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ANALYSIS OF FLOOD RISK IN THE LOWER HYDROGRAPHIC BASIN OF THE RÍO NEGRO (ARGENTINA)

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ABSTRACT. The recurrent floods in the lower hydrographic basin of the Río Negro (RN), documented since 1899, have caused significant damage to the resident population settled in flood-prone areas, whose socioeconomic condition is unfavorable. The aim of this study was to analyze the risk associated with flood occurrences in this area by integrating the flood susceptibility level (hazard) of the study area and the vulnerability of the population. The risk analysis was derived from the algebraic overlay of hazard and vulnerability maps, developed according to criteria published by Renda *et al*. (2017). In the study area, floods are primarily caused by intense rainfall and winds, upstream water discharges from the Limay and Neuquén rivers, and interactions between increased upstream flow from the lower hydrographic basin of the RN and extreme meteorological events known as Sudestadas. Every certain period, such as every 2 years for winds exceeding 75 km/h and precipitation exceeding 37 mm in 24 hours, as well as every 100 years for flows exceeding 4,000 m^3s^{-1}, the occurrence of floods in the lower basin of the RN is expected to be derived from these events. Based on terrain characteristics and topography, 41.7% of the lower RN basin area showed moderate to high susceptibility to flooding. INDEC data (2010) indicated that 51.0% of the population in the study area was vulnerable to floods due to unfavorable socioeconomic conditions. According to hazard and vulnerability analyses, 43.2% of residents in the lower RN basin lived in high-risk areas, with homes located near the riverbank and on the outskirts of the Viedma-Carmen de Patagones urban conglomerate, hence being the most vulnerable. The results obtained in this research showed the influence of the natural and anthropogenic factors on the occurrence of flood-related disasters in the lower hydrographic basin of the RN. In addition, they served as a preliminary study that will enable decision-makers to create better prevention and mitigation plans contributing to improving the quality of life of its inhabitants.

Análisis del riesgo de inundaciones en la cuenca hidrográfica inferior del Río Negro (Argentina)

RESUMEN. Las recurrentes inundaciones en la cuenca hidrográfica inferior del Río Negro (RN), documentadas desde 1899, han causado daños significativos a la población residente asentada en áreas propensas a inundaciones, cuya condición socioeconómica es desfavorable. Por lo tanto, el objetivo de este trabajo fue analizar el riesgo asociado a la ocurrencia de inundaciones en esta área a través de la integración del nivel de propensión ante inundaciones (amenaza) del área de estudio y la vulnerabilidad de sus habitantes. El análisis de riesgo se obtuvo a partir de la superposición algebraica de los mapas de amenaza y vulnerabilidad, elaborados según criterios publicados por Renda *et al*. (2017). En el área de estudio, las inundaciones son principalmente causadas por intensas lluvias y vientos, descargas de agua aguas arriba de los ríos Limay y Neuquén, y la interacción entre el aumento del flujo aguas arriba de la cuenca hidrográfica inferior del RN y eventos meteorológicos extremos conocidos como Sudestadas. Cada cierto período, tales como cada 2 años para vientos que superan los 75 km/h y precipitaciones que exceden los 37 mm en 24 horas, así como cada 100 años para caudales que sobrepasan los 4.000 $m^3 s^{-1}$, se espera la ocurrencia de inundaciones en la cuenca inferior del RN derivadas de estos eventos. Según las características del terreno y la topografía, el 41,7 % del área de la cuenca baja del RN mostró una susceptibilidad de moderada a alta a inundaciones. Los datos del INDEC (2010) indicaron que el 51,0 % de la población en el área de estudio era vulnerable a inundaciones debido a condiciones socioeconómicas desfavorables. De acuerdo con los análisis de amenaza y vulnerabilidad, el 43,2 % de los residentes en la cuenca inferior del RN habitaban en áreas de alto riesgo, en cercanías de la ribera del río y en las afueras del conglomerado urbano Viedma-Carmen de Patagones, siendo, por lo tanto, los más vulnerables. Los resultados obtenidos en esta investigación muestran que los factores naturales y antropogénicos favorecen la ocurrencia de desastres relacionados con inundaciones en la cuenca hidrográfica inferior del RN. Constituyen, también, este estudio preliminar que permitirá a los tomadores de decisiones crear mejores planes de prevención y mitigación que contribuyan a mejorar la calidad de vida de sus habitantes.

Keywords: river, floods, hazard, vulnerability, risk.

Palabras clave: río, inundaciones, amenaza, vulnerabilidad, riesgo.

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1. Introduction

According to OEA (1993) and Lavell (2001), a disaster represents the tangible outcome of risk, which is defined as the likelihood of a hazardous event capable of causing social and economic losses to society (Moreno and Múnera, 2000). In this order, risk evaluation as an useful tool to estimate the level of danger associated with potential hazards and prevailing vulnerability conditions (Rojas Vilches and Martínez Reyes, 2011). This assessment includes the estimation of components of risks such as hazard, exposure, and vulnerability (Olcina and Ayala-Carcedo, 2002).

A hazard is recognized as a potential threat related to adverse phenomena, whether natural or human-induced. It can damage to society since a material and social point of view (Unesco, 2014; Renda *et al*., 2017). Natural events (earthquakes, floods, hurricanes, volcanic eruptions) or human-made incidents (poor flood management, dam breaches, technological origin, and pollution) become hazards when they affect populated regions (Aneas de Castro, 2000). Research about hazards includes different stages, as following (Renda *et al*., 2017):

1. Definition of the area affected by the hazard (neighborhood, district, municipality or region).
2. Identification of the origin of the hazard.
3. Definition of the magnitude of the hazard, its manifestations and return periods.
4. Physical and natural description of the affected area. This characterization includes a spatial study of the factors, which determine the susceptibility to the hazard in the study area (Liendro Moncada and Ojeda, 2018). The floods susceptibility level is expressed through a relative scale index, generated by the weighted sum of conditioning factors, ultimately classified into different levels (low, medium, and high) (SIGMA, 2023).

Vulnerability analysis are based on the social, economic, cultural, institutional, and infrastructural circumstances existing before a disaster, which render a population susceptible to a hazard (Fenoglio, 2019). The disaster occurrence and its magnitude are defined by the hazard and by the precarious conditions, respectively (Unesco, 2014). Vulnerability assessments involves various dimensions (Renda *et al*., 2017), although frequently, the exposure variable is integrated with social vulnerability in risk analysis (Rojas Vilches and Martínez Reyes, 2011):

1. Physical vulnerability (exposure): refers to the location of human settlements and physical deficiencies in structures (buildings and infrastructure).
2. Social vulnerability: is related to overall living conditions and it includes situations related to possibilities for education, health, social equity, and safety.

Globally, floods present a recurring challenge, due to the frequent occurrence of extreme hydrometeorological events and because of historical practices in settling flood-prone areas (Renda *et al*., 2017). The development of urban areas near rivers and flood-prone zones often exposes the resident population to vulnerability and increased risk (Viand and González, 2012). Moreover, the presence of infrastructures such as canals, culverts, dams, and embankments creates a false sense of security, causing the population to underestimate, neglect, or overlook the flood risk in those regions (AIC, 2020).

The risk analysis depends on both hazard occurrence and the society's vulnerability to it. For this reason, an integrated approach to both analyses is necessary (Renda *et al*., 2017). Globally, risk studies have become in a relevant tool for the decision makers. For example, research conducted by Liu *et al*. (2021), along the Dianbao River in Kaohsiung City (southern Taiwan), enabled the identification of areas with higher flood risks. Based on these results, the authors proposed various mitigation strategies to decision-makers. In Marrickville (Australia), a new flood vulnerability index, that combine high-resolution hydrological and hydraulic models with socioeconomic indicators, enabled the implementation of updated flood adaptation policies (El Zein *et al*., 2021).

In Argentina, approximately one in three inhabitants resides in flood-prone areas (Foro Ambiental, 2017). Several studies at a national scale have focused on delineating high-risk flood areas, taking into account hazard and vulnerability maps (Angheben, 2012; Herrero *et al*., 2018). A recent study revealed that floods in the Río de La Plata river and its tributaries contribute to vulnerability in more exposed areas in metropolitan area of Buenos Aires (Rotger *et al*., 2018). The extreme hydrometeorological events occurrence and scarce prevention and mitigation measures implementation showed a 22% of Santa Fe's population vulnerable to floods in 2019 (Cardoso, 2019). Moreover, the residents of Coronel Suárez (Buenos Aires province) underestimate, according to studies, the real flood risk of the town (Moretto and Gentili, 2021).

In the NE of Argentinean Patagonia, the recurrent Río Negro (RN) and the El Juncal lagoon (non-permanent water body) overflows have historically impeded economic development and population growth in the lower hydrographic basin of the RN (Pérez Morando, 2005; Marizza *et al*., 2010; Brailovsky, 2012; Zabala *et al*., 2021). Specifically, the lower sector of this basin has been affected on numerous times by river floods (AIC, 2020; Brailovsky, 2012; DesInventar, 2021; Diario Río Negro, 2021). The impact of floods has harmed economic growth in the lower RN valley, a major area for fruit and vegetable production of Argentina (Mazzulla, 1974). Floods in this region damage infrastructure like roads, railways, and irrigation networks, reduce agricultural potential through soil erosion and crop destruction, and affect nearby urban areas (AIC, 2020). The city of Viedma, located in the lower part of the RN flood valley between 3.5 and 4.5 meters above sea level (Merg and Petri, 1998), has been the most exposed to river overflow (Brailovsky, 2012).

Since the XIX century, flood mitigation measures have been undertaken by residents in response to frequent floods in the lower hydrographic basin of the RN, including building embankments and reforesting the riverbank to shield the coast from fluvial erosion and mitigate damage during floods (Reverter *et al*., 2005). Following the catastrophic flood of July 1899 (Brailovsky, 2012; AIC, 2020), interventions such as artificial channels, embankments, and drainage of the El Juncal lagoon were implemented to reduce the impacts of RN floods (Rey *et al*., 1981). Dams located along the Limay and Neuquén rivers have regulated river flow since 1970, while anthropogenic actions stabilized riverbanks in Viedma and Carmen de Patagones during the 1970s and 1980s (Reverter *et al*., 2005). In 2012, the government, through the Departamento Provincial de Aguas de RN, decided to regulate land use along the riverbank lines for flood evacuation caused by high tides and Sudestadas (Southeast wind associated with low-pressure systems. It persists for hours, bringing rain and strong winds that counteract river drainage, leading to an increase in water levels, SMN, 2021). Additionally, in 2018, the municipality of Viedma announced filling and construction works of a slope to protect against river floods, with a maximum height of 4.5 meters above the river level at low tide (ADN, 2018). Despite these actions, the lower hydrographic basin of the RN continues to be affected by river floods (D'Onofrio *et al*., 2010; Brailovsky, 2012; AIC, 2020; DesInventar, 2021; Diario Río Negro, 2021).

According to Municipalidad de Carmen de Patagones (2019), high intensity of winds from SE are the main cause of the floods. Additionally, the increase of the flow of the tributaries (Limay and Neuquén rivers) (UNL-DPA Río Negro, 2004; Romero *et al.,* 2014), during storm pass and high tide, propitiate the flooding (D'Onofrio *et al*., 2010). Historically, the floods that exceeds the 2700 m^3s^{-1} have been recurrent every decade, showing a high probability of floods (UNL-DPA Río Negro, 2004). About the floods susceptibility areal extension and location, the coastal area of the lower hydrographic basin of RN was identified as vulnerable to sea-level rise (Kokot *et al*., 2004). According to a SSRH-INA(2002) proposal, the 46.7% of the lower RN Valley area exhibited susceptibility to river floods medium to high (García Bu Bucogen *et al*., 2021). Despite some previous studies on flooding risk in Carmen de Patagones, there is still limited research that has analyzed the flood risk of the RN in this area. This study aims to provide a flood risk map in this area, to contribute with the knowledge for the development of facilitating decision-making and of preventive and mitigation decisions in the region.

2. Study area

The lower hydrographic basin of RN belongs to the hydrographic system composed of the Neuquén, Limay, and Negro rivers (AIC, 2022) (Fig. 1a). According to Soldano (1947) and the Atlas de Cuencas y Regiones Hídricas Superficiales de la República Argentina (SSRH, 2010), the sector is extended from Segunda Angostura to the RN mouth (into the Atlantic Ocean) (Fig. 1b), at 40°- 41°S and 63°- 64°W, in the NE of Argentine Patagonia (Fig. 1c). The hydrographic basin shows NO-SE orientation, and it covers around 3,000 km^2. RN have a hydrological anastomosed pattern (Pereyra, 2003) without tributary watercourses. It is characterized by the presence of islands, non-permanent lagoons, and secondary branches, some of them correspond to paleochannels, which are activated during exceptional floods (Prates *et al*., 2019). The average streamflow of the NR is 1020 m^3s^{-1} (Gianola Otamendi, 2019). The hydrological cycle of the river starts in March (Romero and González, 2016) and show two annual maximum flows: autumn-winter and during the spring (Gianola Otamendi, 2019).

In the study area, structural plains, river terraces and flat forms at the south represent the landforms (Fabregat, 2010). Regarding the geomorphological processes, there are noted effects of fluvial erosion (Pereyra, 2003). The landscape is characterized by plains, which shows the presence of depressions, palaeochannels and non permament shallow lakes. At the river's mouth in the Atlantic Ocean, banks are formed, giving rise to an open reflux delta (Piccolo and Perillo, 1999; Longo *et al*., 2018). The most developed soil orders, according to the taxonomic classification of Soil Taxonomy (2006), are Aridisols and Entisols, characterized by moderate to poor drainage (Panigatti, 2010). Prominent pedogenetic features reflect a previous cycle of soil formation, with more humid climatic conditions that allowed for argiluviation (Pereyra, 2003). Due to topographic characteristics, permeability, surface runoff, vegetation cover, and precipitation, the edaphic features in lower hydrographic basin of the RN are prone to water and wind erosion, as well as degradation due to overgrazing (Panigatti, 2010).

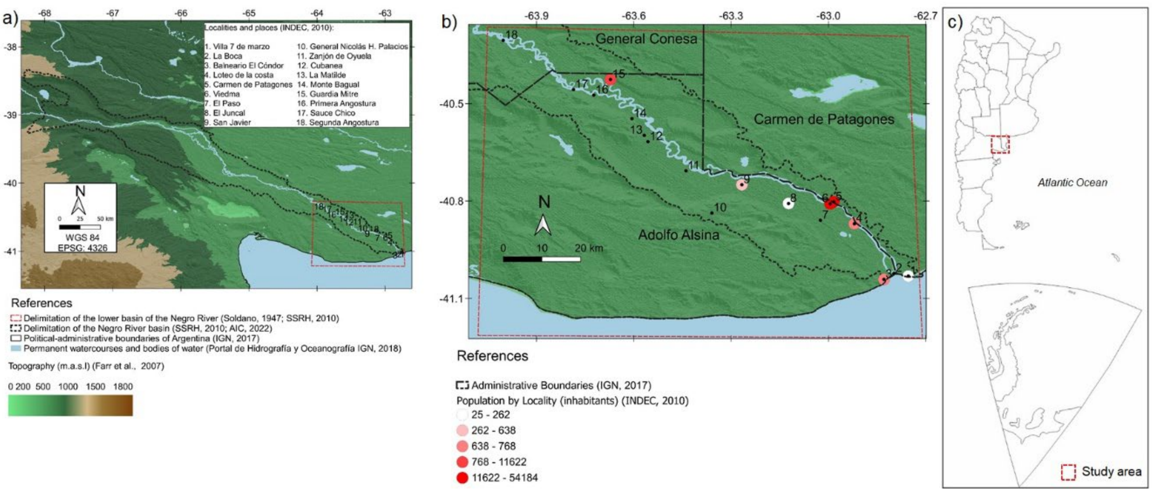

Figure 1. Study area: a) hydrographic basin of the Río Negro, b) lower hydrographic basin of the Río Negro, c) relative location of the study area in the bicontinental Argentinean Map (elaborated by Centro de Documentación Cartográfico Laboratorio de Cartografía Digital. Departamento de Geografía y Turismo, Universidad Nacional del Sur). Other cartographic data sources: Soldano (1947), Farr et al. *(2007), SSRH (2010), INDEC (2010), and IGN (2018 and 2022).*

According to Köppen-Geiger climatic classification (Chen and Chen, 2013), the study area is semi-arid temperate with dry summers. Seasonal climatological variability is defined by atmospheric circulation, topography, and proximity to the sea (Prohaska, 1976; Coronato *et al.*, 2017), with simple and persistent atmospheric patterns derived from the movement of high and low-pressure centers (Prohaska, 1976; Paruelo *et al*., 1998; Coronato *et al*., 2017). Annual precipitation is around 400 mm $year^{-1}$ (Bianchi, 2016). During summer, the movement of high-pressure systems generates arid conditions with sporadic convective precipitations (Gentile *et al.*, 2020). During winter, cold fronts and low pressures cause precipitation, while moist winds from the east, during South Atlantic blocking events, favor winter and spring rains (Gentile *et al*., 2020). The annual temperature ranges between 14 and 16°C, with maximum and minimum values in January and July, respectively (Coronato *et al*., 2017). The latitudinal position of the South Atlantic anticyclone determines the prevailing wind regime in the sector, moving southward in summer, with northeast and east winds prevailing (Musi Saluj, 2018). In winter, it moves northward, with west winds predominating (Frumento, 2017). Occasionally, the combination of high Atlantic pressure and cyclogenesis produces "Sudestadas" with strong south winds associated with a temperature decrease and precipitation. Sometimes, the described conditions cause severe flooding (UNL-DPA Río Negro, 2004).

The study area is located between Adolfo Alsina (Buenos Aires province) and Conesa (Río Negro province) districts. Some localities and cities are Loteo Costa de Río, El Juncal, San Javier, Guardia Mitre, Viedma and Carmen de Patagones cities (Table 1) (INDEC, 2010). Additionally, there are several rural settlements, such as Villa 7 de marzo, La Boca, El Paso, General Nicolás H. Palacios, Zanjón de Oyuela, Cubanea, La Matilde, Monte Bagual and Sauce Chico (Fig. 1b). According to the 2010 Census, the total population of the study area was 77,910 inhabitants (INDEC, 2010). Historically, the Viedma-Carmen de Patagones region show an increasing population (Table 1) (INDEC, 2001; 2010; 2022). The relevant economic activity in the area focuses on intensive agriculture under irrigation and livestock farming (Brailovsky, 2012).

Table 1. Demographics of the localities located in the study area (period 1960 - 2022). Based on data from INDEC (2001, 2010, and 2022)

Census/locality	Inhabitants		
	Census 2001	**Census 2010**	**Census 2022**
Viedma	46,948	52,789	62,000
Patagones	18,189	20,532	-
Viedma-Carmen de Patagones	65,137	73,322	92,914
El Juncal	61	83	-
San Javier	392	530	-
Guardia Mitre	582	856	-

3. Data and methods

A risk mapping was elaborated considering the geographical framework where the hazard and the vulnerable population interact (Ayala-Carcedo, 2000; Ribas and Saurí, 2006; Ríos and Natenzon, 2015; Renda *et al.*, 2017; Zapperi and Olcina, 2021). The risk level was estimated following the methodology proposed by Renda *et al.* (2017) and its estimation was organized into three analyses: hazard, vulnerability, and risk (Fig. 2).

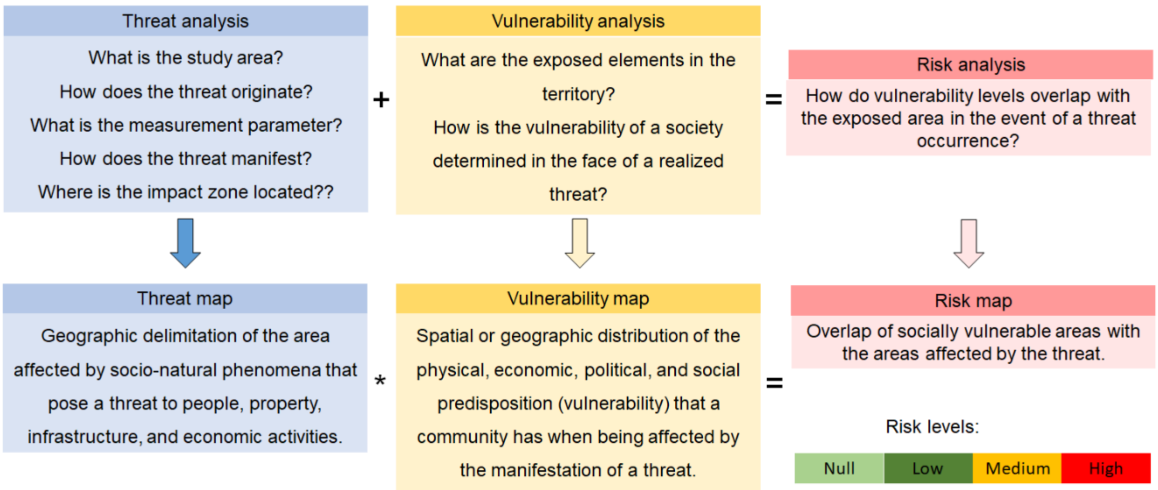

Figure 2. Methodological diagram employed for the mapping of flood risk in the study area. Based on the methodology proposed by Renda et al. *(2017).*

3.1 Hazard Analysis

In the context of hazard analysis, various stages were undertaken following the Renda *et al.* (2017) guidelines. A literature review related to the occurrence of floods and its main causes in the study area, was done. The main source of information was the DesInventar database (DesInventar, 2022) and press articles (Petri, 1992; Río Negro Online, 2001; Río Negro Online, 2003; La Nueva, 2006; Diario la Palabra, 2009; D'Onofrio *et al.*, 2010; Brailovsky, 2012; Diario Río Negro, 2014; Diario Río Negro, 2018a; Diario Río Negro, 2018b; ADN, 2019; Diario Río Negro, 2019; Noticias Río Negro, 2019; Red de Alerta de sudestadas, 2020; Diario Río Negro, 2021; Livigni, 2022).

As the most common factor leading to floods is the occurrence of intense winds and precipitation, and extraordinary increases in river flow (D'Onofrio *et al.*, 2010), the Gumbel distribution was calculated to model the distribution of maximum values and their return periods (Gumbel, 1941). Wind speed and precipitation data were obtained from the Servicio Meteorológico National (SMN,

2021) database, Viedma Aero station (40°52’00’’ S and 63°00’00’’ W). The study of RN floods was based on streamflow data analysis from the Primera Angostura (PA) station (SNIH, 2021). The function was defined according to the methodology published by USACE (2006), and Mayo and Mitrani (2022) (Eq. 1):

$$F(x) = \exp\left[\exp\left[\frac{x-B}{A}\right]\right] \quad (1)$$

where the coefficients are defined as follows: A = 0.779s and B = x − 0.45s. In this case, x is the mean value. The return period (Pr) is calculated according to the following expression (USACE, 2006) (Eq. 2):

$$P_r = \frac{1}{1-P_a} \quad (2)$$

where P_r and P_a are the return period in years and the cumulative probability.

The delimitation of the affected area by flooding was carried out through a Multicriteria Evaluation (MCE). This approach involved the precise delineation of the flood-prone area, using spatial assessments of factors that determine the susceptibility of the area to the phenomena occurrence (Olivera Acosta *et al*., 2011; Carrascal *et al*., 2018; García Bu Bucogen *et al*., 2021). As the main limitation for the MCE estimation was the accessibility to historical flood maps, the Maximum Extent of Water Coverage (MEWC) was delineated. MEWC’s estimation was done using extremely humid periods and for this purpose, the Standardized Precipitation and Evapotranspiration Index (SPEI) data (spei.csic.es) (Vicente-Serrano *et al*., 2010) was employed. The SPEI time series acquisition was performed specifically for the geographic coordinates 40°45'00" S and 63°15'00" W (the available grid close to Viedma). For the areal analysis of the water coverage, satellite data were analysed during the periods in which the SPEI indicated extremely wet (SPEI ≥ 2.00) and very wet (1.99 ≥ SPEI ≥ 1.50) conditions (Vicente-Serrano *et al*., 2010). The satellite data, corresponding to Landsat 8 OLI/TIRS Level 2 product (freely accessible), were provided by the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov) (USGS, 2021) (Fig. 3). Satellite images with cloud coverage of less than 10% were utilized from 1998 to 2021, with a spatial resolution of 30 meters.

The Normalized Difference Water Index (NDWI) was employed to delineate water bodies and flows from satellite images corresponding to very and extremely wet periods, using the near-infrared and shortwave bands of the Landsat 8 OLI/TIRS product through the SNAP software (Fig. 3). The digital processing was performed considering NDWI values greater than 0.0 in the QGIS GIS, an open-source tool (QGIS, 2024) (https://qgis.org/es/site/). Subsequently, a reclassification was done to assign the weights for every variable in the MCE. The assigned values were from 10 (areas covered by water) to 1 (areas with absence of water coverage).

Also, MCE using geographic, geomorphological and geospatial characteristics from freely accessible repositories of official organizations (SAGyP-INTA, 1990; Volante *et al*., 2009; SSRH, 2010). Geomorphological features, drainage, and soil texture were derived from soil maps (Scale 1: 250,000) (Carta de suelos de la República Argentina, SAGyP-INTA, 1990). The digital cartography of land cover was elaborated based on the Mapa de Cobertura del Suelo de la República Argentina (Volante *et al.* 2009). The delimitation of the lower hydrographic basin of RN was according the criteria published by Soldano (1947) and the Atlas de Cuencas y Regiones de Aguas Superficiales de Argentina (SSRH, 2010). Subsequently, the assignment of weights, the prioritization of variables, and the mapping of the flood-affected area were based on previous research (Olivera Acosta *et al.*, 2011; Carrascal *et al.*, 2018; García Bu Bucogen *et al.*, 2021). Based on the results obtained, subzones were delineated according to estimated level of susceptibility to the flood hazard, as following: non susceptible, low, medium, and high.

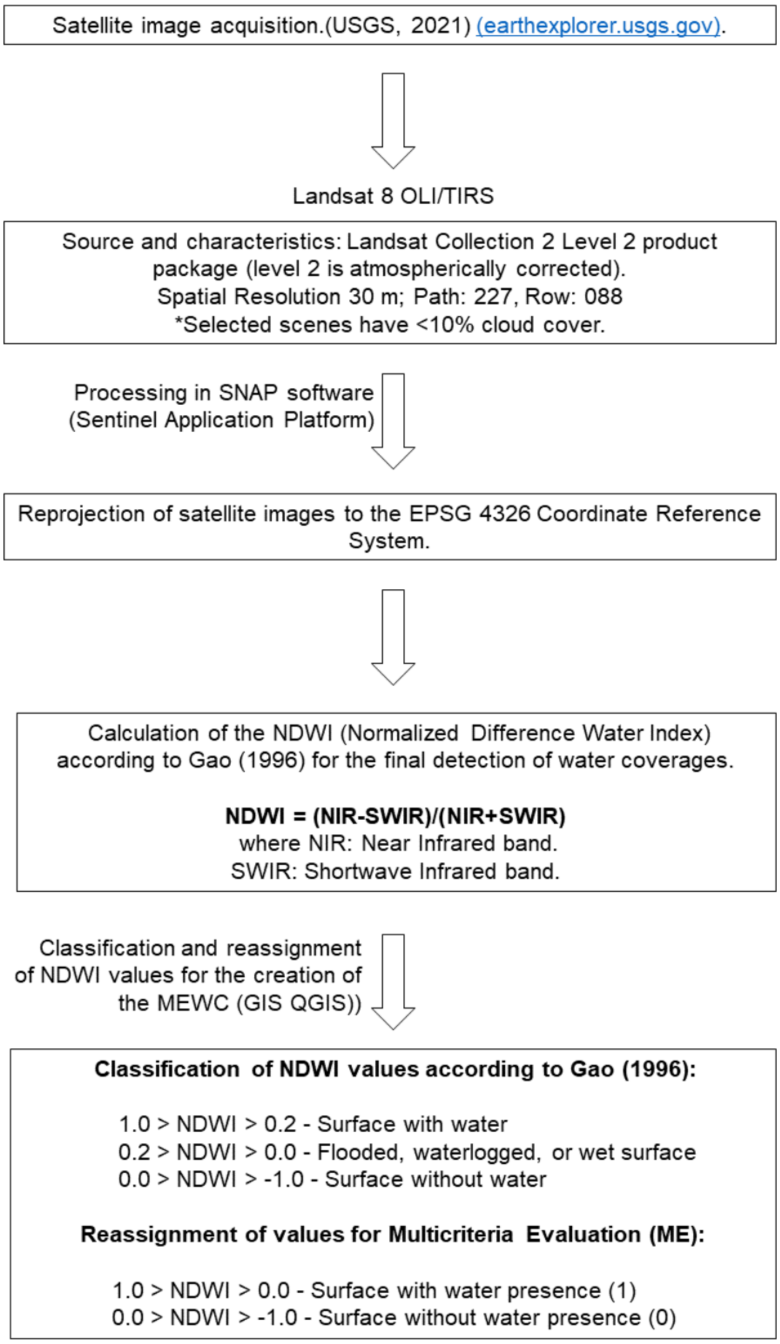

Figure 3. Methodological framework to delineate the Maximum Extent of Water Coverage.

3.2 Vulnerability Analysis

Data on demographics, public service infrastructure, housing construction quality, population overcrowding, individuals with private health coverage (social security), and illiteracy were sourced from the 2010 Population Census provided by the Instituto Nacional de Estadística y Censos (INDEC) of Argentina and compiled by AEROTERRA (2022) (https://datosabiertos.aeroterra.com). The results were based on the 2010 Census data due to the unavailability of socio-economic indicators—such as the percentage of the population with unmet basic needs, housing condition, overcrowding, and unemployment—necessary for vulnerability studies. Additionally, information on streets and roads was obtained from the IGN Transport Portal (2022). The analysis was conducted at the department/municipality level for most indicators, while literacy data were analyzed at the census zone level.

The vulnerability analysis involved evaluating structural poverty conditions (structural poverty refers to entrenched and persistent poverty conditions deeply rooted in the socio-economic structure of a society, often characterized by a lack of access to basic resources such as education, healthcare, adequate housing, decent employment, and economic opportunities). To estimate the vulnerability, the physical, social, and organizational indicators were analyzed according to the Renda *et al*. (2017). The Unsatisfied Basic Needs Index (in Spanish, NBI) was used to map vulnerability to floods, considering households with at least one of the five essential deprivations described in INDEC (2013). Additionally, following the criteria of Renda *et al*. (2017), other vulnerability indicators summarized in Table 2 were considered. The classification of indicators was done by assigning values of 0 and 1, where 0 represented non-vulnerable conditions and 1 indicated high vulnerability. To analyze the population vulnerability associated to the access to the road network were utilized Daga *et al*. (2015) criteria.

Table 2. Criteria used to calculate the degree of vulnerability. Based on the criteria published by Renda et al. (2017)

Indicator	Analysis Unit	Categories	Source
Population concentration	Census zone	0: Moderately populated areas. 1: Densely populated areas and sparsely populated areas.	INDEC (2010)
Access to road network	Department / municipality	0: Distance to road network less than 300 m. 1: Distance to road network greater than 300 m.	Portal Transporte IGN (2022)
Access to basic services	Census zone	0: Low percentage of households with access to public services. 1: High percentage of households with inaccessibility or deficiency in access to public services.	INDEC (2010)
Housing construction status	Census zone	0: Limited number of houses with construction deficiencies. 1: High number of houses with construction deficiencies.	INDEC (2010)
Population age structure	Census zone	0: High percentage of population aged between 14 years <= age <= 65 years. 1: High percentage of population aged <=14 years and >= 65 years.	INDEC (2010)
Overcrowding	Census zone	0: Low percentage of households with critical overcrowding. 1: High percentage of households with critical overcrowding.	INDEC (2010)
Access to medical coverage	Census zone	0: Low percentage of population without health insurance. 1: High percentage of population without health insurance.	INDEC (2010)
Literacy level	Departament / Municipality	0: Low percentage of population over 10 years old who are illiterate 1: High percentage of population over 10 years old who are illiterate	INDEC (2010)

Population concentration is considered when analyzing vulnerability to floods, as densely populated areas can result in a greater number of people being affected by these events, while in sparsely populated areas, such as dispersed rural areas, rescue and assistance efforts may be more difficult due to limited accessibility. Access to road networks influences the population's mobility capacity. Inaccessibility or lack of access to basic services, along with precarious housing conditions, play a significant role in vulnerability to floods as they hinder the population's ability to cope with and recover from the impacts of these events. The population whose age is lower than 14 years old and highest than 65 years old is considered more vulnerable to floods effects than the other age's stages. Overcrowding is a condition of fragility that provides crucial information for effective evacuations. Additionally, it was found that the population without medical coverage is highly exposed to suffering from diseases after floods. High levels of illiteracy due to their impact on job opportunities, economic conditions, and access to housing can increase the population's vulnerability in disaster situations.

Vulnerability map was generated by a map algebra for the criteria mentioned in Table 2 and QGIS GIS (QGIS.org) software. Vulnerability subzoning was defined using Delménico *et al*. (2018) classification criteria, where non-vulnerable areas have only one high indicator, while sectors with at least two, four, and five indicators are classified as low, medium, and high vulnerability, respectively.

3.3 Risk Analysis

After conducting the hazard and vulnerability analyses and obtaining their respective maps, the subzoning of the study area according to its flood risk levels was delimited according the methodological steps shown at the Figure 2 and QGIS GIS functions. The resulting layer was obtained by sum of variables of the affected area (HM) and vulnerability (MV). The risk map (RM) was obtained according to the criteria identified in Table 3.

The number of households and inhabitants residing in high and medium-risk areas in 2010 was identified using INDEC (2010) data. The sensitivity of the results found in the risk analysis was evaluated qualitatively, comparing the results obtained in the RM with flood records provided by Desinventar database (2021) and several newspapers.

Table 3. Applied criteria to calculate the level of flooding risk

Hazard's level	Vulnerability's level	Risk's level
High or High / Medium	High or Medio/ High	High
Medium or Medium /Non susceptible	Medium or Low/ Medium	Medium
Low or Low /Non susceptible	Low or Non vulnerablel/ Low	Low
Non susceptible	Non vulnerable	Null

4. Results

4.1. Floods: recurrence and causes

Between 1899 and 2021, a total of 32 floods were reported by several sources (Table 4). These reports showed that 50% of the cases were triggered by the combination of intense rainfall and winds. Additionally, upstream water discharges from the Limay and Neuquén rivers (Fig. 1a) were responsible of 25% of the floods. Finally, the remaining 25% occurred resulting of the interaction between increased upstream flow from the lower hydrographic basin of the RN and the occurrence of extreme meteorological events.

The recurrence of intense winds, precipitation, and high flows was calculated using the Gumbel statistical distribution at a 95% confidence level, taking into account that floods in the lower RN basin are caused by strong south winds, intense precipitation, and increased upstream flow (Table 4). The results showed that, over a period of 100 years, there is a 1% probability of wind speeds exceeding 120 km/h, while winds exceeding 95 km/h have a 10% probability, and winds exceeding 75 km/h have a 50% probability (Fig. 4a). In terms of precipitation, events surpassing 37 mm in 24 hours have a 50% probability of occurring within a 2-year return period (Fig. 4b). Furthermore, for return periods of 20 and 50 years, the maximum precipitation can exceed 70 mm and 84 mm. The analysis of extreme values reveals that, over a period of 100 years, there is a 1% probability of floods with flows exceeding 4000 m^3/s, while events with flows greater than 2800 m^3/s and 2415 m^3/s have 10% and 20% probabilities, respectively (Fig. 4c).

Table 4. Reports of floods and waterlogging events in the lower Río Negro basin (1829-2021). In the 'Flooding Causes' column, a '' indicates that the cause of the flood was not found referenced in the literature."*

Date	Flooding causes	Affected localities	Source of data
1829	Strong winds and intense precipitation	Viedma	Rey *et al*., (1981)
1870	*	Viedma	Rey *et al*., (1981)
19 - 22/07/ 1899	upstream flow increases (9,000 m^3s^{-1})	San Javier, Guardia Mitre, Zanjón de Oyuela and Viedma	Brailovsky (2012) Livigni (2022)
1904	*	Viedma	Brailovsky (2012)
1914	*	Viedma and San Javier	Brailovsky (2012)
1922	*	Viedma	Brailovsky (2012)
1930	Increase in upstream flow	Viedma	Brailovsky (2012) Rey *et al*., (1981)
1932	*	Viedma	Brailovsky (2012)
1937	*	Viedma	Brailovsky (2012)
1940	*	Viedma	Brailovsky (2012)
1945	Increase in upstream flow (6,500 m^3s^{-1})	Viedma	Brailovsky (2012)
1949	*	Viedma	Brailovsky (2012)
1951	*	Viedma	Brailovsky (2012)
1958	*	Viedma and Guardia Mitre	Brailovsky (2012) Río Negro (2001)
1974	*	Viedma	Brailovsky, 2012
2/02/1976	Intense precipitation	Viedma	DesInventar (2021)
27/09/1976	Intense precipitation (30 mm) and strong winds	Viedma	DesInventar (2021)
8/10/1977	Intense precipitation	Viedma	DesInventar (2021)
03/1992	*	Viedma	Petri (1992) D'Onofrio *et al*. (2010)
6/08/2001	upstream flow increases and intense precipitation (50 mm)	Guardia Mitre	Río Negro (2001)
20/02/2003	Extraordinary tides associated with permanent S winds	Viedma	Diario Río Negro (2003)
10/07/2003	Intense SE winds	Viedma	Río Negro Online (2003)
29/07/2006	Release of water flow from dams located on the Limay and Neuquén rivers in conjunction with strong south winds (60 km/h) and high tide	Viedma	La Nueva (2006)
22/07/2009	Strong S winds	Viedma and Carmen de Patagones	Diario la Palabra (2009)
22/02/2010	Intense precipitation	Carmen de Patagones	DesInventar (2021)
4/01/2014	Conjunction of extraordinary tides and SE winds	Viedma	Diario Río Negro (2014)
21/06/2018	Release of 600 m^3 of water from dams on the Limay and Neuquén rivers	Viedma and Carmen de Patagones	Diario Río Negro (2018a)
24/06/2018	Strong winds (Sudestada)	Viedma	Diario Río Negro (2018b)
23/02/2019	Increase in river flow combined with an extraordinary tide and strong southerly winds	From RN mouth to San Javier	ADN (2019) Diario Río Negro (2019)
3-4/09/2019	Strong winds (Sudestada)	Viedma	Noticias Río Negro (2019)
4/07/2020	Release of upstream flow in interaction with high tide	Viedma	Red de Alerta de sudestadas (2020)
26-27/05/2021	Increase in flow rates in conjunction with high tide and southerly winds.	Viedma and Carmen de Patagones	Diario Río Negro (2021)

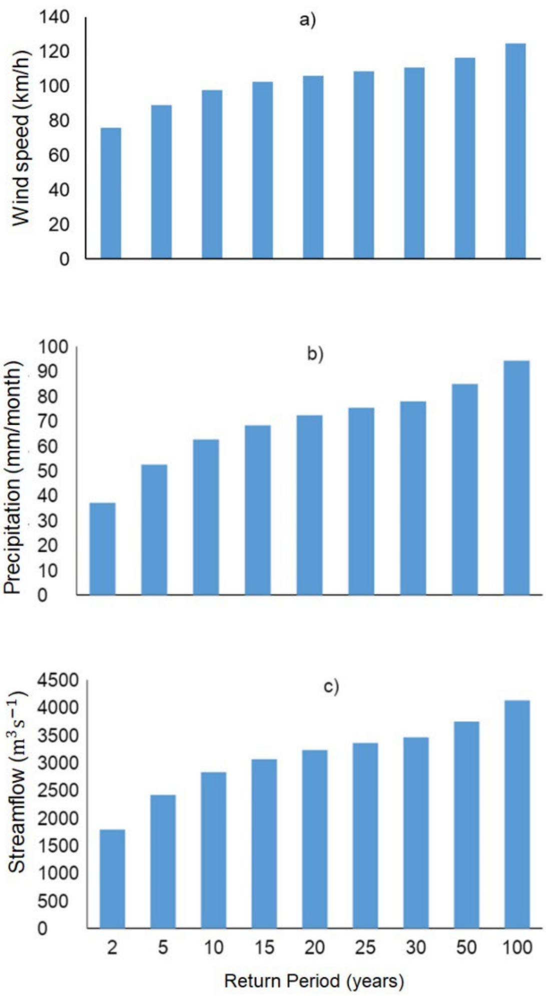

Figure 4. Recurrence of events capable of favor floods through by Gumbel Distribution (1981 - 2020): a) wind speed, b) precipitation, c) streamflow. Based on SMN (2021) and SNIH (2021) data.

4.2. Delimitation of the area affected by floods: hazard map

During 2015, the SPEI (12-month scale) categorized the period of January to August as extremely humid whereas the period from September to December was defined as very humid. For this reason, for the delineation of the maximum area affected by floods, the MEWC was defined according to the climatic conditions of 2015. Satellite data corresponding to the following dates: January, 18th; March, 23rd; July, 13rd and October, 17th, were selected for the analysis. MEWC was delineated by NDWI calculation for the previously mentioned images. Finally, the satellite images were averaged to obtain the representative value of MEWC for the period 1998-2021.

After obtaining the MEWC, the weights were assigned to the geographical, geomorphological, and geospatial shapes according to the criteria published by García Bu Bucogen et al. (2021). Finally, the MCE was completed. In this step, the study area was classified based on its flood susceptibility levels (Table 5), using the criteria adapted from Montecelos Zamora (2010) for this investigation.

High and medium levels of susceptibility were observed in a large portion of the northern area (Fig. 5), with 44.7% of the study area exhibiting these susceptibility levels to floods (Fig. 6). The subzones with medium levels covered 1,396.5 km^2, representing 41.7% of the study area's surface. Areas with high hazard levels were extended over 101.2 km^2 (3.0%). Finally, the subzones with low susceptibility and non-susceptibility to the occurrence covered 1,847.3 km^2 (55.3% of the total study area).

Table 5. Hazard's levels obtained from Multicriteria Evaluation. Based and adapted from Montecelos Zamora (2010) criteria

Hazard's levels	Values range
Non susceptible	0 – 3
Low	3.1 – 5
Medium	5.1 – 8
High	≥ 8.1

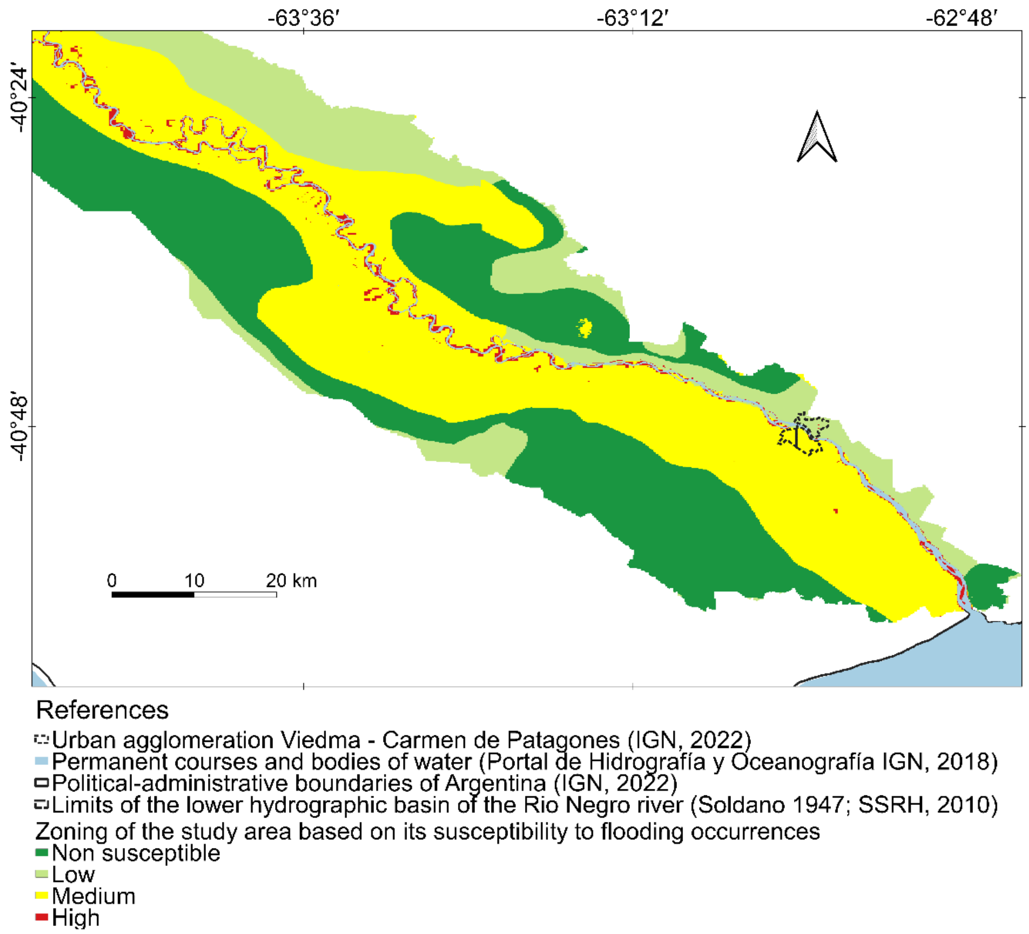

Figure 5. Subzones of flooding susceptibility in the lower hydrographic basin of the Río Negro.

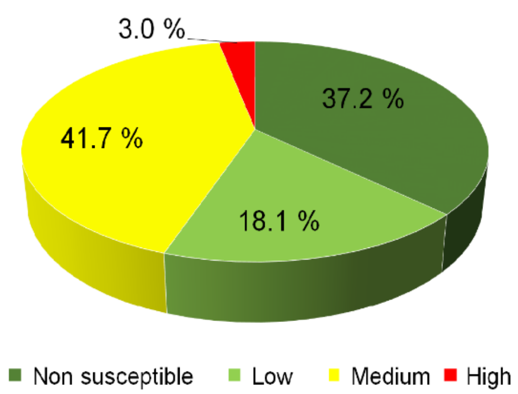

Figure 6. Areal extension (%) of the estimated susceptibility classes in the lower hydrographic basin of the Río Negro.

4.3. Vulnerability analysis

The vulnerability classes were estimated based on the 2010 Population Census data and evaluation criteria proposed by Daga *et al.* (2015), Renda *et al.* (2017) and Delménico *et al.* (2018). In this case, the objective was determining the magnitude of the vulnerability of the local population. The final map showed a spatial resolution of 122 x 149 meters.

The spatial distribution of vulnerability levels showed (Fig. 7) high vulnerability in areas close to the banks of the RN. The peripheral zones of the urban conglomerate Viedma - Carmen de Patagones were identified as high vulnerability areas. Carmen de Patagones town exhibited a low to medium vulnerability level. The area close to the riverbank showed a medium to high vulnerability level. Moderate vulnerability levels were detected in the SW and NW of the study area.

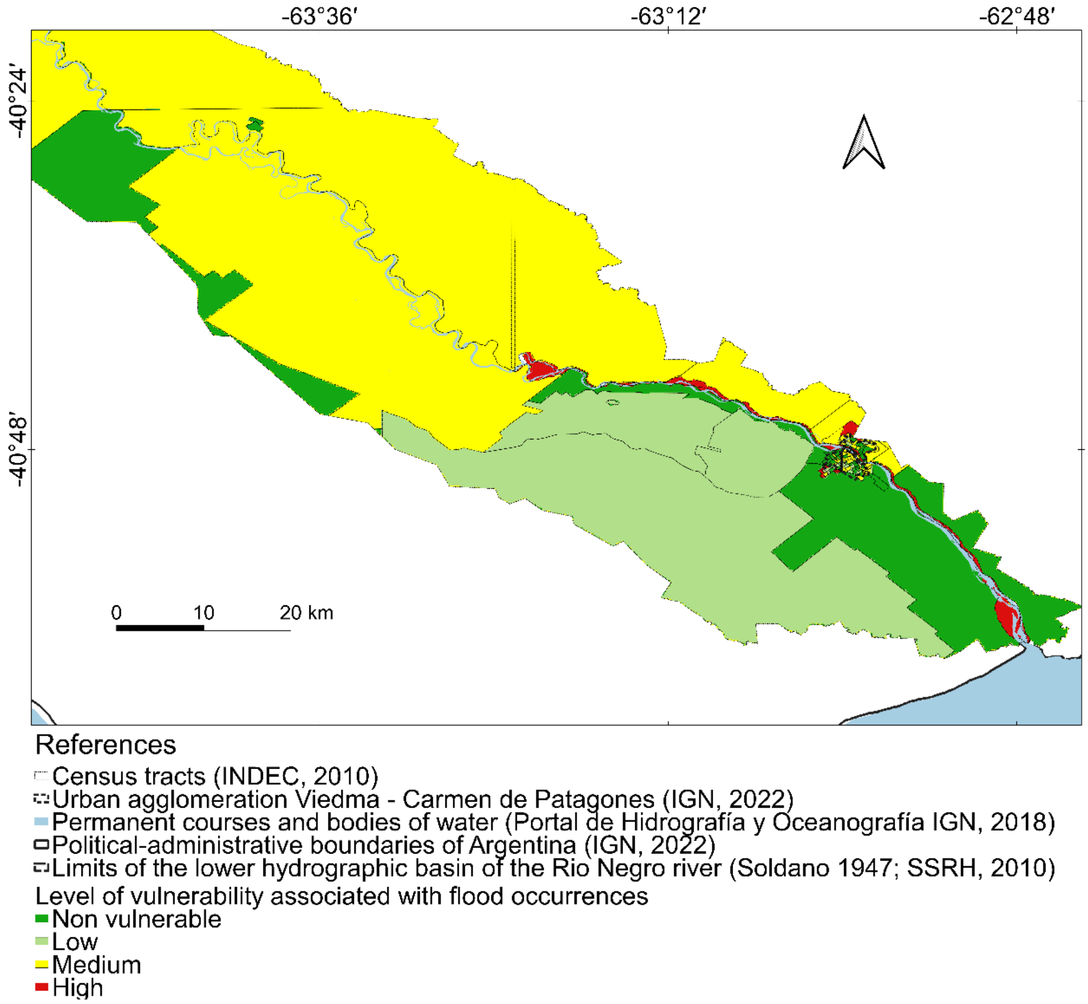

Figure 7. Vulnerability map of the occurrence of riverine floods in the study area.

According to INDEC data (2010), the 51.0% (~ 33,636 inhabitants) of the population in the study area was classified with medium and high vulnerability to RN overfloods (Fig. 8). The 49.0% (~ 44,274 inhabitants) of the total population was included at the low or non-vulnerable levels of vulnerability.

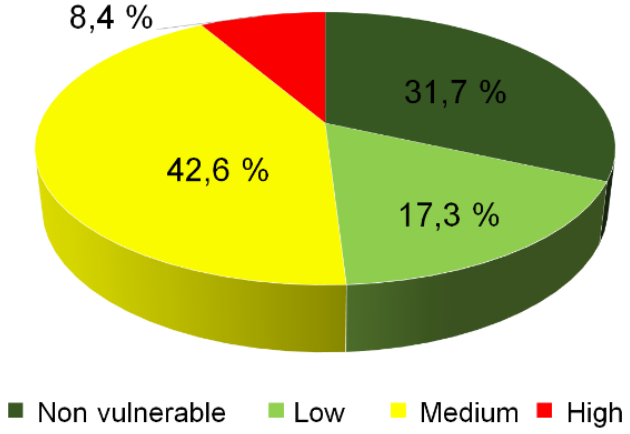

Figure 8. Percentage of inhabitants who lived in vulnerable areas. Based on INDEC data (2010).

4.4. Risk analysis

After conducting hazard and vulnerability analyses, the algebraic sum of both maps allowed the mapping of the risk of flooding occurrences (Renda *et al*., 2017). The RM showed a spatial resolution of 136x176 m, and risk levels were classified according to the criteria identified in Table 3. High-risk zones for flooding were detected on the banks and mouth of the RN (Fig. 9). Additionally, areas with a medium level of risk were located on the outskirts of Viedma. The risk derived from RN floods was medium on the Viedma riverbank, while the risk was low for the rest of the city. The risk distribution in Carmen de Patagones town was heterogeneous.

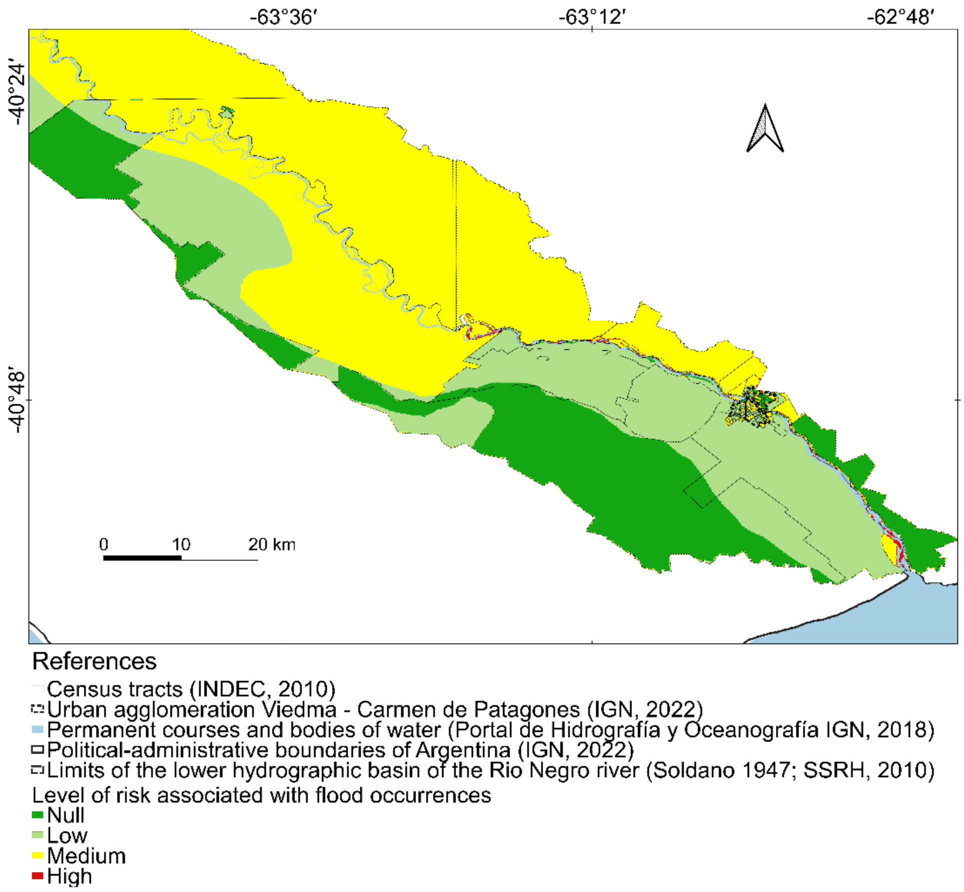

Figure 9. Flood risk map in the study area.

In 2010, 43.2% of the total population of the study area was located in areas categorized as high and medium-risk levels (Fig. 10). The population who lives in high-risk areas were quantified at 1,239 people, while 32,397 residents (41.6% of the total population of the study area) lived in areas with a medium level of risk. The high-risk conditions reported in the lower basin of the RN were due to the location of homes in areas with high levels of susceptibility to flooding (Fig. 5) and unfavorable socioeconomic conditions (Fig. 8). Viedma, Carmen de Patagones, and Guardia Mitre towns showed medium and high-risk levels.

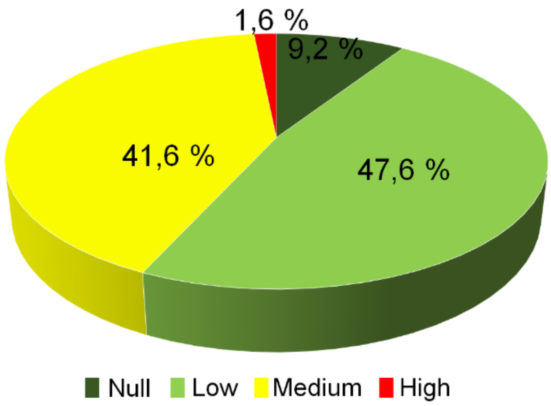

Figure 10. Percentage of inhabitants who lived in flooding risk areas in the lower basin of the Río Negro River in areas with no risk, low, medium and high risk. Developed based on INDEC data (2010).

5. Discussion

Floods are extreme events that have devastating consequences, especially in areas where the vulnerability of the population is high. In the lower basin of the RN, historical floods have caused devastating effects (Petri, 1992; Río Negro, 2002; La Nueva, 2006; D'Onofrio *et al.,* 2010; Brailovsky, 2012). Despite ongoing efforts to regulate floods in the study area (Reverter *et al.,* 2005), the danger persists, as the risk of river overflow cannot be completely mitigated (AIC, 2020).

The complexity of these events requires a holistic understanding that not only considers environmental and geophysical factors but also the social and economic components that influence the vulnerability of communities. This integrated approach allows for a more comprehensive risk assessment and facilitates the design of more effective and equitable mitigation strategies. By simultaneously addressing the physical dimensions of the phenomenon and the socioeconomic conditions, a more accurate view of high-risk areas is obtained, and the most vulnerable populations are better identified, which is essential for disaster planning and management.

Internationally, several authors have conducted risk studies that combine extreme events with social, economic, and physical indicators to estimate risk levels (Birkmann *et al.,* 2013; Godfrey *et al.,* 2015). For example, in Germany, the use of this conceptual framework allowed the observation that low-income populations near the Rhine, Elbe, and Danube rivers are especially vulnerable to flooding (Fekete, 2010). In the USA, it was found that residents of mobile homes and racial minorities are more vulnerable to these phenomena (Tate *et al.,* 2021). In Kaohsiung (Taiwan), mitigation strategies were proposed following an urban flood risk assessment (Liu et al., 2021). In Marrickville (Australia), flood emergency policy and service planning were improved after estimating a vulnerability index that combines hydrological models with socioeconomic indicators (El Zein *et al.,* 2021).

In Argentina, risk indicators have been established that relate adverse phenomena to physical and social vulnerability (Angheben, 2012; Herrero *et al.,* 2018). An example of this, embedded in the study area, was the study conducted by the Municipalidad de Carmen de Patagones (2019), which identified high and medium vulnerability levels in the peripheral areas of the urban core. On the other hand, in the town center and most of the eastern bank of the RN, vulnerability was low, except for the western bank of the river, where vulnerability was high. The risk of flooding was high in peripheral sectors of the city. Studies more focused on the susceptibility analysis of flood occurrence showed that the coastal sector presents moderate to high vulnerability to sea level rise (Kokot *et al.,* 2004), while approximately 46.7% of the lower valley shows medium to high susceptibility to flooding (García Bu Bucogen *et al.,* 2021). Finally, adverse meteorological conditions, such as storms and heavy rains, can trigger floods in the study area (Table 4).

In this study, a conceptual framework was established to understand the area's susceptibility to hazards and the vulnerability of its inhabitants, allowing for a flood risk study. The subsequent development of flood risk maps identified areas with a higher probability of disaster events. The findings of this study regarding the vulnerability of the peripheral sector and the western sector of the Río Negro bank for Carmen de Patagones are consistent with the results of the Municipalidad de Carmen de Patagones (2019) study, although they differ with the vulnerability detected on the eastern bank of the river, which was indicated as medium-high. The detected differences may be attributable to variations of indicators, scales, or data used. Furthermore, differences in data spatial resolution, information availability, and analysis methods may contribute to the observed variations. The Gumbel distribution analysis shows a 50% probability of floods due to strong winds (return period of 2 years) and a 10% probability of floods due to heavy rainfall (return period of 10 years). Additionally, it was estimated that floods associated with flows exceeding 2800 m^3/s in Primera Angostura have a 10% probability of occurrence (return period of 10 years), surpassing the flood susceptibility threshold (2700 m^3/s) established by UNL-DPA Río Negro (2004).

The main limitation of this study was the use of outdated data (INDEC, 2022). Although data from the 2010 National Population and Housing Census (INDEC, 2010) were used, the population's vulnerability may have changed since then. However, the results obtained are a valuable precedent for studying flood risk in this area. With the population growth reported by the 2022 Census (INDEC, 2022) in the urban conglomerate of Viedma-Carmen de Patagones (Table 1), the number of vulnerable individuals has likely increased. Therefore, the methodology used remains relevant and can be applied in the future after the final publication of the 2022 Census data.

The areas of highest flood risk in the study area are coincident with the zones where the most flood occurrences were reported (Table 4), demonstrating that the methodology used provides an accurate representation of the areas at greatest flood risk. This suggests that it can be a useful tool for decision-makers in disaster risk management. However, it is important to note that risk validation is an ongoing process that requires constant monitoring to ensure the accuracy and relevance of the results.

6. Conclusions

Despite significant efforts in constructing various defensive structures that have mitigated flood-related damages in the RN region, the level of risk remains considerable. The analysis results showed that 43.2% of the population in the study area was residing in medium and high-risk zones in 2010. Of this total, 1.6% of the inhabitants were in high-risk areas, with their homes located near the riverbank and on the outskirts of the Viedma-Carmen de Patagones region.

The susceptibility of areas near the river is due to geomorphological characteristics, including a natural propensity for flooding and river flow dynamics. This risk is exacerbated by social factors such as population density, infrastructure quality, and socioeconomic conditions. These results highlight the need for a comprehensive and multidimensional flood risk assessment that integrates both physical and social aspects. Such integration will enhance understanding of risk factors and support the development of more effective mitigation strategies. Risk management policies and urban development plans should incorporate these findings to address flood preparedness and response deficiencies.

The study's information can guide future research and the implementation of measures to reduce risk in vulnerable areas. Collaboration among local authorities, urban planners, and the community is essential for designing and implementing solutions that improve resilience to flooding. Continuous monitoring and adjustment of strategies are also crucial as new data emerges and local conditions evolve.

Acknowledgments

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