that re-sectioning and embanking homogenize the velocity of the river flow, decreasing rapids, depth and substrate types (Smith and Fernald, 2006), while stabilizing works produce a loss of sinuosity, eliminating meanders and thus decreasing the presence of pools (Huang et al., 2014). Moraga (2018) analyzed studies on the abundance and diversity of the ichthyofauna of the Andalién River published between 1919 and 2018, indicating that there has been a significant decrease in native species and an increase in invasive species in the channeled zones. Rambaud et al. (2009b) suggested that channeling affects the spatial and temporal dynamics of the physical and floristic composition of rivers, which are linked to the biological traits of species.

3.1.5. Landfills

One percent of the watershed has high vulnerability to this high-impact anthropogenic stressor. Since 1998 a sanitary landfill has been operating in the transference zone, and in the depositional zone of the watershed near the river systems (<200 m) an illegal dump, where waste from the Concepción Metropolitan Area was deposited (Table 1, Fig. 4), was established in about 1990. This dump included different types of waste; among the main sources of pollution were materials from excavations and leachate, which is liquid that is very damaging to surface and groundwater (Moody and Townsend, 2017). Runoff and infiltration from dumps can be a complex problem due to lack of treatment, lining and action to make the soil impermeable, generating a mixture of atmospheric oxygen and rainwater in the dump (Zafar and Alappat, 2004). Comstock et al. (2010) indicated that the major pollutants contained in leachate are biodegradable/non-biodegradable organic materials and heavy metals with anthropogenic organic chemicals such as phthalates and other endocrine-disrupting compounds (Moody and Townsend, 2017; Yao, 2017).

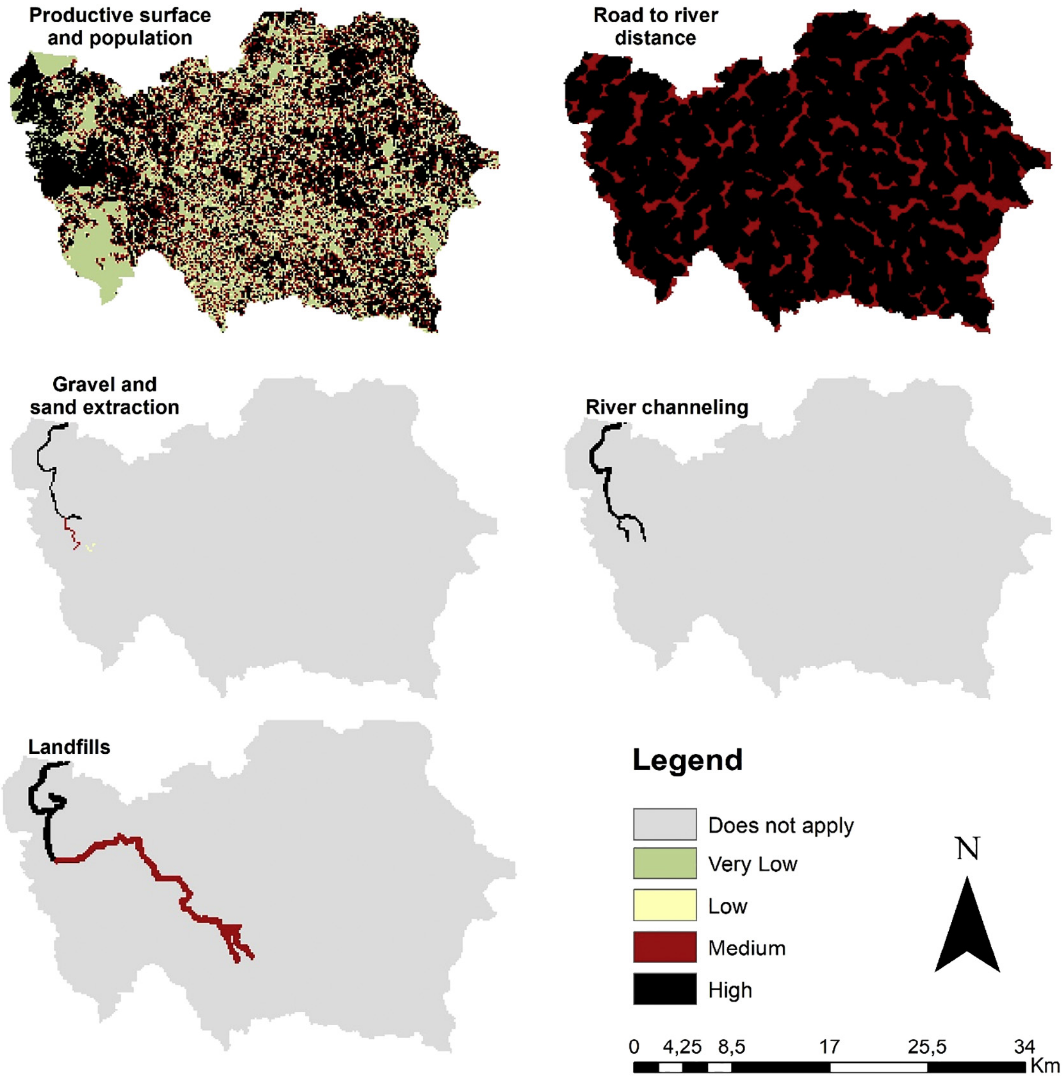

Fig. 4. Thematic map of the anthropogenic stressors sub-index (ASS) factors.
Made by the authors.

3.2. Environmental fragility sub-index (EFS)

The factors that most determined the environmental fragility of the watershed according to their weight were plant cover and riparian zones. Environmental fragility was very low in 71.6% of the study area, low in 27.8% and medium in 0.6%, and explained mainly by the physical properties of the watershed such as soil classes, erosion degree, slope and slope exposure (Dalla Corte et al., 2015) (Table 2, Fig. 3).

3.2.1. Soil class

The environmental fragility of the soils depositional zone is medium, since they are shallow sandy loam soils with a clay matrix (Table 2, Fig. 5). Fragility is low in the depositional zone, due to a similar composition of sand, silt and clay (San Esteban and Curanipe series) (CIREN, 1999; Jaque, 1996). The depositional zone adjacent to the coast exhibits high fragility, since the soils there are composed mainly of sand, which has high drainage and permeability (CIREN, 1999). Soil fragility is related to its physical and mechanical characteristics, which determine its resistance to erosion (Bünemann et al., 2018). Thus, soils with high sand or silt content, such as those of the section along the coast (sandy series), are more fragile or sensitive, while those with higher clay content, located in the headwaters zone of the study area, are more stable (Curanipe, San Esteban) (Bughici and Wallach, 2016). When river systems are exposed to fragile soils and rock types that can be lost through sedimentation they may undergo morphometric alterations, modification of bottom composition, alteration of flow velocity and decreases in aquatic flora and fauna assemblages (Zalidis et al., 2002; Efthimiou, 2018).

3.2.2. Erosion degree

Three percent of the watershed has very serious, high fragility due to an erosion degree associated mainly with farmland, while 11% of the watershed exhibits slight fragility in the depositional zone, where the wetland is located. In general, erosion was concentrated in areas of the watershed with low plant cover, agricultural zones, old riverbeds and hillsides, with significant repercussions in the form of increases in erosion and runoff (Castro and Vicuña, 1990). There was considerable erosion in the headwaters zone of the study area due to major forestry activity; >75% is covered by forestry plantations (CIREN, 2016). Intense erosion processes occur on the slopes of the watershed after tree harvests, as well as due to the construction of roads and inappropriate drainage systems (Gaoyoso and Iroume, 1995). Extensive farming was

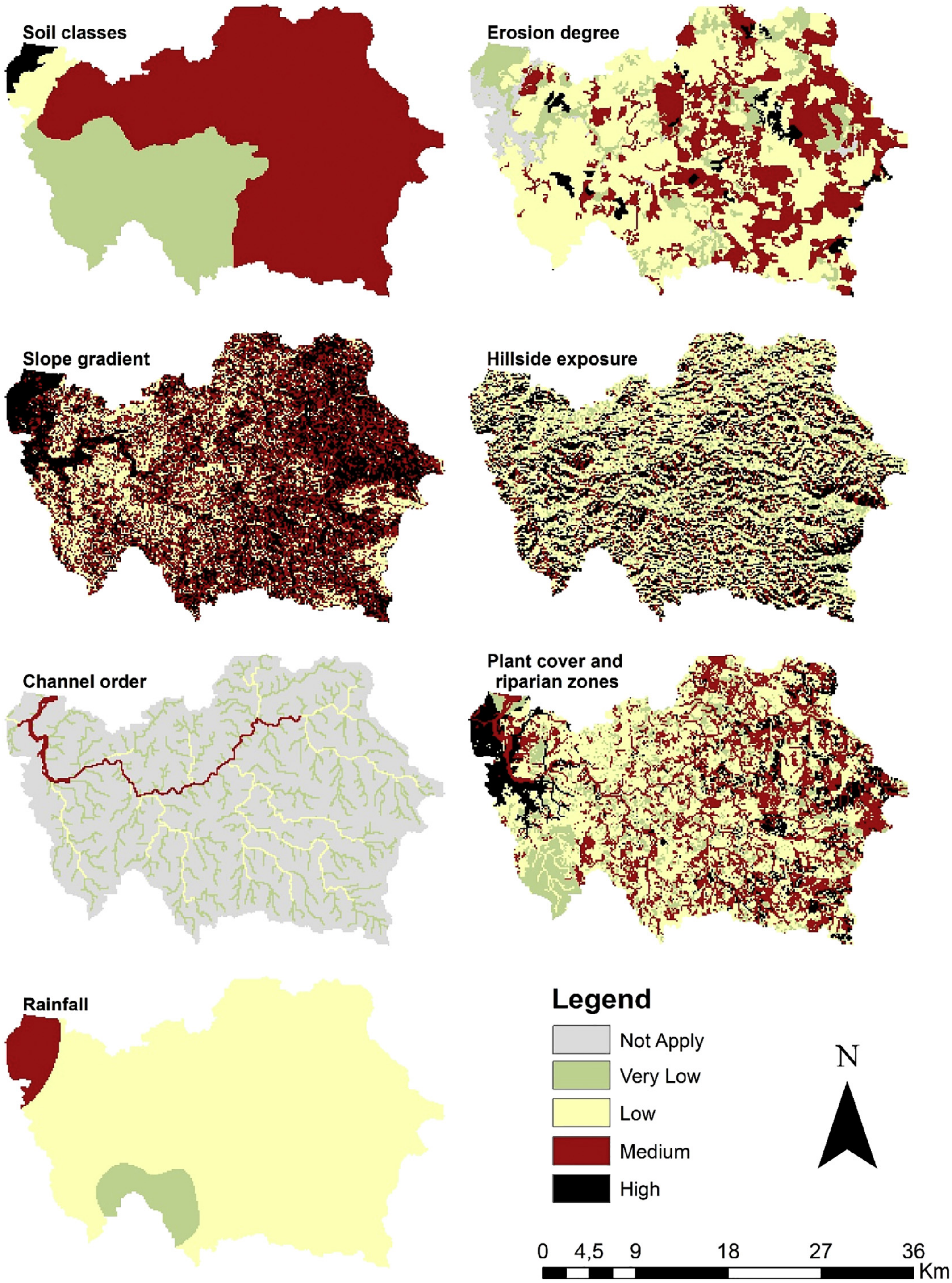

Fig. 5. Thematic Maps of the environmental fragility sub-index (EFS) factors.
Made by the authors.

the main economic activity in the region during the 18th and 19th centuries (Jaque, 1996), and at the end of the 20th century agrarian reform and changes in macroeconomic policy contributed to the modernization and intense productivity of the farming sector (Gwynne and Kay, 1997). Nevertheless, this productivity caused a rise on the environmental degradation as soil degradation, salinization of irrigated areas (Blanchard and Lerch, 2000), drinking water overdraft, pest accumulation and pesticide and herbicide use (Grecchi et al., 2014). In general, human activities tend to accelerate natural erosion processes (eolic and hydric) until the soil loss cannot be counterbalanced by the natural formation ratio; in these cases loss or soil degradation under arid, semiarid and subhumid dry environments could result.

3.2.3. Slope gradient

High fragility is presented in the depositional zone, which has a gradient <4.9° and river slopes, while very low fragility is presented at gradients >25° in the headwaters zone (Table 2, Fig. 5). Forty percent of the study area presented medium environmental fragility associated with slope gradient, while 33% presented high fragility, which is associated with lower gradients in the transfer and depositional zones of the watershed; meanwhile, in the headwaters zone fragility was very low, associated with greater slopes. Coblentzl and Riitters (2004) indicated that slope plays an important role in the distribution of vegetation and biodiversity. The slope of a watershed is one of the main factors that explain freshwater fauna and aquatic biota variation. Organisms adapted to cold water with high levels of dissolved oxygen are found in the headwaters of watersheds with high slopes, while organisms adapted to lower oxygen concentrations are found in areas with low slopes (Vannote et al., 1980). Watersheds with low elevations, intermediate slopes and forest plantations are more fragile. Some authors have indicated that in watersheds with a negative water balance the flat sedimentary sectors evaporate a large portion of the precipitation (Brown et al., 2013); the low slope allows only the development of extremely slow subterranean, sub-surface and surface water gradients; thus, the horizontal flow of water in the soil is slow (Yuan et al., 2017).

3.2.4. Hillside exposure

The fragility of the Andalién watershed according to hillside exposure is low in areas with an E–SE–SW orientation, while a N–NW orientation results in high fragility (Table 2, Fig. 5). N-NW exposure in the watershed resulted in high fragility because slopes with greater exposure receive greater solar radiation (i.e., N exposure), which may increase evapotranspiration and favor erosion processes due to greater exposure to precipitation. E, SE and SW exposures result in low fragility because these slopes have the least solar radiation and evapotranspiration in the watershed (Katra et al., 2007). In Chile the numbers of evergreen species and plant dimensions on south-facing slopes are greater compared to those on north-facing slopes (Armesto and Martínez, 1978). Martínez-Murillo et al. (2013) found differences in soil humidity among the orientations (S > N), which affect the distribution of vegetation. López-Gómez et al. (2012) discussed the effect of slope orientation as a determining factor in plant community structure, since plants have morphological and physiological differences.

3.2.5. Channel order

First- and second-order rivers are headwaters rivers with very low environmental fragility and steep gradients, into which sediment erodes from slopes of the watershed, resulting in the predominance of particulate allochthonous matter intrusion (Vargas et al., 2013). Third- and fourth-order rivers account for 3% of the river system and present low environmental fragility, mainly in the transfer zone of the watershed, which receives eroded material (Table 2, Fig. 5). Elliott and Vose (2016) indicated that low-order drainages constitute up to >50% of the total length of a river. First and second-order rivers in the study area are under several anthropogenic pressures such as forestry plantations and agriculture. Bendix and Stella (2013) suggested that low-order rivers in the headwaters zones of watersheds are vulnerable to changes in land use (e.g., intensive agriculture, forestry plantations), producing displacement, soil compaction and fertilizer and pesticide input (Taniwaki et al., 2017). In the depositional zone of the river, which presents medium environmental fragility, there are a number of anthropogenic pressure types, which have modified the main course of the river. Elliott and Vose (2016) indicated that headwaters rivers are vulnerable to flooding, terrace development and alluvial deposits. The literature also discusses the implications of altering headwaters rivers, as modifying flows in the headwaters zone of a watershed produces effects downstream; thus, these zones are vital to maintaining ecosystem health (Freeman et al., 2007; Segurado et al., 2018).

3.2.6. Plant cover and riparian zones

Forty-six percent of the plant cover and riparian zones presented low fragility, which is associated with scrublands, grasslands and native forest, while the plant cover and riparian zones composed of forestry plantations and agriculture presented medium and high vulnerability. High plant cover and riparian zone fragility was presented mainly in the depositional zone (Table 2, Fig. 5), where most of the stressors are located (see Section 3.1), except for the area of the NNR, which had low fragility. There are forestry laws concerning riparian vegetation (Gayoso and Gayoso, 2003); however they are scattered among different laws and include contradictory and expired regulations (Romero et al., 2014). The most applied are Decree Law 701 (1974) on forestry development and Forest Law N° 20.283 of 2008 on the fund for conservation, recovery and management of native forests. The literature indicates that the quality and efficiency of riparian zones is related to the width of the buffer zone, which depends on river order, slope, vegetation type and soil characteristics (Garlapati et al., 2010; Andreoli et al., 2012; Picco et al., 2017). Gurnell and Petts (2011) and Hession and Curran (2013) suggested that greater riparian plant diversity is more efficient at maintaining the health of river ecosystems. In addition, Elliott and Vose (2016) indicated that protection of riparian zones in low-order rivers can improve the quality of the riparian forest and the diversity and abundance of aquatic biota (Fierro et al., 2017). It has been demonstrated that buffer zones minimize the negative impacts of agriculture and forest plantations, given that riparian vegetation is capable of sequestering nutrients and filtering sediments (Little et al., 2015; Taniwaki et al., 2017).

3.2.7. Rainfall

The fragility index in the case of rainfall was low (>1500) and very low (1499–1200); however, since 1970 there has been a decrease in annual precipitation in the watershed (Rojas et al., 2015) (Table 2, Fig. 5). These results match those of Trenberth et al. (2007), who reported on rainfall in south-central Chile. Rainfall has decreased by 40% over the last century, which has affected groundwater storage and, therefore, baseflow in the summer period. The situation could have worsened due to the substitution of native forest with forestry plantations (Echeverria et al., 2006). These changes in rainfall patterns could exacerbate water quality issues in coastal urban areas (Shehane et al., 2005).

3.3. Natural disturbances sub-index (NDS)

Forest fires had the highest mean weight among the factors of this sub-index due to their historical recurrence. The headwaters and transfer zones of the watershed had very low (37%) and low (53%) impacts associated with landslides; however, in the depositional zone the impacts were medium (11%) and high (2%) (Fig. 3) due to the concentration of floods, tsunamis, landslides and forest fires (Table 3, Fig. 3).

3.3.1. Floods and tsunamis

These disturbances, categorized as high and medium, were observed mainly in the depositional zone of the watershed, generating significant geomorphological changes (Table 3, Fig. 6) (Rojas et al., 2017). These changes included an increase in aggradation (Thompson and Croke, 2013), erosion and widening of canals (Bowen and Juracek, 2011), loss of alluvial plains (Righini et al., 2017) and the vegetation response. The highest level of impact associated with floods was linked to tsunamis, which are less frequent than river floods. The 2010 tsunami in Chile entered the rivers, with the propagation of saltwater depending on the tide level (Tolkova, 2013). This natural disturbance generated impacts on the structure of the physical habitat, water quality and the aquatic biota of the wetland (Valdovinos et al., 2017). For example, The Great East Japan Earthquake generated extreme tsunami waves that flooded watercourses up to 25 km from the river mouths, causing a significant reduction in the richness (an average of −54%) and total abundance (−91%) of the macroinvertebrate taxa in the river communities (Watanabe et al., 2014).

3.3.2. Landslides

Susceptibility to landslides was mainly moderate and low; however, significant landslide processes were found amid the river system

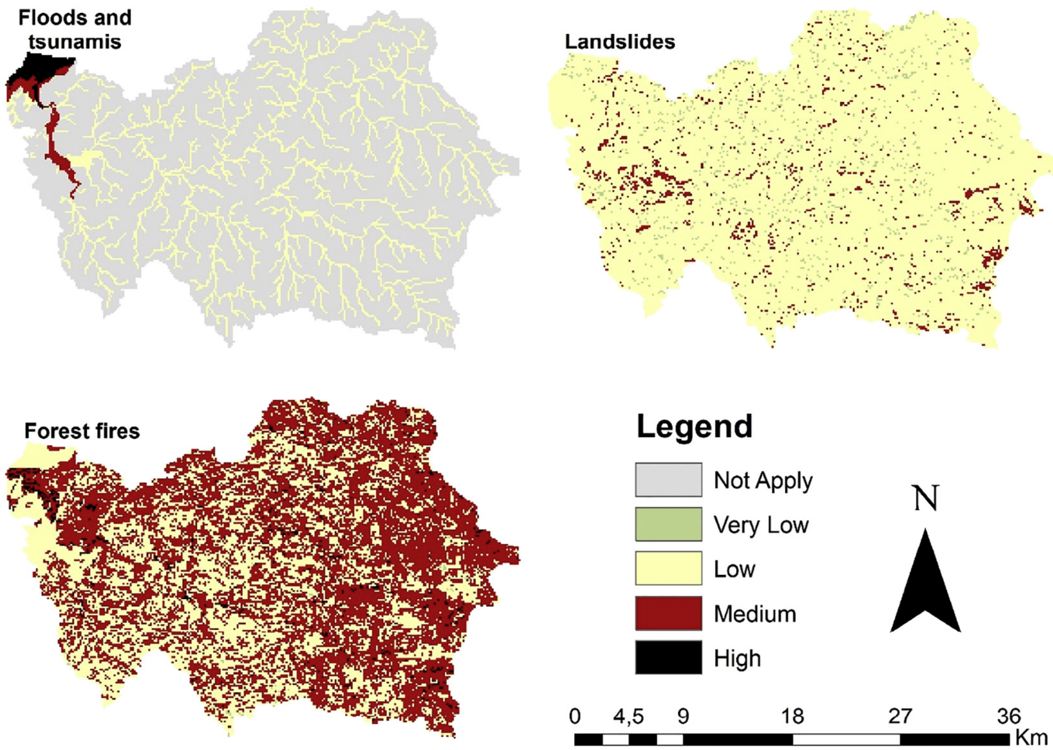

Fig. 6. Thematic maps of the natural disturbances sub-index (NDS) factors.
Made by the authors.

(Table 3, Fig. 6). Mardones et al. (2004) suggested that the main causes of landslides are related to climate anomaly thresholds (intensity and duration of precipitation), strong earthquakes, plant cover and economic activities (urban expansion and settlement in areas susceptible to landslides) (López, 2013; Mardones and Vidal, 2001). The impacts of landslides on the river system include morphological changes in the alluvial channel, intrusion of debris flows that may erode or block stretches of the river system and addition of sediments and foreign organic matter from the slopes and the alluvial channel. These impacts may affect the biotic integrity and health of the river system, as well as sources of drinking water, due to the intrusion of fine suspended allochthonous matter (Geertsema et al., 2009; Vargas et al., 2013).

3.3.3. Forest fires

The vulnerability of the watershed to forest fires was medium in areas such as the headwaters zone (Table 3, Fig. 6), where they were concentrated in the exotic plantations, which are sensitive due to their high combustibility (Pausas et al., 2008). There was low susceptibility to forest fires in the Nonguén Reserve and the Andalién wetland, where fragments of native vegetation predominate (Rojas et al., 2015; Bocaz-Torres et al., 2013) (Fig. 1). Altamirano et al. (2013) indicated that forest fires have increased in Chile in recent years, with a frequency of 5000 per year, associated with proximity to cities. We found that the impact of forest fires was very low in the depositional zone of the watershed, where the Rocuant-Andalién wetland, the Natural Reserve and the Concepción Metropolitan Area are located. Quintanilla (2000) suggested that native mediterranean vegetation is very resilient and older trees are fire tolerant. However, this vegetation is threatened by cohorts of new growth, which create fuel ladders that alter possible succession after a fire (Hessburg et al., 2016). Fire has been a recurring component in the evolution of ecosystems; its main effect is the removal of plants and leaf litter (Seidl et al., 2014), along with the organic components of the soil (Alcañiz et al., 2018). These plant components protect the soil surface; thus, their removal may affect water quality (Temporetti, 2006) due to the increase in the concentration of fine sediments in the river system.

3.4. Integrated map of WVI

Forty-three percent of the vulnerability in the watershed was low and 46% was very low, whereas 11% was medium, mainly in the transference zone; meanwhile, only 0.6% of the watershed presented very high vulnerability, in the depositional zone (Fig. 3). When evaluating the WVI along the watercourse we determined that 3.3% of the total length of the river system has high WVI, 26% has medium WVI, 46% has low WVI and 25% has very low WVI. There were significant differences in vulnerability among the three zones of the watershed (Table A3: $F(2.16) = 8.15$: $p < 0.05$), between the depositional and transfer zone (Tukey test, $p = 0.05$) and the headwaters and transfer zones, as well as the significant difference between the depositional and transfer zones.

The results of the ASS and NDS indicate that the impacts of the different types of stressors converge in the depositional zone of the Andalién River watershed; however, the EFS results indicate that this part of the watershed presents low and medium environmental fragility. The headwaters and transfer zones do not present significantly different results, probably due to the heterogeneous distribution of the ASS and NDS. Mulia and Prasetyorinia (2013) suggested that the impacts in headwaters zones decrease the total load capacity of watersheds, given the important functions of headwaters zones as conservation areas. The headwaters of the Andalién watershed are impacted by anthropogenic stressors (deforestation and agriculture), which are the main causes of the environmental and ecological effects (Nowak and Schneider, 2017; Shao et al., 2014). Thus, anthropogenic impacts in the watershed worsen the problem of fragmentation and deterioration of the river ecosystem in the depositional zone of the Andalién River.

Despite the major forestry development in the headwaters of the Andalién River, the upper zones of the tributaries (Nonguén, Queule and Chaimavida streams) are still characterized by deciduous remnants with low WVI. However, the only area where conservation and preservation measures are in place is the headwaters of the Nonguén Stream sub-watershed (Jaque, 1996), which can be classified as having a high conservation value due to the native forest of *Nothofagus* sp., in contrast to most coastal watersheds in south-central Chile (Habit et al., 2003). This zone presents high stream habitat heterogeneity, with riffles, different depth, and diversity of sediments (Palma et al., 2009). Besides, it presents an elevated number of benthic macroinvertebrates and fish native fish species (Habit et al., 2003). These results suggest that the national reserve continues to play an important role in maintaining biodiversity and improving water quality in the headwaters of the sub-watershed.

The stressors mostly produce multiple impacts that affect the temporal and spatial dynamics of the river system. They cause loss or disruption of the habitat and biodiversity, disturb the hydrogeomorphology, generate greenhouse gas emissions (GHGE) and ammonia emissions and change leaching and surface runoff patterns. They also cause an increase in allochthonous material in rivers and streams, eutrophication in the depositional zone and flood risk after the filling of wetlands for urbanization and farming. Overall, these stressors reduce the health of the river ecosystem. However, some authors such as Zalidis et al. (2002) and Zia et al. (2013) argue that the extent of the impacts depends on the natural conditions, including topography, soils, climate and geology, which significantly influence the vulnerability of the landscape to different types of environmental degradation (Lassaletta et al., 2009).

3.5. Validation of the WVI

The correlation of WVI values with those of the physicochemical parameters (Table A4) showed that the correlation with NO_3^- was strong but not significant ($r = 0.6$; $p > 0.05$). However, the correlations with NO_2^- ($r = 0.8$; $p < 0.05$) and pH ($r = 0.8$; $p < 0.05$) were strong and significant. The lowest NO_3^- and NO_2^- concentrations (0.14 and 0.009 mg/L^{-1}) were found in the national reserve, which presents low anthropogenic impacts, natural disturbances, environmental fragility and watershed vulnerability. Correa-Araneda and Salazar (2014) reported very low NO_3^- and NO_2^- concentrations in this part of the watershed, emphasizing that water quality decreases as human activity increases. The highest NO_3^- (2.98 and 1.14 mg/L^{-1}) and NO_2^- concentrations (0.08 and 0.03 mg/L^{-1}) were found in the depositional zone, where human activities predominate (population, gravel and sand extraction, channeling, garbage dumps), generating increases in NO_3^- and NO_2^- concentrations (Vargas et al., 2013). Water degradation is usually attributed to the load of nutrients, chemicals and pathogens, which have non-point sources and thus are difficult to identify and quantify (Zia et al., 2013; Nowak and Schneider, 2017). Hence, our results show a direct, significant correlation between WVI and water quality measured in situ in the Andalién River watershed.

3.6. Future considerations

The WVI has some limitations that must be considered. For example, it was developed in a coastal watershed in which there are no dams/reservoirs. Our WVI is a preliminary approach; therefore, in order to apply it in Andean watersheds, other human activities and natural disturbances (e.g., withdrawals and intakes, dams/reservoirs, livestock activity, mining, invasive species, water stress, drought and volcanic eruptions) must be taken into account. Our WVI is thus adaptable to other climate ecoregions with different natural events or human activities; nonetheless, we suggest modifying the factors of each sub-index according to the stressor types and natural disturbances in the study area. For example, in watersheds with a pluvio-nival regime, snow and glacier melt should be considered. However, we feel that it is necessary to quantify the synergistic effects of multiple stressors, which potentially contribute continuously to the degradation of ecosystem health.

4. Conclusions

The results are a first methodological approximation of the spatial distribution of the cumulative impacts of anthropogenic intervention, environmental fragility and natural disturbances in a mediterranean watershed, facilitating the identification of the degree of vulnerability according to the intrinsic properties of the watershed for the detection of priority restoration, conservation and mitigation sites. Among the ASS the factors with the greatest impact were productive surfaces and population, along with river channeling. These stressors cause complex and constant river system impacts, generating hydrogeomorphological changes and deterioration of ecosystem health, mainly in the depositional zone of the Andalién River watershed, which should be a priority for restoration measures. The most important factors in the NDS were floods, tsunamis and forest fires, the last of which have been increasing in the last two decades. The most important factors in the EFS were plant cover and riparian zones, which act as buffer zones for a number of impacts.

There is no current consensus in Chile on a minimum riparian width according to river order, soil class, type and amount of plant cover and hillside slope. We suggest that it is necessary to develop a methodology to establish riparian zones in accord with human activities, since doing so could contribute significantly to the health of the river ecosystem in sectors with the greatest watershed vulnerability.

Our results suggest that multiple stressors in the watershed have direct and indirect cumulative negative impacts on the biotic integrity of aquatic and terrestrial ecosystems (Delgado et al., 2004). In addition, they influence the hydrogeomorphological, biological and ecological processes of the rivers (Barber et al., 2014), reducing the health of the river ecosystem.

The WVI is a simple, easy to-apply and validated method to evaluate watershed vulnerability using GIS that takes into account multiple stressors in accord with the intrinsic characteristics of the watershed and the cumulative effects of the stressors on the river system. However, we feel that it is necessary to quantify the synergistic effects of multiple stressors, which potentially contribute continuously to the degradation of ecosystem health. Our WVI may be applied to other coastal mediterranean watersheds to identify the level of watershed vulnerability by incorporating other anthropogenic factors such as livestock activity, sewage dumping and extraction of water for irrigation, which were not considered in this study due to their minor importance in the watershed.

According to Segurado et al. (2018), management of river systems should be based on a set of system characteristics and stressor types in order to implement strategic and effective integrated management actions. The proposed index facilitates the recognition of very vulnerable areas, priority areas for conservation and areas for strategic restoration.

Acknowledgments

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Appendix A

Table A1
Classification and characterization of soil classes.
Source: Elaborated by the authors. Revised from Jaque, 1996 and CIREN, 1999.

Soil series	Soil types	Surface (ha)	Composition (%)	Fragility type
Cauquenes	Palexeralf CQ Sloping phase	29.40	75.1 sand, 18.6 silt, 6.3 clay. Soil class III low productivity, arboreal and forestry crops.	Medium
	Palexeralf CQ, Flat phase	7.78	65.8 sand, 14 silt, 20.2 clay.	
San Esteban	Palexeralf. Slightly deep sloping phase	20.00	59.7 sand, 19.7 silt, 20.6 clay, Soil class IV reforestation.	Very low
Curanipe	Malic Haploxeralf	782	34.4 sand, 33.0 silt, 32.7 clay, Soil class IV, suitable for forest.	Low
Arenales		656	87.5 sand, 8.9 silt, 10.6 clay. Soil class III Marginal lands for arboreal crops of fruit-growing.	High
Asociación Constitución			Franc sandy clay.	Medium

Table A2
Classification of the pedon depth (cm) and composition of the texture classes of the soils in order to determine the clay range.

Class	Description	Depth range	Clay range
1	Deep	>100	>2.31
2	Moderate	75–100	2.31–5.14
3	Slightly deep	50–75	5.14–7.44
4	Thin and very thin	<50	<7.44

Table A3
One-way ANDEVA results.

Effect	GL	MC	F	p
Zone	2	3.63	8.15	0.003
Error	15	0.44		

Table A4
Spearman correlation matrix between fluvial vulnerability and chemical physical parameters.

	NO_3^-	NO_2^-	pH	DO	TDS	FNU	T°C	COND
NO_3^-	–	–	–	–	–	–	–	–
NO_2^-	0.392	–	–	–	–	–	–	–
pH	0.785**	0.535	–	–	–	–	–	–
DO	−0.535	−0.392	−0.142	–	–	–	–	–
TDS	0.500	0.214	0.500	0.178	–	–	–	–
FNU	0.535	0.607	0.428	−0.678	0.107	–	–	–
T°C	0.714	0.321	0.785**	−0.464	0.285	0.428	–	–
COND	0.259	0.222	0.481	0.148	0.444	0.592	0.222	–
WVI	0.580	0.879**	0.804**	−0.299	0.187	0.598	0.505	0.368

$^{**}p = 0.05$.

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