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Article

Seasonal flood risk assessment in agricultural areas

Evaluación estacional del riesgo por inundación en zonas agrícolas

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Abstract

The agricultural sector in Mexico is exposed to various hydrometeorological risks, the negative effects of which can reach disastrous proportions, causing significant financial loss to producers and the family economy due to the partial or total loss of the investment and the reduction in income from the sale of crops by farmers. These disasters can also damage the regional and national economy by interrupting the production cycle, reducing income, and creating unemployment and food shortages, among others. This study presents a method that evaluates the risk due to flooding in agricultural areas. The method proposed uses a two-dimensional hydrodynamic model to obtain the parameters of the natural hazard, including the depth, duration, and velocity of the flood. Damage curves were constructed from data obtained by administered surveys to scientific, technical, and farming personnel, supplemented with bibliographic information. These curves considered the various stages of the vegetative crop cycle in such a way that by relating them to the probability estimate of an extreme flow occurring each month of the year, it was possible to calculate the expected damage associated with each magnitude of the extreme flows. The study area corresponds to the Champoton River basin in the state of Campeche, Mexico, where the duration of floods, which are slow, is more important than the velocity of the water.

Keywords: River flooding, hydrodynamic modelling, damage functions for crops, agricultural damage, flood seasonality, development stages of crops, flood risk, annually expected damage.

Resumen

El sector agrícola en México está expuesto a diversos riesgos hidrometeorológicos, cuyos efectos negativos pueden alcanzar dimensiones de desastres, ocasionando grandes daños patrimoniales a los productores y a la economía familiar, ya sea por pérdida parcial o total de la inversión y del ingreso esperado. También pueden generar daños a la economía regional y nacional por la interrupción del ciclo productivo, reducción de los ingresos, desempleo y desabasto de alimentos, entre otros. Este trabajo presenta una metodología que permite evaluar el riesgo por inundación en áreas de uso agrícola. El método que se propone utiliza un modelo hidrodinámico bidimensional para obtener los parámetros del peligro natural, como son profundidad, duración y velocidad de la inundación. Se construyeron curvas de daño a partir de datos obtenidos mediante la aplicación de encuestas a personal científico, técnico y agricultores, complementadas con información bibliográfica; dichas curvas consideran las distintas etapas del ciclo vegetativo del cultivo, de manera que al relacionarlas con la estimación de la probabilidad de que una creciente ocurra en cada mes del año es posible calcular la esperanza de daño asociada con cada magnitud de la creciente. La zona de estudio corresponde a la cuenca del río Champotón, en el estado de Campeche, México, en la cual las inundaciones, al ser lentas, se caracterizan porque la duración es de mayor relevancia que la velocidad de la corriente.

Palabras clave: inundación fluvial, modelación hidrodinámica, funciones de daño en cultivos, daño agrícola, temporalidad de las inundaciones, etapas de desarrollo en cultivos, riesgo por inundación, daño anual esperado.

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Introduction

The devastating effects of floods are reflected in both the social and economic aspects of a country or region. In recent years, considerable effort has been made worldwide to identify the causes of floods and their characteristics, the degree of affectation, and the preparation that populations undertake when facing these natural phenomena. Moving beyond structural mitigations, the concept of integrated risk management has been developed (van Westen, 2010). Thus, the activities associated with each stage of flood risk management depend particularly on the results of the economic assessment of the impact of floods (Dutta, Herath, & Musiake, 2003; Li, Wu, Dai, & Xu, 2012).

In the agricultural sector, the standard economic damage due to floods tends to be considerably less than in urban zones for the same level of exposure (Merz, Kreibich, Schwarze, & Thieken, 2010). Therefore, even though several methods have been developed to estimate monetary losses in the agricultural sector, damage assessment in rural zones has been carried out using simple and approximate methods (Förster, Kuhlmann, Lindenschmidt, & Bronstert, 2008; Merz *et al*., 2010; Brémond, Grelot, & Agenais, 2013). This justifies the development of a method that considers the essential elements involved in the production process and that enables estimating the loss of crops due to floods.

To assess flood damage in the agricultural sector, several methods of varying complexity have been proposed, primarily developed in European countries. The differences between the methodologies are a function of the scale of the analysis, size of the study area, accuracy of the analysis, number of resources required, amount of data needed to apply the available numerical models, and number of components in the agricultural system being considered (Meyer & Messner, 2005; Merz *et al*., 2010). According to several quantitative studies on the impacts of floods on agriculture (Pivot, Josien, & Martin, 2002; Twining *et al*., 2007; Posthumus *et al*., 2009; Chatterton, Viavattene, Morris, Penning-Rowsell, & Tapsell, 2010; Morris & Brewin, 2013), the elements which may be directly damaged by a flood are: crops, perennial plant material, soil, buildings, machinery, livestock, animal products, and stored material. Compared to agricultural zones, damage to infrastructure, such as highways and roads, is rarely mentioned, although it is indicated by Förster *et al*. (2008); Chatterton *et al*. (2010), and Morris and Brewin (2013). Most studies that evaluate agricultural loss due to flooding mainly consider damage to crops. Dutta et al. (2003) examined other elements, such as damage to farmhouses and agricultural infrastructure, as well as harvest losses. Meanwhile, Pivot *et al*. (2002) addressed the effects of flooding on soil characteristics, the potential reduction in soil quality, and the loss of soil structure.

For a methodology to provide realistic damage estimates, it is important to select suitable flood risk parameters. Generic parameters and those which can be obtained through hydraulic models are the most widely used and have the greatest influence on the calculation of direct damage (Brémond *et al*., 2013). There are currently several numerical models available to characterise floods caused by overflowing rivers, for example: the *HECRas* (Posada, Veja, Ruiz, Echávez-Aldape, & Martínez, 2011; Martínez, 2011); *ISIS*, *Mike 11*, and *Mike Flood* (Patro, Chatterjee, Mohanty, Singh, & Raghuwanshi, 2009; Kadam & Sen, 2012), which are one-dimensional models (1D). Among the most common two-dimensional models are *Telemac2*, *Mike 21*, *RisoSurf* (Sommer *et al*., 2009), and TrimR2D. The choice of the numerical model to be used will depend on factors such as the quality of the information available and the scale of the study. The flood parameters that can be considered for the construction of direct damage functions for agriculture are: the seasonality of the floods, water depth, duration, current velocity, deposits, environmental pollution, and water salinity (Brémond *et al*., 2013).

The relative importance of each flood parameter varies from one region to another and depends on the conditions of the flood and the characteristics of the study area. The flood depth is the most widely used parameter in the construction of direct damage functions. In the case of housing, services, and household infrastructure, the percentage damage is associated with the height the water reaches in these buildings. It is also used in agriculture to evaluate damage to plant material, and in some cases to the soil (Brémond, 2012). The seasonality of floods links different damage coefficients to each season. With regards to duration, the number of days the crop is submerged has been used to evaluate the damage to plant material, however, in some cases, it is not clear if this parameter refers to the number of days the soil took to dry, which depends on soil type. Velocity is a parameter that is rarely used in damage functions in agriculture, unlike in the assessment of domestic buildings. In specific cases, ranges are established such as medium, low, and high to determine the potential damage to the plant (Dutta *et al*., 2003; Förster *et al*., 2008; Brémond *et al*., 2013). The deposition of sediments on flood plains is a parameter that can affect production, with repercussions on livestock feed (USACE, 1985). In addition, salt can have specific impacts on crops and soil. In the case of marine intrusion, the effect reduces production because of the toxicity of the salt in the soil (Roca *et al*., 2011).

To date, no method has included all the parameters mentioned in one damage estimation model (Vozinaki, Karatzas, Sibetheros, & Varouchakis, 2015), however combinations of the most influential parameters have been used. Förster *et al*. (2008), and Pistrika (2010) considered seasonality and duration, and Citeau (2003) used immersion time, velocity, and depth. Other more complex combinations have been presented by the USACE (1985), which considered seasonality, water depth, duration, velocity, and sediment deposition. Brémond and Grelot (2012) combined four flood parameters to generate their damage functions: seasonality, water depth, duration, and velocity.

For damage estimation methods, the development of damage functions or damage curves is essential and involves a complex process (Smith 1994; Vozinaki *et al*., 2015). Two types of curves exist: 1) historical, which are obtained from databases on past flood damage, such as HOWAS 21, developed in Germany, and 2) synthetic damage curves, which are based on theoretical analyses of the damage expected under certain flood conditions (Vosinaky *et al*., 2015). In the past, various damage functions have been used in the agricultural sector, such as functions that have combined historical and synthetic data (Merz *et al*., 2010), and curves derived from averaged and normalized historical data from the Japanese Ministry of Construction, which take into account the depth and duration of the floods (Dutta *et al*., 2003). Pistrika (2010) used empirical functions based on data related to agricultural damage, recorded by the Greek Ministry of Rural Development. Brémond and Grelot (2010) constructed damage functions from data obtained from literature and interviews. Thieken *et al*. (2008) conducted online surveys to create a database on damage in the rural sector. And impact factors for different types of crops have been generated based on empirical data obtained from interviewing experts (Förster *et al*., 2008).

The agricultural sector in Mexico is exposed to various hydrometeorological risks, the negative effects of which can reach catastrophic dimensions, resulting in property damage for the producers and the family economy, including the partial or total loss of the investment and expected income. Similarly, they can cause damage to the regional and national economy by interrupting the production cycle, reducing profits, and creating unemployment and food shortages, among other effects.

This study aimed to develop a methodology to assess the risk of floods in agricultural areas. The method was based on previous studies adapted to the conditions of the study area and the information available. The proposed method used a two-dimensional model to obtain risk parameters, including the depth, duration, and velocity of the flood. The damage functions took into account the seasonality of the floods relative to the vegetative crop cycle. Due to the lack of a historical database on agricultural damage, damage curves were constructed through interviews conducted with scientific, technical, and agricultural personnel, supplemented with bibliographic information. The study area corresponded to the Champoton River basin in the state of Campeche, Mexico, where floods are slow; hence the parameter of duration is more important than velocity in the agricultural areas.

Study area

The proposed methodology was applied to the Champoton River basin, located in the central part of the state of Campeche (Figure 1). It belongs to hydrological region (HR) number 31 Yucatan West, of the National Water Commission (CONAGUA, 2015), which has a total surface area of 649 km^2, with a maximum elevation of 120 m above sea level. To the north, the area is delimited by HR number 32 Yucatan North, to the south by HR number 30 Grijalva-Usumacinta, and to the east and west by the Gulf of Mexico.

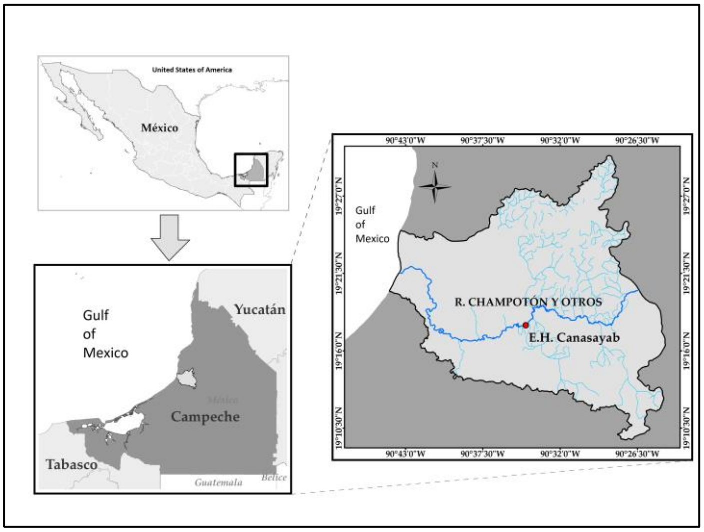


Figure 1. Study area.

The river is approximately 48 km long, from its origins near the town of San Juan Carpizo to its mouth in the Gulf of Mexico (Posada-Vanegas, Vega-Serratos, & Silva-Casarín, 2013). The river mainly follows a smooth slope, and has a maximum average width of 50 m and a mouth with a maximum width of 80 m; its average depth is 4 m. Along the river, there are several freshwater springs, intermittent currents, the Nayarit de Castellot lagoons, known locally as Nilúm lagoon, and the Noch lagoon, as well as the Xbacab, Chuina, and Hool waterfalls (Ramírez, 2015). Its general trajectory is east-west and it is fed underground by the Desempeño and Las Pozas rivers, which begin in hydrological region number 31 Yucatan West and flow towards the Champoton River. Gleysols soils predominate, with a high clay content and low drainage capacity, which leads to rapid saturation and impermeability. Lictic rendzina is found towards the coast, where there is a thin layer of shallow limestone (Sagarpa, 2009).

Methodology

The method proposed for estimating the risk of flood loss in agricultural zones is divided into three sections: the first part assesses the flood hazard by applying a two-dimensional numerical model, which is based on design hydrographs for various return periods and a digital topo-bathymetric model which integrates the topography of the river basin, the bathymetry of the Champoton River, and the coastal zone near the river's mouth in the Gulf of Mexico. The second part of the two-dimensional hydrodynamic model consists of the deduction of flood damage functions for the most important crops in the Champoton River basin. For this stage, an analysis of the historical production of all the crops was performed for the study area, and a literature search was carried out on the different methods for assessing agricultural damage and the most important variables considered. Field trips were also made to conduct interviews with farmers, researchers. and state and federal officials whose work was associated with agriculture. Finally, reviewing these elements and the information available, criteria were adapted to construct crop damage curves, in particular, the relationship between the development stage of the crop and the likelihood of significant floods associated with each stage. The third stage consisted of constructing a model to evaluate the annual expected flood damage in agricultural zones, which considers the first two stages, land use, and vegetation, as well as the expected production costs. Figure 2 presents the main steps of the methodology proposed to assess flood damage in agricultural zones.

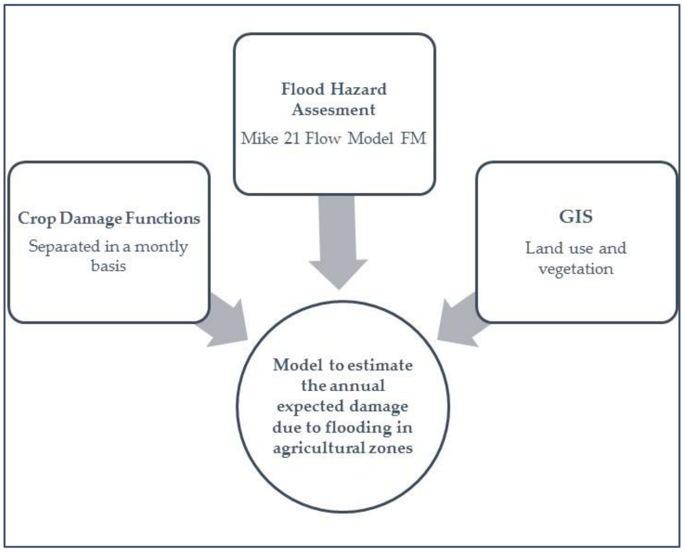


Figure 2. Flow diagram of the proposed methodology.

Flood hazard assessment

With regard to risk, a hazard is defined as the probability of occurrence of a potentially damaging phenomenon of a certain intensity, over a given period and at a particular location. It is important to define the disturbance through quantitative parameters with a precise physical meaning that can be measured numerically and be associated by physical relationships with the effects of the event on exposed goods (Guevara, Quaas, & Fernández, 2006).

To characterise flood risk, this study used the Mike 21 Flow Model FM (DHI, Water & Environment, 2014a), which was developed by the Danish Institute of Hydraulic Engineering. This has a complete modelling system for 2D free surface flows, applicable to the simulation of hydraulic and related phenomena in lakes, estuaries, bays, coastal zones, and seas (DHI, Water & Environment, 2014b). The hydrodynamic module (HD) was used to simulate the variation in water levels and flows subject to a variety of boundary conditions in the coastal area and the river. Figure 3 shows the flow diagram of the applied procedure.

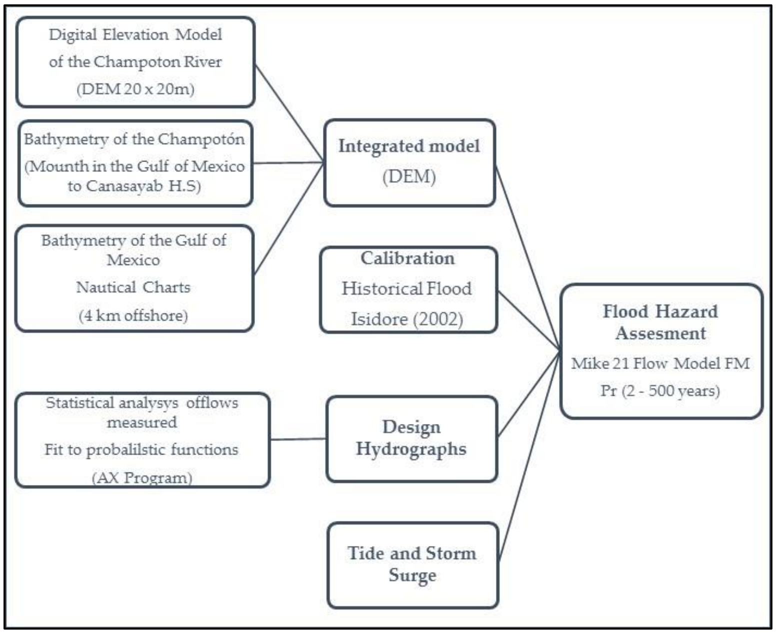


Figure 3. Flow diagram of the hydraulic models.

The complete topo-bathymetric model was generated by assembling a Digital Elevation Model (MDE, 20 x 20 m pixel) of the Champoton basin, with the Champoton River bathymetry obtained from field measurements using an echo sounder and GPS, from the coast of the Gulf of Mexico near the river mouth to the coastal zone of the city of Champoton (Posada-Vanegas *et al*., 2013). The bathymetry of this zone was complemented by Nautical Chart 28260, which corresponds to the Gulf of Mexico-Barra Tupilco to Isla Piedra, 1981, from the Mexican Secretary of the Navy (SEMAR) (Figure 4). The study area was discretized into a grid of triangular cells of varying size, which provides greater detail of the zones of interest, such as the river, the city of Champoton, the river mouth, and the coastline. The model was calibrated based on the historic floods caused by Hurricane *Isidore* (2002), field data, storm surge (Posada-Vanegas *et al*., 2013), and the measured runoff hydrograph.

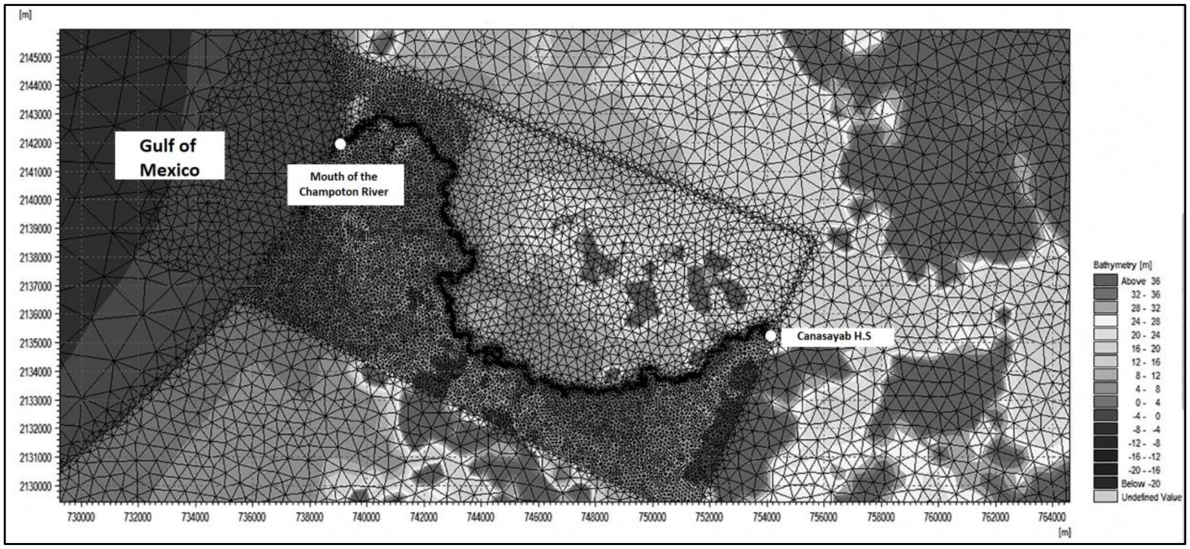


Figure 4. Flexible mesh with variable resolution. Champoton River basin.

Design hydrographs

Frequency analysis is used as a tool to predict the future behavior of the flows generated by hydrometeorological events based on historical information. Statistical procedures are used to calculate the magnitude of the flow associated with a return period (*Tr*), where *Tr* is defined as the average number of years it takes for a given event, *x*, to be equaled or exceeded in magnitude at least once during that time period (Escalante-Sandoval & Reyes-Chávez, 2002). The methodologies described by Domínguez *et al*. (2008) were used to generate the design hydrographs.

Water Flows

To characterize the flood hazard, records of measured flows from the Canasayab hydrometric station (Canasayab HS) on the Champoton River from the period of 1956-2011 were used. This station is located 39 km from the mouth of the Champoton River. There are no tributaries between the location and the study area. Based on mean daily flow records from the Canasayab HS, a frequency analysis of the maximum annual flows was performed. The AX V.1.05 program (Jiménez, 1992) was used to carry out the analysis of probability, which resulted in the double Gumbel function, providing the best fit to the selected data set, with the lowest standard error. Events for the return periods of 2, 5, 10, 20, 50, 100, 200, and 500 years were subsequently calculated (Figure 5).

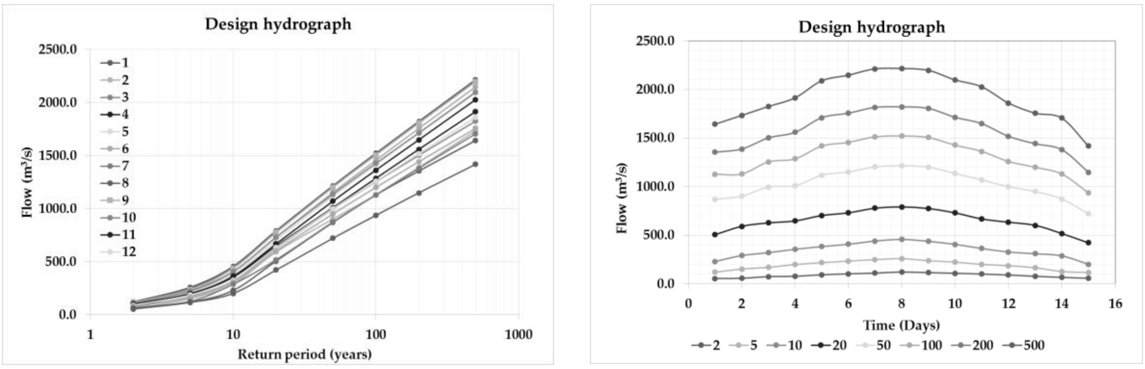


Figure 5. Frequency analysis of maximum annual flows for different durations (days)

The flood simulation process is described in Ramírez (2015). The output parameters used were the maximum water depth, flow duration, and velocity in each of the cells of the flexible mesh.

Agricultural flood damage functions

The development of flood damage functions is one of the most important procedures in modeling to estimate the loss in agriculture (Yu, Qin, & Larsen, 2013). In some developed countries, historical data on flood damage exist for the various systems affected, which allows damage curves to be generated (Meyer, Scheuer, & Haase, 2009; Yu *et al*., 2013; Vozinaki *et al*., 2015). For the present study, no database was available on crop damage due to floods, hence the criteria and methodologies were adapted, similar to those of Förster *et al*. (2008), Brémond *et al*. (2013), and Chau, Cassells y Holland (2014) for the construction of crop damage curves. Figure 6 shows the proposed sequence for the development of the functions.

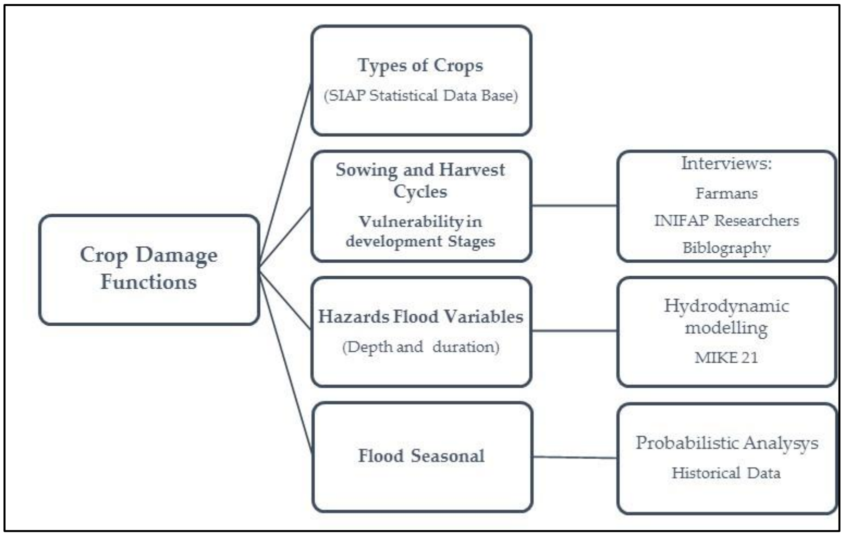


Figure 6. Flow diagram for the construction of crop damage functions.

Flood hazard parameters that affect crops

The selection of the hazard parameters that most influence direct agricultural damage is crucial in order to produce a realistic estimaion. In this study, the selection criteria for the parameters were based on the information collected in the field from farmers, researchers at the Centro Experimental Edzná-INIFAP (Campeche), and from a literature search (Förster *et al*., 2008; Brémond *et al*., 2013; Chau *et al*., 2014; Vozinaki *et al*., 2015). In accordance with the information obtained and with the characteristics of the study area, the hydraulic parameters that most affected the agricultural zones were water depth, flood duration, and seasonality (temporality). With respect to the water depth, damage begins with the drowning of the plant's root. The length of time that the plant is submerged, regardless of the water depth, generates hydric stress. Temporality refers to the crops' growth stage at the time of the flood. For the study area, due to the flat slope of the flood zone, flow velocity did not significantly affect damage.

Types of crops

As previously mentioned, there is no historical floods database in Mexico that indicates the damage to the agricultural sector as a function of the hydraulic parameters that primarily affect crops.

In order to estimate the expected losses due to flooding in the agricultural zones in the study area, information is needed on the types of crops grown in the arable areas. The decision of farmers as to the type of plants to cultivate in a region depends on the cost-benefit relationship, the specific objectives of the farmer, and the characteristics of the soil (Förster *et al*., 2008).

In an initial stage, official sources of information from different government entities were consulted. One of the consultation services, provided by the Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA), is the Agricultural and Livestock Information System (SIAP, March 2015), which provides historical statistical information about the production sectors in Mexico.

The database from 1980 to 2013 was extracted for all the crops grown in the study area, separated into spring-summer (S-S) and autumn-winter

(A-W) cycles and irrigation technique. Figure 7 shows that corn is the most representative grain, followed by sorghum, palay rice, soybeans, beans, and several vegetables in a lower percentage, for seasonal irrigation. Hence, corn was chosen to develop the methodology for the construction of damage curves.

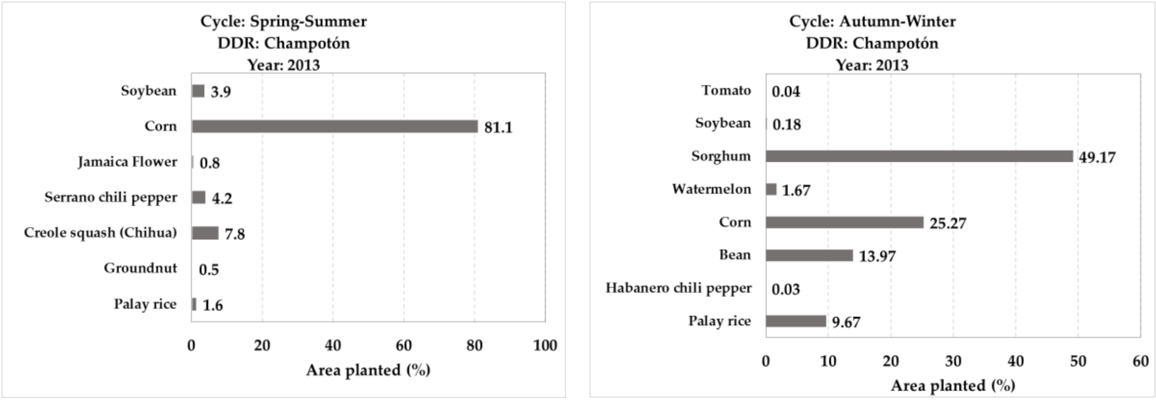


Figure 7. Area planted in the DDR Champoton, 2013. Seasonal irrigation mode. (Source: SIAP-Sagarpa, 2014).

Crop growth stages

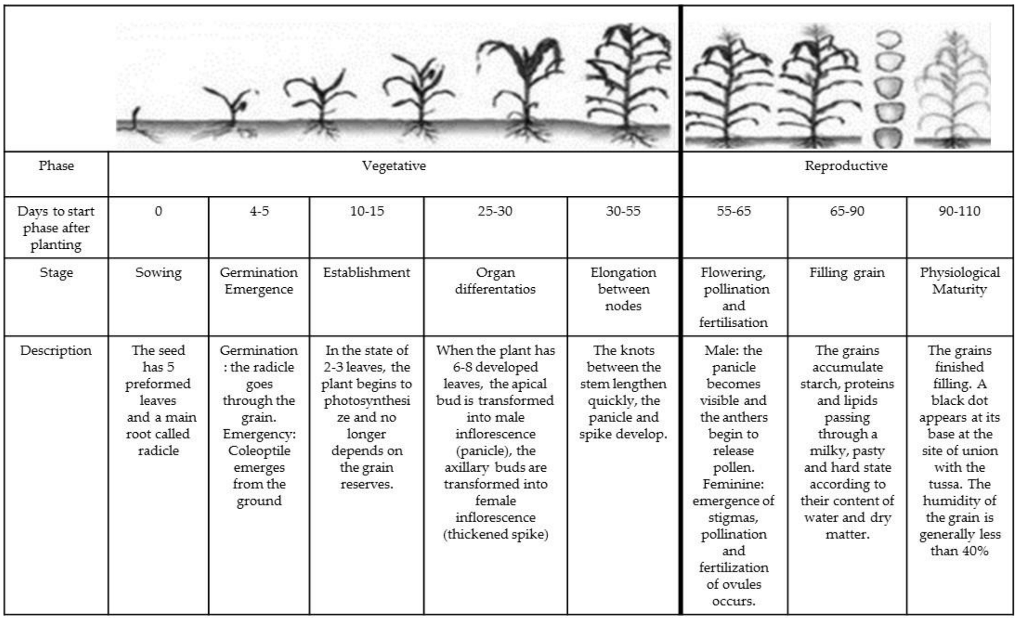
The impact of the damage on crops depends on their development or growth stage at the time of the flood. According to the International Corn and Wheat Improvement Center (IMWIC, April 2016), the different growth stages of corn can be divided into two categories: vegetative (V) and reproductive (R). Furthermore, they can be grouped into four main periods:

1. Growth of seedlings (stages VE and V1)
2. Vegetative growth (stages V2, V3..., Vn)

3. Flowering and fertilization (stages VT, R0, and R1)

4. Grain-filling and maturity (stages R2 to R6)

Figure 8 shows the Ritchie and Hanway (1982) scale, which contains the stages considered in this study. The number of days in each stage depends on the particular characteristics of the area of study in terms of the climate conditions, soil type, temperature, and seed variety, among other aspects. In the Experimental Field of Edzná-Campeche of the National Institute of Forestry, Agriculture and Livestock Research (INIFAP, SAGARPA), various materials (seeds) have been tested in central and northern Campeche, including different varieties such as VS-535 (commercial name) and hybrids such as H-431, to determine the average yield of grain in weather conditions ranging from excellent to adverse.



Phase	Vegetative					Reproductive		
Days to start phase after planting	0	4-5	10-15	25-30	30-55	55-65	65-90	90-110
Stage	Sowing	Germination Emergence	Establishment	Organ differentatios	Elongation between nodes	Flowering, pollination and fertilisation	Filling grain	Physiological Maturity
Description	The seed has 5 preformed leaves and a main root called radicle	Germination: the radicle goes through the grain. Emergency: Coleoptile emerges from the ground	In the state of 2-3 leaves, the plant begins to photosynthesize and no longer depends on the grain reserves.	When the plant has 6-8 developed leaves, the apical bud is transformed into male inflorescence (panicle), the axillary buds are transformed into female inflorescence (thickened spike)	The knots between the stem lengthen quickly, the panicle and spike develop.	Male: the panicle becomes visible and the anthers begin to release pollen. Feminine: emergence of stigmas, pollination and fertilization of ovules occurs.	The grains accumulate starch, proteins and lipids passing through a milky, pasty and hard state according to their content of water and dry matter.	The grains finished filling. A black dot appears at its base at the site of union with the tussa. The humidity of the grain is generally less than 40%

Figure 8. Phenological stages of the corn plant. Source: Ritchie and Hanway (1982).

Seeding and harvest dates

For both agricultural cycles, spring-summer (S-S) and autumn-winter (A-W), the areas sown with the first grains must be under rainy conditions. The seeds are planted between the 1st of June and the 31st of July. When the traditional soil tillage system is used, sowing begins when the rainy season is well under way, with an optimum period between the 15th of June and the 15th of July. With the zero-tillage system, this job can be carried out after the first rains, since the mulch from the vegetal residues left on the soil preserves the mositure longer (Experimental Field of Edzná-Campeche, INIFAP. March 2015). Figure 9 shows the calendar for sowing, harvesting, and marketing for the S-S agricultural cycle in 2015 for the corn, sorghum, rice, and soybean crops.

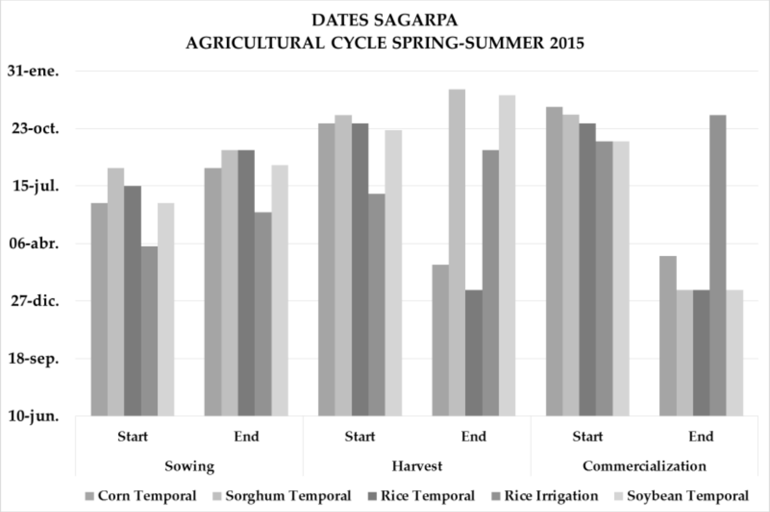


Figure 9. Dates of agricultural production, state of Campeche. S-S cycle 2015. Source: Sagarpa, Local Campeche office.

Damage impact

The impact of the damage depends mainly on the development stage of each crop at the time the flood occurs. The impact values range from 0 to 100%. Based on the sowing, harvesting, and marketing calendar (Sagarpa, 2015), the crop development stages were separated on a monthly basis.

The hydraulic parameters of flood depth, duration, and season were included in the construction of the damage functions. Based on the different flood depths, 4 ranges of flood duration were established. A damage function was constructed for each range according to the studies by Vozinaki *et al*. (2015), Brémond *et al*. (2013), and Förster *et al*. (2008) (Table 1).

Table 1. Format of the survey tables used to determine crop damage from flooding.

% Impact of damage to the crop from flooding				
Month	**Duration (days)**			
	1 a 3	4 a 7	8 a 11	>11
January	...	...	...	...
February	...	...	...	...
March	...	...	...	...
April	...	...	...	...
May	...	...	...	...
June	...	...	...	...
...	...	...	...	...
December	...	...	...	...

During 2012 and 2013, field trips were carried out to collect information from farmers growing mainly corn, sugar cane, and sorghumIn addition, interviews were conducted with researchers from the National Institute of Forestry, Agriculture and Livestock Research (INIFAP), from the Experimental Field of Edzná, who have studied different crops in the state of Campeche and provided their opinions and experiences on the effects a flood can have on crops such as soybean and corn. The sowing and harvest information was complemented by technological packages for sowing corn in the state of Campeche.

The general considerations for the study area were:

- The events considered were slow floods, i.e., flow velocity was slow;
- Water drainage as a result of the floods was slow;
- A single type of crop was planted in each plot or area of cultivation;
- The direct damage to the crops was evaluated;
- In the study areas, the slope of the land was small, on the order of 0.1%;
- The soil in the study area consisted of mollic and eutric gleysol, i.e., with low permeability;

In addition, in the calendar used by Sagarpa in 2015, for the S-S cycle, the sowing season was established between June and July, hence for this study, the start of the production process was considered to be in May with the preparation of the land. Preparations for the A-W cycle began following the harvest in the S-S cycle.

Land use

To delimit the agricultural zones in the study area, a vector dataset on land use and vegetation was used from the National Institute of Statistics and Geography (INEGI), scale 1: 250 000, series V (2011-2012), updated with LANDSAT 2011 satellite images. From this information, the polygons dedicated to agriculture and the type of vegetation cover were obtained, respectively (Figure 10).

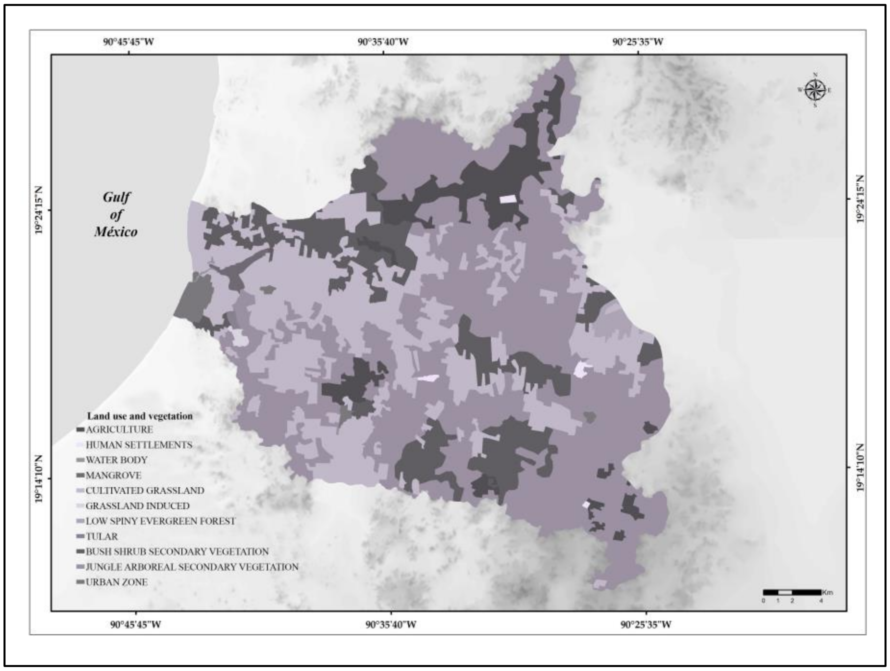


Figure 10. Land use and vegetation in the Champoton River basin.

Damage estimate

There are several models that estimate flood damage in the agricultural sector, the differences of which lie in the number of variables they consider and in the existence or availability of measured information for their application. The aim of this paper was to assess the agricultural damage caused by floods based on the impact of the damage and the production costs of the crop in the month the events occurred, as a function of the development stages. The following model was used:

1. Estimate the probability of a flow *Q* associated with a return period (*Tr*) in each of the months of the year. This possibility was considered to be proportional to the mean monthly flows recorded at the Canasayab station. The data generated is the value of a probability *P*(*i*) for each month *i.*

2. Obtain the crop damage percentage (from 0-1) for each month in the event of a flood caused by a flow associated with a *Tr* (Q_{Tr}). This data is extracted from the damage function proposed for the different flood durations. Four flood durations were proposed: 1-3d, 4-7d, 8-11d, and >11d. The data generated are called %D (i, d).

3. Determine the cost per hectare ($/ha) of the crop for the month according to its development stage in the production process. The values obtained are called *CPHC*(*i*).

4. Estimate the annual damage, DC_d, for each flood associated with a *Tr* and for each duration interval, as the weighted sum of the damage corresponding to the 12 months of the year:

$$DC_d = \sum_{i=1}^{n} P_i \cdot \%D_{i,d} \cdot CPHC_i \tag{1}$$

5. Determine the flooded area as a flow *Q* associated with a *Tr* for the different duration intervals. This variable is called *ACI*(*j*), and is measured in ha, where *j* varies as a function of the number of *Tr* analyzed.

6. Calculate the damage, *D*, for each duration interval:

$$D(Q_{Tr}) = \sum_{j=1}^{m} DC_d * ACI_j \tag{2}$$

7. Construct risk curves for each duration interval. Each point of the curve has coordinates $D(Q_{Tr})$, *Tr*).

8. Obtain the annually expected damage, *DAE*, as the area below the risk curve for each duration interval (Meyer, Priest, & Kuhlicke, 2012):

$$DAE = \sum_{j=1}^{m} \frac{D(P_{Trj-1}) + D(P_{Trj})}{2} * \Delta P_j \tag{3}$$

where ΔP_j is the increase in the probability of exceedance between return periods.

9. Obtain the average total damage based on the sum of each duration interval. This is called *DTP*.
10. Construct the risk curve with the total average damage for each *Tr* (*DTP*, *Tr*).
11. The area below the risk curve gives the average annual expected damage, *DAEP*.

Results and discussion

Hydrodynamic modelling

The modeling, carried out using a hydrodynamic program, made it possible to evaluate the hazard associated with the Champoton River overflowing in the flood zones. The maximum depth values, velocities, and duration of the floods were obtained from each flexible mesh. The measured hydrograph of Hurricane *Isidore* (2002) was used to calibrate the model, comparing the modeled results with those obtained in the field by interviews conducted with the residents of the agricultural towns and the populations affected. Figure 11 shows the sites where damage surveys were conducted.

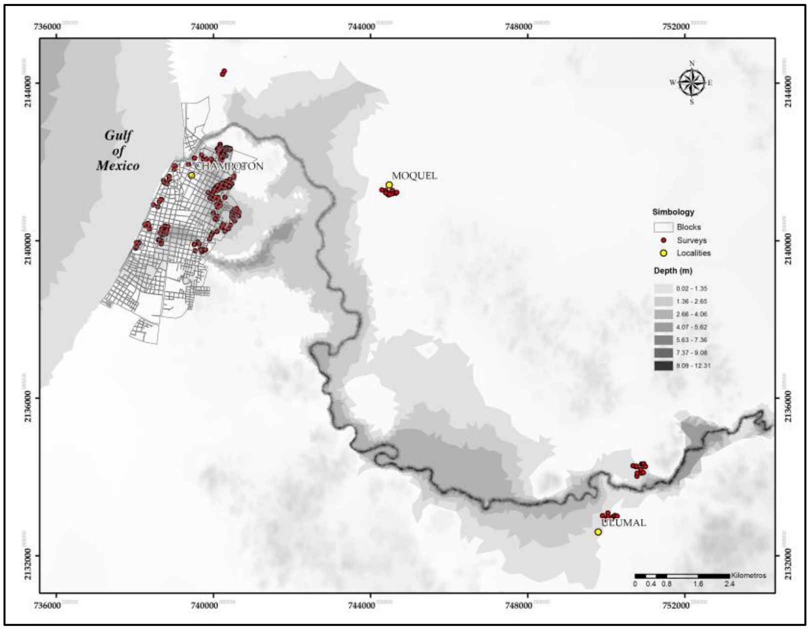


Figure 11. Results of the hydraulic model, maximum depth values (*Isidore* 2002).

Flood seasonality

To obtain the agricultural damage, the production cost and the impact of the damage on the crops were disaggregated by month, and the historical analysis of the flows from the Cansayab HS (1956-2011) was carried out in a comparable manner. Figure 12 shows the distribution of the average monthly runoff values from the entire record. In accordance with Agraz-Hernández *et al*. (2015), three seasons were identified in the state of Campeche: dry, rainy, and northerlies. During the dry season (February to April) the magnitude of the peak flows is relatively small, but the impact of the damage is greater than during rainy season. Meanwhile, the rainy season is well under way in the months of May to October, and according to the frequency analysis, the maximum annual flows primarily occur in the months of September and October. It is important to mention that during the "northerlies" season, moisture is accompanied by strong cold winds from the northeast, which are present in the months of November to January, and although the order of magnitude of the flows is small compared to those of the rainy season, due to antecedent soil moisture the vulnerability of the agricultural zones is considerable.

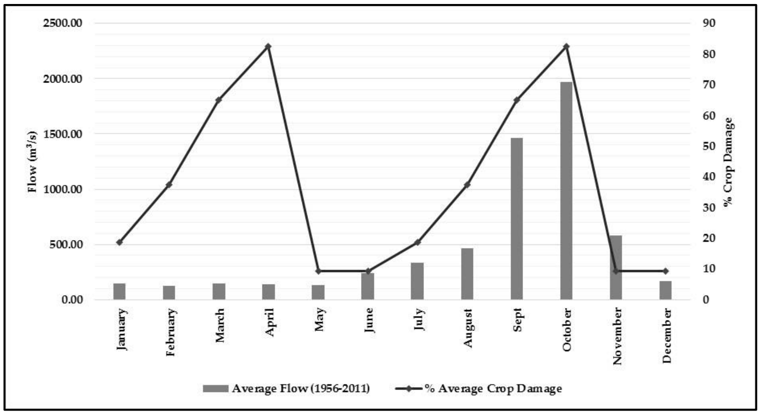


Figure 12. Flows from the Canasayab HS (1956-2011).

The monthly disaggregation of the probability of occurrence of a flood was considered important since the losses in agriculture greatly depend on the month in which the flood occurs (Förster *et al*., 2008). Table 2 shows the values of the average monthly runoff and their values relative to the annual total. The extreme floods associated with a maximum peak flow occurred in the months of September and October, and according to the average function of damage to corn (Figure 12), the crops' most vulnerable stage in the S-S cycle occurred during these months, just before and during harvest.

Table 2. Monthly historical flow, Canasayab Station.

Month	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Average monthly flow	142.98	121.82	145.78	137.08	133.75	242.14	331.17	466.43	1465.52	1971.99	579.30	164.88

P(*i*)	0.024	0.021	0.025	0.023	0.023	0.041	0.056	0.079	0.248	0.334	0.098	0.028

Damage functions and production costs

As corn is one of the main crops in the study area, the case of analysis for this work was applied exclusively to those farms where this type of crop was identified. The impact of the damage was divided into 4 categories, according to the duration of the flood in the different stages of crop development. According to the results of the interviews, in the months of May and June, the impact of the damage was small for the ranges of duration of 1 to 3 days and 4 to 7 days, since the affectations only involved a delay in the preparation of the land and the sowing date. Meanwhile, the percentages of damage were greater for all the other ranges from July to August. This coincides with the critical period of development of the crop, which goes from 45 to 75 days of age of the plant, during which the crop develops in height and the flowering is established. Then the grain-filling stage occurs between September and October and harvesting begins, depending on the moisture conditions of the grain. The impact of the damage that occurs during this stage is a complete loss (Figure 13).

Figure 13 present the monthly direct costs of the production process. As the crop develops, several activities are added which increase the costs, including, in particular: soil preparation, seed costs, fertilization, weed control, pest control, and labor costs for the harvest.

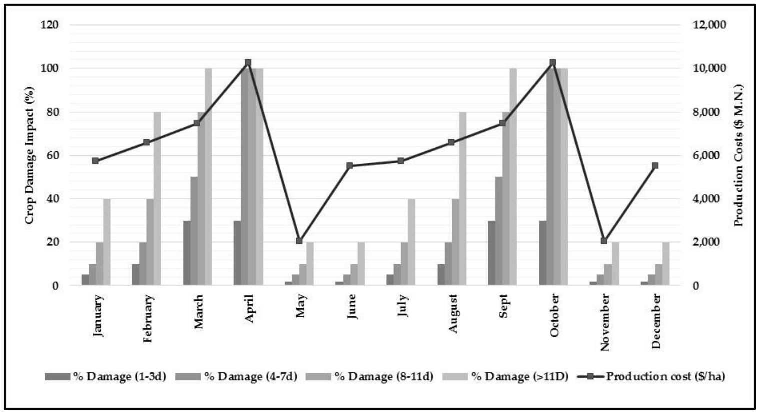


Figure 13. Damage impact and production costs of growing corn. Source of the costs: Experimental field Edzná-INIFAP, 2015).

Damage estimate

Flood damage in agricultural areas was evaluated with Equations 1 to 3, based on the interaction of flood results meshes, land use and vegetation, damage functions by crop type, and production costs.

The calculation process begins with the DEM mesh. In each hydraulic simulation for a certain return period (*Tr*), a results grid is obtained. Each cell contains information about the maximum flood stress, its duration, and maximum speed. Subsequently, the use of soil is identified for each cell, as shown in Figure 10. Damage functions are applied in each cell, according to the duration interval and the production costs obtained from the technological package for seasonal corn in the state of Campeche (Figure 13).

Next, the proposed methodology for a flood scenario with a return period (*Tr*) of 10 years is applied.

Table 3 indicates, for each scenario analyzed in the hydraulic simulation, the size of the crop areas disaggregated by the range of duration of the flood.

Table 3. Flooded crop areas

Tr (Years)	**Area (ha)** **Flood duration (days)**			
	1-3	**4-7**	**8-11**	**> to 11**
2	0.1488	1.96847	2.46554	6.4838
5	0.25843	2.0113	4.08826	22.42063
10	0.51453	3.15503	4.20933	37.32747
20	0.65314	3.67466	5.6057	48.87276
50	0.9211	9.01778	14.08794	52.27633
100	1.87926	16.56971	27.21081	79.03159
200	11.5739	21.13848	39.96751	81.53425
500	21.4516	48.66245	52.79741	97.70343

The following are obtained in the first stage: the damage *D* (Q_{Tr}), considering the probability, *P*(*i*), that a flood occurs in the different months of the year; the percentage of the impact of the damage, %*D* (*i*,*d*), of a flood in month *i* with a certain duration; and the production cost of the *CPHC* (*i*) crop in month *i* of development. These are disaggregated monthly and obtained for each flooded cultivated area, *ACI* (*j*), for each scenario, *Q*(*Tr*), and for each interval of duration, *d*(*i*) (Table 4).

Table 4. Damage evaluation in corn crop areas. Scenario *Tr* = 10 years.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
P*(*i*), probability of occurring in month *i	0.024	0.021	0.025	0.023	0.023	0.041	0.056	0.079	0.248	0.334	0.098	0.028

% Damage impact (1-3d)		5	10	30	30	2	2	5	10	30	30	2	2
% Damage impact (4-7d)		10	20	50	100	5	5	10	20	50	100	5	5
% Damage impact (8-11d)		20	40	80	100	10	10	20	40	80	100	10	10
% Damage impact (>11d)		40	80	100	100	20	20	40	80	100	100	20	20
Production cost ($/ha)		5,740.00	6,596.00	7,452.00	10,252.00	2,050.00	5,500.00	5,740.00	6,596.00	7,452.00	10,252.00	2,050.00	5,500.00
Duration (days)	***ACI* (ha)**	**Damage($)**											
1-3d	0.5145	3.58	7.00	28.41	36.75	0.48	2.32	8.28	26.82	285.59	528.67	2.07	1.58
4-7d	3.1550	43.87	85.90	290.32	751.13	7.33	35.59	101.60	328.88	2,918.62	10,805.78	31.74	24.24
8-11d	4.2093	117.05	229.20	619.74	1,002.13	19.55	94.97	271.11	877.56	6,230.27	14,416.70	84.69	64.67
>11d	37.3275	2,075.99	4,065.07	6,869.63	8,886.71	346.77	1,684.30	4,808.28	15,563.95	69,060.98	127,844.28	1,501.95	1,146.92

The sum of the damage is calculated for each duration interval, disaggregated by month. Based on this, the total values for the scenario *Tr* = 10 years are obtained, as well as the total average *DTP* damage for all the time intervals (Table 5).

Table 5. Damage by flood duration interval for corn crops. Scenario *Tr* = 10 years.

Exceedance probability (P = 1/Tr)	**d = 1-3days**	**d = 4-7days**	**d = 8-11days**	**d >11days**	**Average Total Damage, *DTP* ($)**
0.1	931.55	15,424.99	24,027.63	243,854.84	284,239.01

The procedure described above was conducted for floods of different return periods and duration intervals. Table 6 summarizes the results obtained, as well as the average total damage (*DTP*).

Table 6. Summary of damage by scenario and flood duration interval for corn crops.

Exceedance probability	**Damage ($)**				**Average Total Damage *DTP* ($)**
P=1/Tr	**d= 1-3days**	**d= 4-7days**	**d= 8-11days**	**d>11days**	
0.5	269.40	9,623.88	14,073.76	42,357.71	66,324.74
0.2	467.88	9,833.28	23,336.54	146,470.66	180,108.36
0.1	931.55	15,424.99	24,027.63	243,854.84	284,239.01
0.05	1,182.50	17,965.47	31,998.37	319,278.51	370,424.85
0.02	1,667.63	44,088.07	80,416.56	341,513.53	467,685.80
0.01	3,402.36	81,009.58	155,324.33	516,301.68	756,037.96
0.005	20,954.31	103,346.37	228,141.93	532,651.19	885,093.81
0.002	38,837.69	237,911.50	301,377.37	638,282.05	1,216,408.62

Figure 14 shows the curves that enable obtaining the risk in terms of the expected annual damage to the corn crop. The risk curve was constructed for the average total damage for each *Tr*, with coordinates (*DTP*, *Tr*). Equation 3 was applied to calculate the value of the expected annual average damage (*DAEP*), which resulted in $ 102 494.29 / ha.

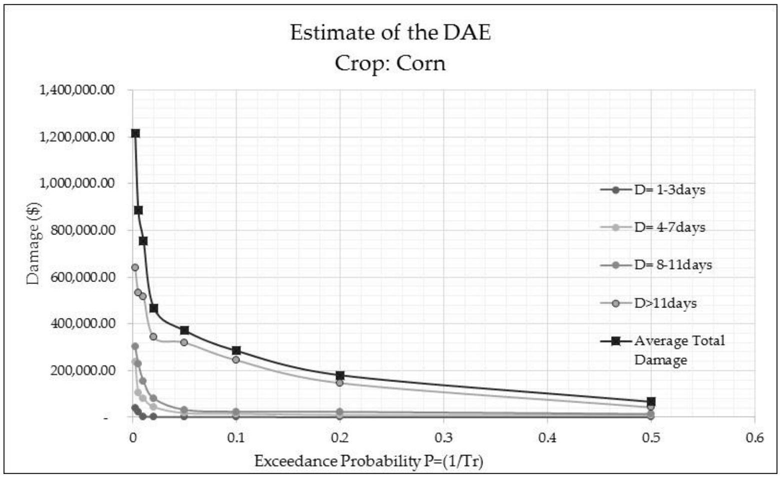


Figure 14. Annually expected damage (DAE) to crop corn.

Conclusions

In the present study, a novel methodology was applied to zones where information on the flooding of crop farms was limited, supported by two-dimensional hydrodynamic simulations. The proposed method enables the annually expected damage to be estimated, taking into account the duration, seasonality, and depth of the flood in order to construct damage functions. Due to the lack of a database on damage in the agricultural sector, criteria cited in the literature and from interviews with farmers, researchers, and officials in the agricultural sector were used as a reference. The construction of damage functions was based on a combination of the development stage of the crop and four flood duration ranges in order to quantify the effects, ranging from a small decrease in production to the total loss of the crop. With respect to the parameter of water depth, in the analysis the damage was considered to occur when the cell was wet to the maximum depth, since the damage caused by flooding starts when the oxygen in the ground decreases, which is generated by deterioration in the root of the plant, and consequently, an inadequate development and yield.

The model proposed for the assessment of crop losses was applied to the Champoton River basin, which due to its location has been exposed to various historical floods associated with the presence of hurricanes. Some of the most severe tropical cyclones recorded are *Gilberto* (1998), *Opal* and *Roxanne* (1995), and *Isidore* (2002). The results of this study are important for the flood risk assessment of the Champoton River and can be used by decision-makers in different government entities to establish better management plans as well as to adjust the costs of premiums paid for agricultural insurance.

It is important to mention that the availability of information on land use is limited, since there is no detailed typology of the crops in the zone, favoring simplifications in the methodology. However, a more detailed analysis is recommended for the crops that are grown in the region, such as sorghum, rice, soybean, pasture, and sugar cane, ones that consider more complex cropping patterns that include the rotation of crops between the spring-summer (S-S) and autumn-winter (A-W) cycles. Similarly, other elements that intervene in agriculture need to be involved in the damage estimate, for example: agricultural machinery, buildings, and silos, among others. The above implies generating more detailed information in the field at the plot level.

Finally, historical databases on damage in agricultural areas need to be improved, which would allow the results obtained to be validated. Similarly, since they are a fundamental part of estimating damage, the proposed damage functions or curves should be updated as much as possible with databases that are being generated and with experimental data.

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