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Spatial Limit of Agricultural risk and its Economic Impact Due to Flooding in the Chillon River, Peru

Límite espacial de riesgo agropecuario y su impacto económico por inundaciones en el río Chillón, Perú

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ABSTRACT: Agricultural planning and disaster risk management are essential for preventing and preserving socioeconomic development. The study aimed to define the spatial limits of agricultural risk and its direct economic impact due to flooding in the Chillón River in the Carabayllo district, Peru. Geographic Information System (GIS) tools and reliable databases were used for the research. Seven hydrological scenarios were applied with rigorous statistical analysis, along with numerical models for one-dimensional (1D) hydraulic modeling. Agricultural risk was defined by the relationship between hazard and vulnerability, considering the economic impact on different sectors. The main results indicated that the extreme maximum flood scenario reached 102,17 m^3/s. The hydraulic modeling identified two agricultural risk limits due to river flooding, affecting the yield of vegetables, poultry farms, and pig production over an area of 0,24 km^2 and 0,37 km^2 in the 20 and 1000 year scenarios, causing economic losses of 5,169.14 USD and 6,509.04 USD, respectively. In conclusion, an integrated method was developed to simulate agricultural risk from river flooding.
Keywords: Flood limits, Natural disasters, Vulnerability, Agricultural Losses.

RESUMEN: La planificación agropecuaria y la gestión de riesgos por desastres naturales es importante para la prevención y conservación del desarrollo socioeconómico. El objetivo del estudio fue definir los límites espaciales de riesgo agropecuario y su impacto económico directo por inundaciones en el río Chillón en el distrito de Carabayllo, Perú. Para el desarrollo de la investigación se utilizaron herramientas del Sistema de Información Geográfico (SIG) y bases de datos confiables. Se aplicaron 7 escenarios hidrológicos con rigurosos análisis estadístico, así como la aplicación de modelos numéricos en el modelamiento hidráulico unidimensional (1D). Mientras que el riesgo agropecuario fue definido por la relación del peligro y vulnerabilidad considerando la repercusión económica de los sectores. Como principales resultados se alcanzó que el escenario extremo de máxima avenida fue de 102,17m^3/s. La modelación hidráulica identificó dos límites de riesgo agropecuario por inundaciones fluviales afectando el rendimiento de hortalizas, granjas avícolas y la producción porcina en un área de 0,24 km^2 y 0,37 km^2 en los escenarios de 20 y 1000 años, que generó pérdidas económicas de 5169,14 USD y 6509,04 USD respectivamente. En conclusión, se desarrolló un método integral para simular el riesgo agropecuario frente a inundaciones fluviales.
Palabras clave: Límites de inundaciones, desastres naturales, vulnerabilidad, pérdidas agropecuarias.

INTRODUCTION

Worldwide, agricultural and livestock zones have been developed near floodplains to facilitate access to water resources (Hartnett & Nash, 2017). However, these developments also contribute to natural disasters by significantly altering the river's morphological pattern, which modifies the hydrodynamic conditions of the riverbed. As a consequence, severe flooding problems occur, affecting agricultural areas, causing loss of human lives, and generating economic and environmental damage (Zhu *et al.,* 2019).

In particular, the Chillón River basin in Peru faces various agricultural and livestock challenges due to the lack of preventive planning in response to climate change phenomena, such as El Niño, which exacerbates the frequency of floods. The Carabayllo area is largely characterized by the agricultural sector, with an irrigated area exceeding 3,000 hectares. This area accounts for 45% of Lima Metropolitana's horticultural production, with 52 species and varieties of vegetables. Meanwhile, the livestock sector focuses on cattle, goat, pig, and poultry farming (Galagarza *et al.,* 2021).

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Disaster risk management and mitigation of natural disasters are crucial factors for effectively addressing floods and their adverse effects. Spatiotemporal modeling of natural disasters mainly employs disaster system simulation methods, including hydrological and hydraulic models capable of simulating river flooding. In particular, HEC-RAS is recognized for its working range and accuracy in addressing uncertainty and flood impact (Kim & Cho, 2019; Mokhtar *et al.,* 2018; Pinos *et al.,* 2019).

Additionally, various methodologies exist worldwide for preventing and reducing the risk of natural disasters. However, recent studies propose new multi-criteria evaluation methods based on the tools used in these assessments. Volonté *et al.* (2021) consider historical, ecological, and geomorphological factors. López-Martínez (2019) quantifies the influence of different causal agents that shape and condition vulnerability levels in their analysis and diagnosis. Meanwhile, Vega-Ochoa (2020) proposes a local land-use planning methodology with a sustainable approach to river systems. However, an essential aspect that prevention methodologies must integrate is the estimation of direct economic losses, defined as the temporary disruption of economic flows in the affected area. In this regard, the scientific literature cites analytical models to determine the true economic costs of floods, which must be adapted to each country's circumstances.

The Chillón River is both a source of water and life and a latent threat to the agricultural sector that develops along its banks when it carries peak flows. Therefore, the purpose of this study is to define the spatial limits of agricultural risk and its direct economic impact due to flooding at different probability levels in the Chillón River in the district of Carabayllo, Peru.

MATERIALS AND METHODS

The study focused on the Chillón River as the population of interest, with a sample of 21 km of the river located in the Carabayllo district, which has a population density of 315 inhabitants/km² (INEI, 2017). The topographic data was obtained from a study conducted by CENEPRED using a DJI MAVIC 2 PRO drone with a 0.1m x 0.1m grid. Source: https://sigrid.cenepred.gob.pe/sigridv3/drones

Regarding the geographic database for the urban area, the study used current land-use data from the Global Land Cover by National Mapping Organizations (GLCNMO). Source: (Kobayashi *et al.,* 2017). Agricultural areas were estimated using the satellite tool provided by the Ministry of Agricultural Development and Irrigation (MIDAGRI). Source: https://minagri-geoespacial.users.earthengine.app/view/pastosv2. Meanwhile, the economic information for the study area was extracted from the World Bank. Source: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

For hydrological factors, a 55-year historical discharge series from 1964 to 2018 was used, compiled by the National Meteorology and Hydrology Service of Peru (SENAMHI) and the National Water Authority (ANA). The HEC-RAS numerical model version 6.2 was applied for one-dimensional (1D) hydraulic simulation. Seven flood scenario models were proposed with hydrometeorological probabilities of 0.1% (1,000 years), 0.2% (500 years), 0.5% (200 years), 1% (100 years), 2% (50 years), 5% (20 years), and 10% (10 years).

The river section geometry was delineated using the 0.1m x 0.1m grid with the RAS Mapper interface linked to ArcGIS Pro 2.0, considering the most representative cross-sections to minimize model bias.

The boundary conditions of the river section were set as normal, with uniform and constant flow. Meanwhile, Manning's n coefficient was calibrated for low and high flows based on the model's statistically rigorous performance.

The spatial limits were determined based on flood risk along the margins of the Chillón River. A specific methodology was developed, as shown in Figure 1, to assess flood risk. The risk analysis flowchart was structured around three dependent variables: hazard, vulnerability, and direct economic impact. The latter introduced a new approach to measuring direct economic effects induced by floods, integrating aspects of the CENEPRED and CEPAL methodologies.

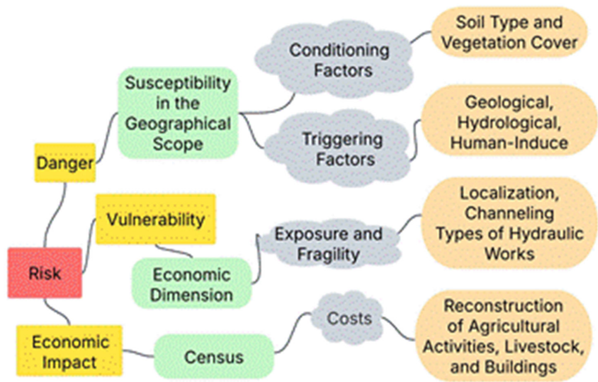

FIGURE 1. Flowchart of the risk analysis.

The estimation of direct economic impact was analyzed primarily based on water depth in the flooded area, the fraction of the flooded area, and the probability of the event-factors related to water exceeding the river's capacity and flood protection standards. Finally, direct economic losses were estimated based on flood extent according to probabilistic scenarios. These direct economic losses were defined in terms of disruptions to the agricultural and livestock sectors (Tanoue *et al.,* 2020) as shown in the following equation:

$$Loss = \left(D_{flood} + \frac{D_{recov}}{2}\right) * P \qquad (1)$$

Where: Loos represents economic losses (USD), Dflood is the number of flood days, P is the daily production value (USD/day), and Drecov is the recovery period after the river flood (days), defined as Drecov = α × Dflood, where α is the recovery parameter ranging from 2.0 to 11.5 (Tanoue *et al.,* 2020). The α parameter depends on disaster experience, mitigation measures, and policies. P represents the relationship between the GDP of the agricultural and livestock sectors and the GDP of the services sector, estimated at 0.864 based on the Central Reserve Bank of Peru's analysis at the time of the study.

RESULTS AND DISCUSSION

As a result of the hydrological analysis, peak flows ranging from 40.84 to 102.17 m^3/s were obtained for the best-fit Log Pearson III function. Meanwhile, the hydraulic model validation, comparing observed and simulated water surface levels for Manning’s n, showed high accuracy with an RMSE of 0.018 to 0.023 and an NSE of 0.92 to 0.962 for calibrated Manning’s n values ranging from 0.035 to 0.040.

The spatial risk limits are shown in Figure 2. However, the most significant return periods were 20 and 100 years, which allowed for precise estimates of flooded areas of 0.24 km^2 and 0.37 km^2, respectively. For other probabilities of peak flow occurrence, overlapping of spatial risk limits was observed.

The possible causes of this spatial risk limit overlap are due to the river channel width, which reaches up to 100 meters in certain sections, as well as the natural riverbank height, which ranges from 1 to 3 meters. These factors facilitate the evacuation of peak flows but increase flood frequency for return periods of 20 years. Figure 3 illustrates some characteristics of the studied river section, where fluvial terraces and a natural slope composed of sandy gravel with rounded particles, prone to erosion, worsen the river’s hydraulic conditions, affecting agricultural zones and nearby buildings along the riverbanks.

The risk and vulnerability analysis of the study area is presented in Table 1. The conditioning factor value was higher than the triggering factor value, primarily due to current land use. However, both factors reflected the same weight concerning the susceptibility of the geographical area. Consequently, the hazard value obtained was 0.173, interpreted as unfavorable geographic conditions for agricultural activities in these zones. Therefore, the area is classified under the category of frequent occurrence susceptibility, according to (Román & Orozco, 2019).

Similarly, vulnerability was assessed by considering social and economic impacts, as shown in Table 1. The obtained vulnerability value was 0.23, interpreted as high exposure for a fragile population engaged in the agricultural sector. In line with López-Martínez (2019) , who highlights the integration of natural and societal relationships in risk management based on specific needs, greater weight is given to vulnerability due to exposure, fragility, and resilience in the evaluation. Overall, the resulting risk value was 0.13, representing a very high level. However, Reyna-García *et al.* (2020) emphasize the importance of resource interaction in determining hazard and vulnerability. Additionally, Alcocer-Yamanaka *et al.* (2016) argue that such information is valuable for defining safer agricultural zones.

Since the most significant return periods were 20 and 1,000 years, the direct economic impact analysis of river floods was conducted only for these scenarios. Figure 4 presents the results for the 20-year scenario, showing that the agricultural sector is the most affected, with 94% of flooded areas, leading to direct economic losses exceeding USD 5,000. The most affected crops include celery, parsley, broccoli, lettuce, and cabbage. On the other hand, the livestock sector is affected by only 6% of the flooded areas, resulting in minimal losses of just USD 40. Specifically, livestock losses are concentrated in stables, poultry farms, and pig farming. Thus, the minimum estimated cost for agricultural and livestock recovery is USD 5,169.14.

FIGURE 2. Spatial risk boundaries for flooding.

FIGURE 3. Physical conditions of the river.

TABLE 1. Hazard and Vulnerability

Susceptibility of the geographic area				
Conditioning factor		**Triggering factor**		**Value**
Value	**Weight**	**Valor**	**Weight**	
0,194	0,5	0,152	0,5	**0,173**
Vulnerability				
Social dimension		**Economic dimension**		**Value**
Value	**Weight**	**Value**	**Weight**	
0,262	0,713	0,149	0,287	**0,230**

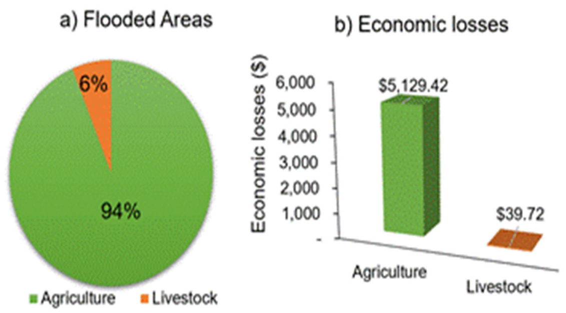

FIGURE 4. Economic scenario for river flooding over a 20-year period.

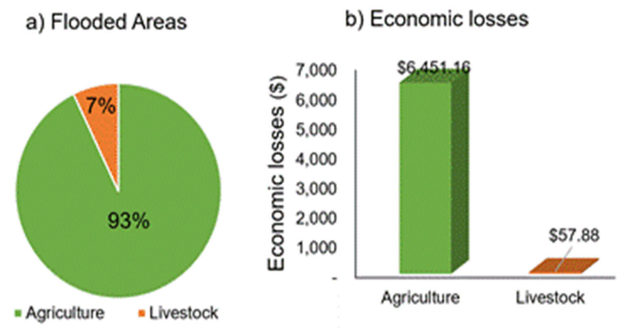

FIGURE 5. Economic scenario for river flooding over a 1000-year period.

In comparison, for the 1,000 year scenario shown in Figure 5, the probability of occurrence is low, and the flooded areas increase by only 1% in both sectors. However, economic losses rise by 26% in the agricultural sector and 46% in the livestock sector.

As a result of the floods caused by peak river flows, the study identified 514 affected residents and 185 impacted homes in the 20-year scenario. In contrast, for the 1,000 year scenario, these numbers rise to 1,105 families and 335 homes.

CONCLUSIONS

This study enabled the delineation of two spatial risk boundaries for the occurrence of peak flows with return periods of 20 and 100 years, which result in flood areas of 0.24 km² and 0.37 km², respectively.

A flood risk of 0.13 was determined for the agricultural sector, indicating both total and partial deterioration in the yield of cultivated crops. Additionally, there were impacts on stables, poultry farms, and pig farming operations in the region, as well as failures in irrigation and drainage infrastructure and access roads.

The identification of the riverbed characteristics, composed of sandy gravel, highlights that during peak flow events, the unevenness of riverbanks is exacerbated, leading to fluvial erosion, sediment transport, and flooding in agricultural areas.

The study demonstrated that the agricultural sector experienced economic losses of USD 5,169.14 and USD 6,509.04 for flooded areas of 3.96 ha and 5.03 ha in the 20-year and 100-year scenarios, respectively.

This research establishes a new approach for delineating safe zones for agricultural producers to protect against natural risks. Furthermore, for future studies, it is recommended to classify risk based on cultivated agricultural areas and categorize the livestock sector accordingly.

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