Agrociencia

A METHODOLOGICAL APPROACH TO QUANTIFYING FLOOD RISK IN AGRICULTURAL AREAS: MAIZE CROP

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ABSTRACT

The agricultural sector is vulnerable to flooding, as it causes damage to soil, crops, and hydro-agricultural infrastructure, thereby limiting production. Quantifying and delineating flood-prone areas is important, as food security is at stake. This study was conducted in Irrigation District (ID) 008 Metztitlán, Mexico, which experiences recurrent flooding that affects the production system and hydro-agricultural infrastructure. The objective of this study was to develop and apply a methodology to assess flood risk in agricultural areas focused on maize cultivation. A basic hydrological and hydraulic model was developed for the proposed methodological framework for agricultural risk analysis, considering three flood factors that affect crops: A) duration, B) depth, C) velocity, and the phenological stage of growth. Based on these factors, parameters were proposed for assessing hazard, vulnerability, and exposure value to calculate risk in monetary terms using map algebra. The scenario analyzed was for a 20-year return period, determining that 94.7 % of the total area of the ID presents some degree of risk. The proposed methodology allowed for the generation of risk maps. Delineating risk zones can aid decision-making to mitigate flood damage in the agricultural sector.

Keywords: hydrological modeling, hydraulic modeling, return periods, hazard, vulnerability.

Citation: Cruz-Santiago MD, Roblero-Hidalgo R, Ballinas-González HA, Gómez-Martínez JF, Quevedo-Tiznado JA, Simuta-Champo R. 2026. A methodological approach to quantifying flood risk in agricultural areas: Maize crop. **Agrociencia.** https://doi.org/ 10.47163/agrociencia.v60i4.3283

Editor in Chief:
Dr. Fernando C. Gómez-Merino

Received: December 16, 2025.
Approved: June 05, 2026.
Published in Agrociencia:
June 22, 2026.

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INTRODUCTION

Floods are natural disasters of hydrometeorological origin that represent 50 % of all natural disasters and significantly affect society (Mendoza-Cariño *et al*., 2018). In Mexico, they cause substantial economic losses (Hernández-Uribe *et al*., 2017). The agricultural sector is vulnerable to flooding, causing damage to the regional and national economy through the disruption of the production cycle, reduced income, unemployment, and food shortages (Vega-Serratos *et al*., 2018). In 2023, national agricultural production amounted to MXN 921 877 021.79 thousand, corresponding to a planted area of 20 023 594.61 ha and a harvested area of 18 383 456.31 ha, implying a loss due to natural disasters (floods, frosts, and winds) of 1 640 138.3 ha (SIAP, 2024).

Flood risk assessment has become an increasingly common practice because it enables disaster mitigation. Quantifying flood risk is a complex task due to the variables involved (depth, duration, and velocity) and its dynamic nature (every flood behaves differently) (Hernández-Uribe *et al*., 2017). Studies conducted in Europe indicate that the most advanced methodologies for assessing flood risks are linked to the economic evaluation of tangible direct damages (Vega-Serratos *et al*., 2018).

Flooding is an environmental stressor that negatively affects the growth of crops (Aslam and Aslam, 2023). The links between flooding and food security are extremely significant (Pacetti *et al*., 2017). The economic damage caused by flooding in the agricultural sector is less severe compared to urban areas; therefore, damage assessment is often neglected or addressed only through simple approaches and rough estimates (Merz *et al*., 2010). The impact of floods on final crop yields is not well understood due to the scarcity of datasets and the lack of quantitative models (Shirzaei *et al*., 2021). Among studies focusing on direct damage to agriculture, hazard parameters are considered the most influential in calculating direct damage. However, the parameters used are restricted to those that can be obtained from hydraulic models (Brémond *et al*., 2013).

Based on flood damage assessments in agricultural areas conducted in Europe, Förster *et al*. (2008) identified the main influencing variables as the time of year when the flood occurs, water depth, flood duration, flow velocity, and the deposition of pollutants. Brémond *et al*. (2013) indicate that the flood parameters that can be used to construct damage functions for agriculture are the seasonality of the flood, water depth, duration, flow velocity, sediment deposition, environmental pollution, and water salinity. Citeau (2003) assessed the effects of flooding on soils and crops in relation to water depth. Tariq *et al*. (2021) calculated risk in agricultural areas as the interaction of hazard with vulnerability, exposure, susceptibility, intensity, and probability, using damage curves for maize and rice. Yildirim and Demir (2022) conducted a comprehensive assessment of agricultural flood risk using flood maps, analyzing the seasonal variation in flood risk focused on maize, soybean, and alfalfa.

In Mexico, Baró-Suárez *et al*. (2007) developed a methodological framework for assessing flood damage to maize crops using a function based on the parameters of flood duration, depth, and seasonality. Vega-Serratos *et al*. (2018) developed a methodological framework for constructing damage curves using the parameters of flood duration, depth, and seasonality.

There is a need to identify and assess agricultural areas at risk of flooding using new methodological approaches; therefore, the objective of this study was to develop and apply a methodology for assessing flood risk in agricultural areas, with a focus on maize cultivation. The methodology involved proposing values for depth, duration, and velocity that could cause irreversible damage to the maize plant depending on its current phenological stage during growth. The values proposed facilitated the development of criteria for assessing hazard, vulnerability, and exposure. This approach aimed to calculate risk in monetary terms through the application of map algebra. The case study focused on Irrigation District (ID) 008 Metztitlán, which faces recurrent flooding due to the overflow of the lagoon and the Metztitlán River, resulting in significant impacts on the production system.

MATERIALS AND METHODS

Information used

This study utilized relevant data, such as the topographic survey of the Metztitlán River from the Venados Bridge (0+000) to km 23+630, conducted using a total station with cross-sections every 20 m. In addition, the Digital Elevation Model (MDE) obtained from the Mexican Elevation Continuum (CEM) 3.0 was used, with a resolution of 15 × 15 m. For edaphology and land use data, the vector dataset from Series VI, scale 1:250 000, 2016 edition, was used (INEGI, 2016).

The precipitation data corresponds to daily precipitation from 19 conventional weather stations with an average of 30 years of records: 13015-San Agustín Metzquititlán, 13029-San Lorenzo Sayula, 13031-Santiago Tulantepec, 13033-Singuilucan, 13041-Tulancingo (Obs), 13042-Zacualtipán, 13061-Alcholoya, 13077-Metztitlán, 13082-Presa La Esperanza, 13087-San Cristóbal, 13093-Venados, 13095-Agua Blanca, 13096-Atotonilco, 13098-Huasca, 13099-Metepec, 13116-El Zembo, 13121-Santa María Amajac, 13130-Santa María Asunción, and 30359-Palo Bendito (SMN, 2024). Additionally, information on instantaneous discharge corresponding to hydrometric station 26042-Venados was obtained from the National Surface Water Data Bank of the National Water Commission (BANDAS, 2024).

The overall methodology consisted of four phases: I: data collection (MDE, vector data on soil science, land use and vegetation, daily precipitation, measured discharge, and derivation of design storms); II: hydrological modeling using HEC-HMS software version 4.2 (basin model, meteorological model, time series, control specifications, calibration, and derivation of hydrographs by sub-basin); III: hydraulic modeling using Iber software version 3.3 (geometry, roughness, boundary conditions, problem data, maximum cumulative enclosure, calibration, and determination of flood depth, velocity, and duration, which are the hazard criteria); and IV: agricultural analysis (phenology and crop characteristics, flood seasonality, flood duration, and characterization of flood-prone areas, which are part of the vulnerability criteria).

Study area

The ID 008 Metztitlán is located within the Metztitlán River basin, in the state of Hidalgo, Mexico. The basin covers an area of 2937.03 km^2. The length of the main channel is 109.54 km. The average annual precipitation is 450–700 mm, the concentration time is 1671.58 min, and the lag time is 1002.95 min (16.7 h). The ID is located at the extreme coordinates 20° 28′ 02.56“ N, 98° 40′ 15.24″ W and 20° 40′ 41.69“ N, 98° 51′ 37.92″ W, covering an area of 3553.7 ha.

Base information processing

A key part of the research involves the collection, review, and analysis of historical data on daily precipitation recorded at weather stations and daily instantaneous discharge data from the hydrometric station. Based on the MDE and using a geographic information system, 38 sub-basins and the river network were delineated. The characteristics of each sub-basin were determined: area, channel length, concentration time, delay time, and weighted curve number. For the precipitation analysis, the annual maximum precipitation (mm d^{-1}) was determined. A frequency analysis of these maximum precipitation events was conducted to obtain values associated with different return periods (RP) using probability distribution functions such as normal, lognormal, log-Pearson III, gamma, Gumbel, and double Gumbel.

Once this process was completed, the function that best fit the maximum annual precipitation was selected using the mean square error criterion. The frequency analysis was conducted at 19 conventional weather stations. For the instantaneous discharge rates at the Venados hydrometric station, which measures runoff from the upper part of the basin comprising 22 sub-basins, the daily maximum values were determined, and the corresponding frequency analysis was performed.

Hydrological modeling

The hydrological model was developed using HEC-HMS software version 4.2. For the basin component, data on area, length of the main channel, weighted number of curves, and lag time were used for each sub-basin. For the meteorological component, the precipitation weighting method was employed, using precipitation data based on the catchment area of each station within the basin. For the time series component, the rainfall distribution was modeled using centered unitary hyetographs.

The simulation was performed for return periods (RP) of 2, 5, 10, 20, 50, 100, 500, and 1000 years. Subsequently, the model was calibrated by comparing the simulated peak discharges for different return periods with those obtained from the frequency analysis of the maximum daily instantaneous discharges at the hydrometric station. The model was considered calibrated when a difference of ±15 % in discharge and an R^2 of 0.98 were obtained. The adjusted parameter was the curve number within a 10 % range.

Hydraulic modeling

The hydraulic model was developed using Iber software version 3.3. To construct the model, hydrometric station 26042-Venados was designated as the starting point of the river channel and the inlet to ID 008. The channel is 38.75 km long and has 11 tributaries along its course before emptying into Lake Metztitlán. The basin is exorheic, as it discharges into the Almolón River through two tunnels with maximum discharge rates of 53 and 11 $m^3 s^{-1}$, which are considered in the model as outlet conditions. The inflow hydrographs (19 tributaries) were obtained from the hydrological model.

The model setup included: 1) geometric definition using an unstructured mesh with cell sizes of 10 m for the main channel and tributaries, 15 m for the lagoon, and 30 m for the remaining surfaces; 2) assignment of roughness based on land use and vegetation for each non-uniform rational B-spline (NURBS) surface; 3) mesh generation and elevation assignment based on the topographic survey of the channel, integrated with the MDE; 4) definition of initial and boundary conditions by inputting hydrographs; and 5) flow simulation over 172 800 s, with 1000-s intervals.

The model was calibrated by comparing the simulated floodplain with a satellite image corresponding to the October 5, 1999 event, which occurred from the community of Venados to Lake Metztitlán and affected 3363 ha (94.6 % of the area of ID 008). The comparison with the flood extent generated by the hydrographs for that date yielded a percentage error of 17.5 %.

Agricultural analysis

Maize cultivation is of national importance because it is the primary grain used in the Mexican diet, as reflected in the average annual per capita consumption, which stood at 196.4 kg in 2017 (SAGARPA, 2017). Maize is planted in two growing seasons: spring-summer (March 1 to September 30) and fall-winter (October 1 to February 28). Depending on the season in which flooding occurs, the effects may have a greater or lesser impact.

The plant is robust in stature, with a single, erect stem that can reach up to 4 m in height, without branches or internodes, and has a spongy pith; it bears separate male and female inflorescences on the same plant (SAGARPA, 2017). Phenological stages mark its growth according to the number of days after sowing, reaching heights of 0.5, 1, 1.5, 2, and 2.5 m at 20, 30, 40, 60, and 80 d, respectively.

Water stress caused by flooding is a limiting factor in maize production (Jiménez *et al*., 2012). Citeau (2003) indicates that the maximum submersion time the plant can withstand is one day, with a water velocity of 0.5 m s^{-1}; Baró-Suárez *et al*. (2007) note that if the plant exceeds 30 cm in height, it can withstand more than 6 d under wet conditions, whereas below that height it is more susceptible, and if flooding persists for more than 3 d, negative effects are inevitable.

Agricultural risk

To calculate risk, an equation was developed based on the National Center for Disaster Prevention (CENAPRED) definition of risk, in which risk is the combination of three factors: hazard, vulnerability, and value of exposed assets. For agricultural areas, the main factors affecting crops were considered: depth, duration, and velocity in relation to the phenological stages of maize, such that each factor contributes a component to risk, hazard (Equation 1), vulnerability (Equation 2), exposure value (Equation 3), and risk (Equation 4):

$$Hazard\ (H) = depth\ (m) \times velocity\ (m\ s^{-1}) \tag{1}$$

$$Vulnerability\ (V) = f\ (depth\ (m),\ crop\ phenology) \tag{2}$$

$$Exposure\ value\ (E) = f\ (duration\ (h),\ crop\ yield\ (Mg\ ha^{-1})) \tag{3}$$

$$Risk\ (R) = P \times V \times C \tag{4}$$

Hazard index

Hazard is defined based on the depth and velocity of the flood (Equation 1). The hazard criteria assume an average maize plant height of 2 m and a maximum tolerable velocity of 0.5 m s^{-1}, such that the product of water depth and velocity determines the hazard classification. The hazard index was constructed on a dimensionless scale ranging from 0.05 to 1, where 0.05 corresponds to low hazard, 0.25 to medium hazard, and 1 to high hazard (Table 1).

Table 1. Hazard index classification.

Depth (m)	Velocity (m s^{-1})	Depth × Velocity	Hazard	Typification (dimensionless)
0.5	0.10	0.05	High	0.05
1.0	0.25	0.25	Medium	0.25
2.0	0.50	1.00	Low	1.00

Vulnerability index

Vulnerability depends on the depth of flooding and the plant's phenology (Equation 2). For depth, the values from the hazard index were used: 0.5 m (P1), 1 m (P2), and 2 m (P3). The phenological stages considered, due to their greater sensitivity to flooding, were V7 (internode elongation, 30–55 d after sowing), VT (flowering, pollination, and fertilization, 55–65 d), and R1 (grain filling, 65–90 d). Plant height as a function of days of development was considered to define vulnerability functions.

The vulnerability index was categorized on a dimensionless scale ranging from 0.25 to 1, where 0.25 corresponds to low vulnerability (L), 0.5 to medium vulnerability (M), and 1 to high vulnerability (H). Thus, vulnerability depends on the depth of the flooding and the plant's phenological stage (Table 2).

Exposure value

The exposure value depends on the duration of the flooding and crop yield (Equation 3). Yield losses are associated with the duration of the flooding. The values used were adapted from Citeau (2003) and Baró-Suárez *et al*. (2007) (Table 3).

The exposure value will be equal to the economic losses (Equation 5), where the area is given in hectares (ha), the yield in megagrams per hectare (Mg ha^{-1}), and the price in MXN Mg^{-1}.

$$Financial\ losses = Affected\ area \times Yield \times Price \tag{5}$$

Table 2. Vulnerability index classification.

	V7	VT	VR	Vulnerability	Typification	Vulnerability function for phenological stage V7		Vulnerability function for the VT and R1 phenological stages	
						Depth of flooding (m)	Vulnerability index	Depth of flooding (m)	Vulnerability index
P1	M	B	B	Low	0.25	0.5	0.5	0.5	0.25
P2	A	M	M	Medium	0.5	1.0	1.0	1.0	0.5
P4	A	A	A	High	1.0	2.0	1.0	2.0	1.0

P1, P2, and P3: flood depth levels (0.5, 1, and 2 m, respectively); V7: phenological stage of internode elongation (30–55 d after sowing); VT: stage of flowering, pollination, and fertilization (55–65 d); R1: grain filling stage (65–90 d); B: low vulnerability; M: medium vulnerability; A: high vulnerability.

Table 3. Impact on yield in relation to the duration of the flooding.

Duration (days)	Impact on yield
Flash flood (1)	10 %
2 to 3	40 %
3 to 5	60 %
Above 6	100 %

RESULTS AND DISCUSSION

The methodology was applied to a 20-year RP using map algebra. The first step was to calculate the hazard. The rasters of the maximum flood extent corresponding to velocity and depth were multiplied, and the resulting raster was classified according to the hazard index (range from 0.05 to 1). This yielded the hazard map for a 20-year RP for ID 008 (Figure 1), where 2692.25 ha were classified as high hazard, representing 75.7 % of the district's total area.

The second step was to calculate vulnerability. To do so, the phenological stage affected by the flood was determined by analyzing monthly average and instantaneous precipitation, which showed peak values in September and October. This indicates that the affected cycle corresponds to spring-summer. According to the planting dates, the crop is in stages R1–R6. Based on the above, the vulnerability function for stage R1 was used, and the depth raster was classified, yielding the vulnerability map for a 20-year RP for ID 008 (Figure 2), in which 3027.39 ha exhibit high vulnerability, equivalent to 85.2 % of the district's total area.

The third step was to calculate the exposure value. This was done using, as reference values, a maize yield of 9.8 Mg ha^{-1} at a price of MXN 6000 Mg^{-1}, taken from the agricultural cost system for the state of Hidalgo published by the Trusts Established

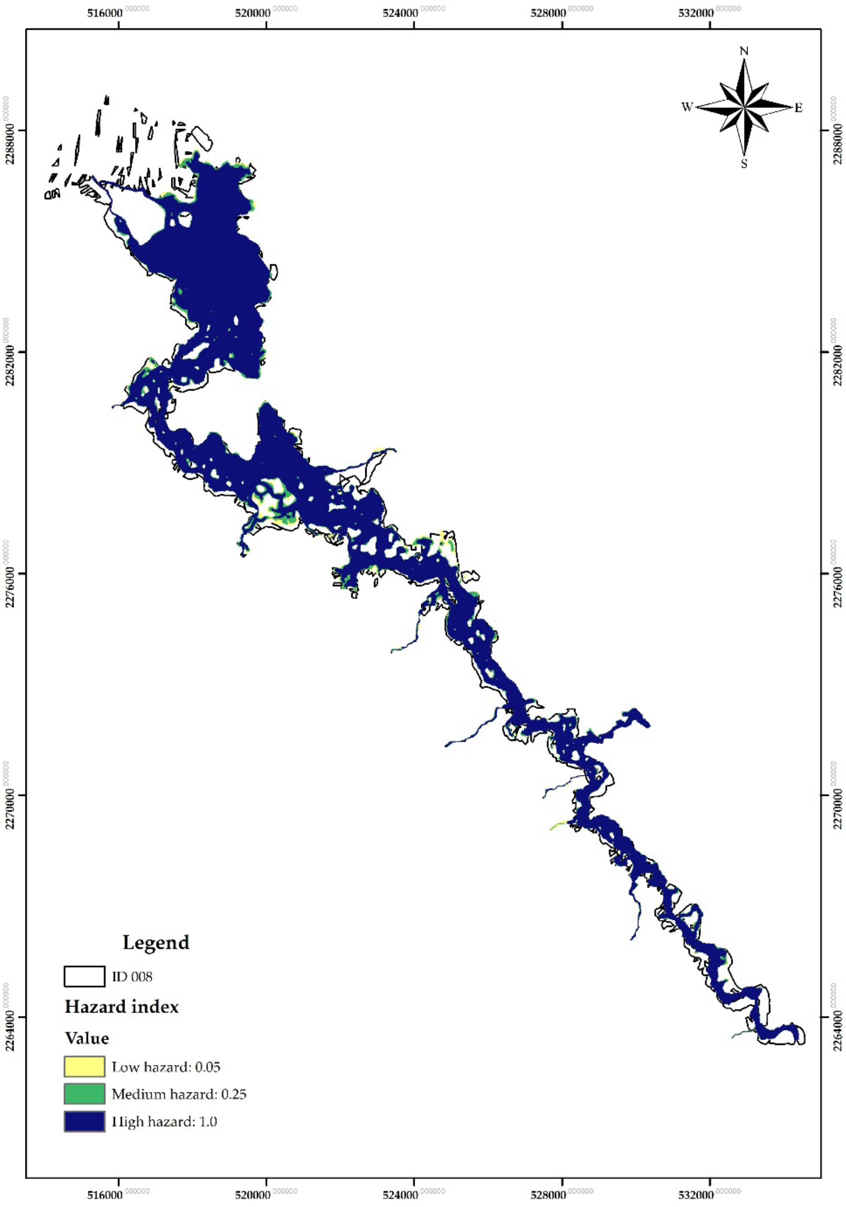

Figure 1. Twenty-year return period hazard map for Irrigation District (ID) 008 Metztitlán, Mexico.

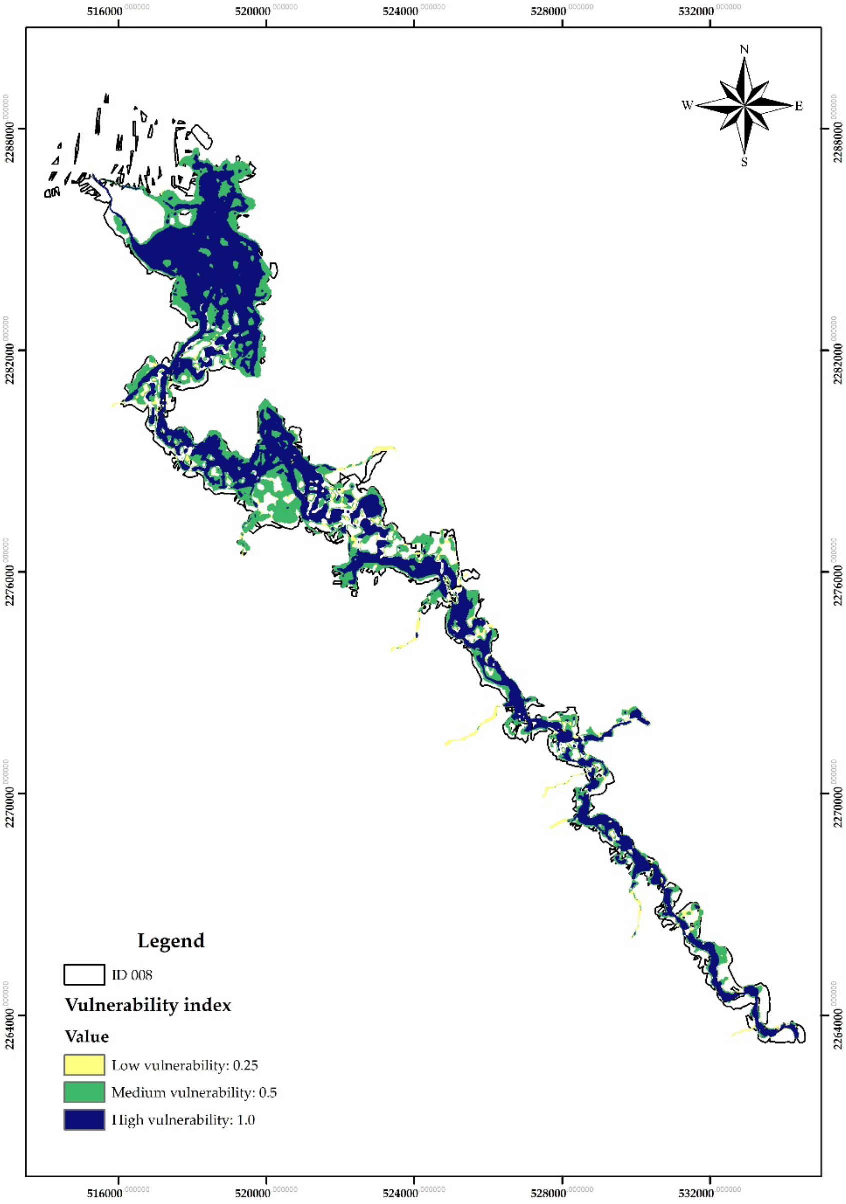

Figure 2. Twenty-year vulnerability map for Irrigation District (ID) 008 Metztitlán, Mexico.

in Relation to Agriculture (FIDA, 2024). A flood duration of 4 d was assumed, corresponding to the transit time of the complete hydrograph, which implies a 60 % reduction in yield based on the proposed values. Likewise, the hazard classification raster was used to quantify the area affected by the flood extent.

Based on these data, economic losses were estimated for each hazard classification (Table 4). These values were represented in a raster file, with each area assigned the corresponding loss value, resulting in a map of the exposure value for a 20-year return period of ID 008 (Figure 3). This indicates that, for a high exposure level, losses amount to MXN 75 819 307.2.

Table 4. Economic losses based on the classification of risk in Irrigation District 008, Metztitlán, Mexico.

Hazard	Affected area (ha)	Yield (Mg ha^{-1})	Price × Yield (MXN ha^{-1})	Economic losses (MXN)
Low	87.69	3.92	23 520.00	2 062 468.80
Medium	232.62	3.92	23 520.00	5 471 222.40
High	3223.61	3.92	23 520.00	75 819 307.20

The risk was calculated using raster algebra by multiplying the hazard, vulnerability, and exposure value rasters, which generated a risk raster in economic terms. The risk map for a 20-year RP of ID 008 (Figure 4) shows its spatial distribution based on flood exposure. The low-risk area, corresponding to losses of less than MXN 25 780.86, covers 45.2 ha, while the high-risk area, with losses between MXN 3 790 965.2 and 75 819 304, covers 1999.29 ha, equivalent to 56.25 % of the total area of ID 008. During the return period analyzed, 3348.96 ha are at some degree of flood risk, corresponding to 94.23 % of the district's total area.

The methodological approach considers the factors that influence crops, including depth, duration, rate, and seasonality, the latter of which relates to the phenological stage. According to Merz *et al*. (2010), there are few studies that incorporate velocity and seasonality in the agricultural sector; Förster *et al*. (2008) make the same point in their damage assessment proposal, which is conducted on a monthly basis considering the probability of flooding for a 100-year RP.

The agricultural vulnerability assessment methodology by Blanc *et al*. (2010) focuses on the classification and characterization of damage to the element, with an approach aimed at its reduction. In contrast, the proposed methodology is based on the characterization of the crop, the potential damage from flooding, and its tolerance, which allowed for the definition of vulnerability functions. The assessment of economic losses was carried out in a general manner to obtain damages on a large scale and over extensive areas, unlike the cost estimation by Morris and Brewin (2014), which was developed at the farm level.

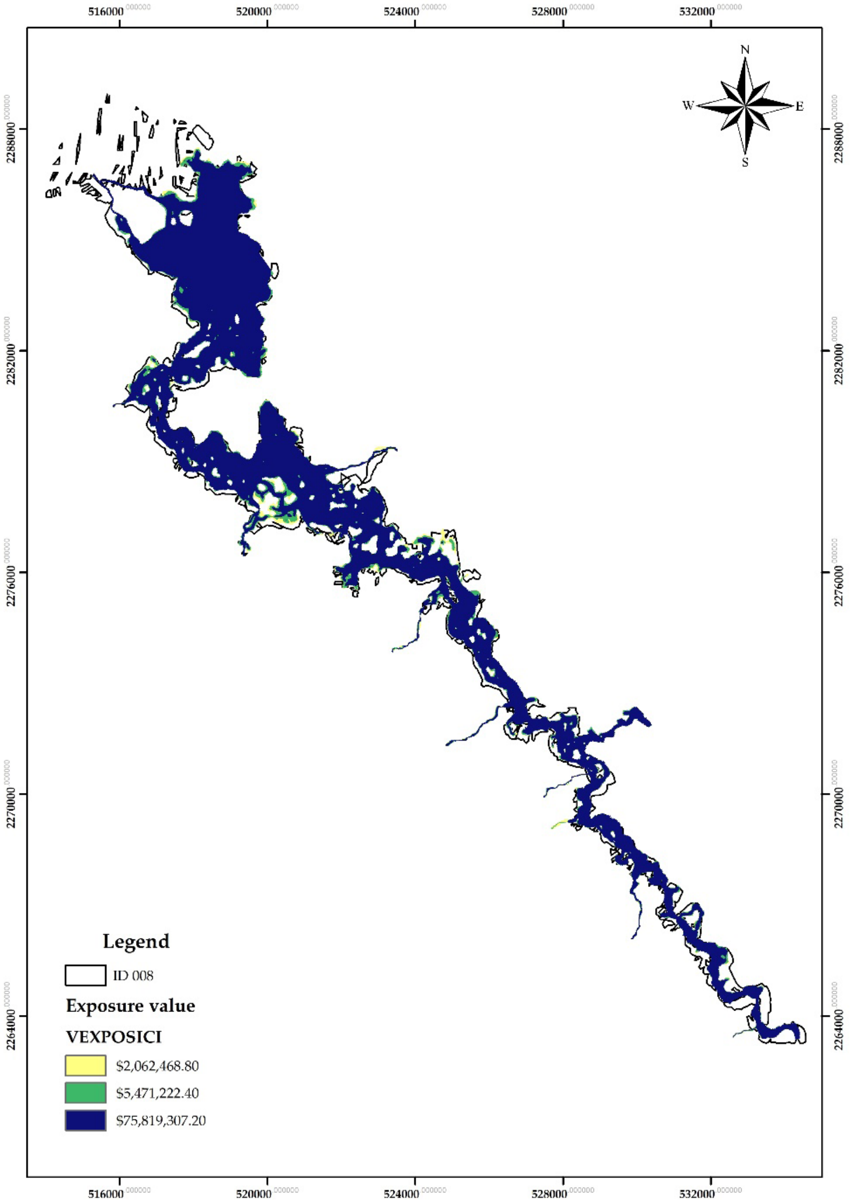

Figure 3. Exposure map for a 20-year return period (RP) for Irrigation District 008 in Metztitlán, Mexico.

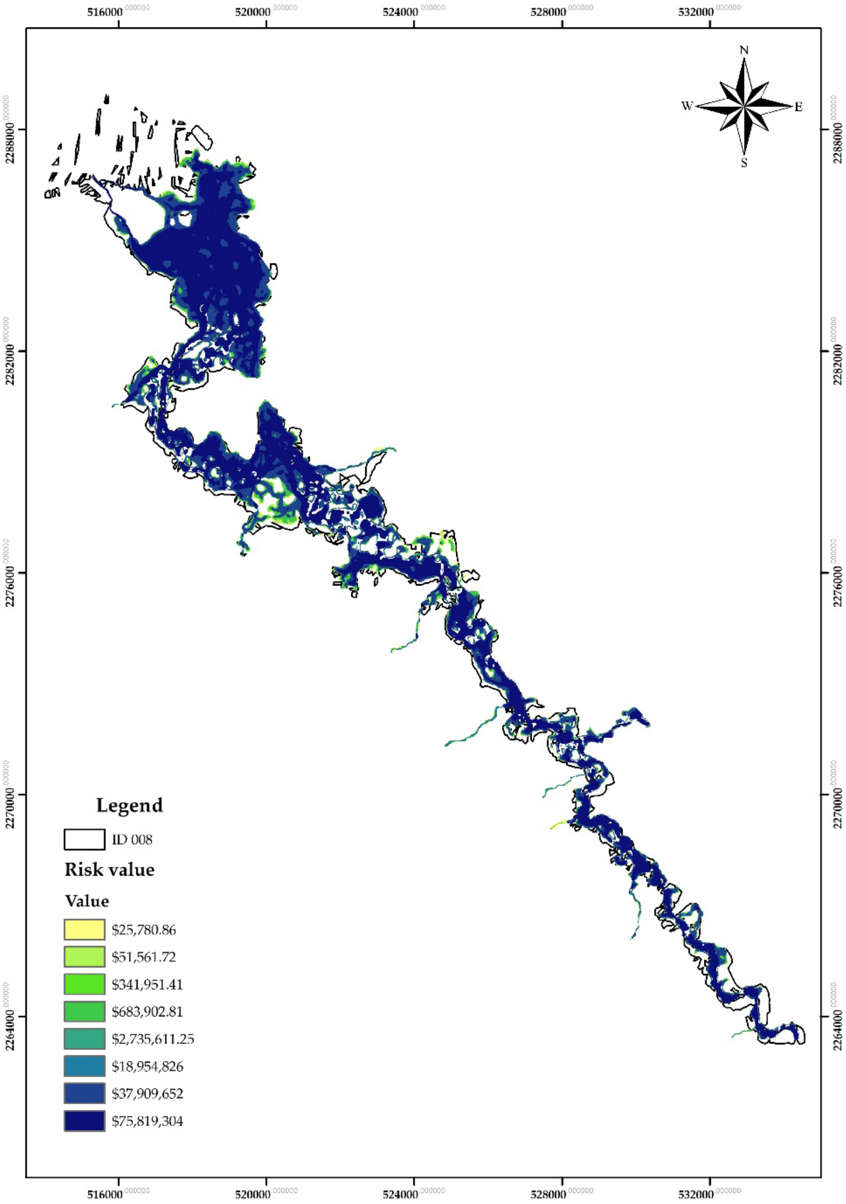

Figure 4. Risk map for a 20-year return period (RP) for Irrigation District 008 in Metztitlán, Mexico.

When comparing this methodology to approaches used in Mexico, such as the maize damage curves developed by Baró-Suárez *et al*. (2007), which are based on flood duration and apply only to plants taller than 30 cm while estimating damages in terms of minimum wages, and the methodology proposed by Vega-Serratos *et al*. (2018), which calculates average damage based on duration and probability of exceedance with monthly disaggregation, it becomes evident that the proposed methodology offers distinct advantages. It not only assesses economic damage but also allows for the calculation of hazard, vulnerability, and risk in economic terms, without being restricted to plant height. Additionally, it incorporates map algebra, simplifying the process and facilitating the generation of maps that identify zones with varying levels of hazard, vulnerability, and risk. The results illustrate a method for obtaining zoned risk maps, contrasting with the use of curves that rely on information about probability of exceedance or duration and only provide general estimates of damage.

CONCLUSIONS

The proposed methodology allows for the estimation of areas with varying degrees of risk, vulnerability, and hazard posed by flooding in the agricultural sector, specifically on plots planted with maize. The resulting risk map illustrates economic losses by area based on their exposure to flooding. Identifying the areas of greatest risk allows for the implementation of mitigation measures to reduce the effects of these events. For a more comprehensive analysis of risk quantification in an irrigation district, it would be valuable to have access to information such as crop patterns, production costs, crop value, yields, and detailed data on production cycles. Additionally, an assessment of the infrastructure is crucial; however, this information was not available in the case study.

ACKNOWLEDGMENTS

To the Mexican Institute of Water Technology and the National Council for Science and Technology for the scholarship awarded to the first author.

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