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Coastal flood and damage assessment under sea level rise projections: a case study in San Francisco de Campeche, Mexico

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ABSTRACT

The city of San Francisco de Campeche, located in the Yucatan Peninsula, Mexico, is vulnerable to coastal flooding due to its geographical location and low altitude terrain. Under these inherent site conditions, sea level rise associated with climate change represents a potential threat to people's property and goods in the coming decades. In this work, three scenarios of sea level rise in the coastal area of the city of San Francisco de Campeche were evaluated through numerical simulation and using wave and wind data obtained from the ERA5 reanalysis model as inputs: astronomical tide data and a high-resolution topobathymetric model. The scenarios evaluated correspond to the periods 2031-2050, 2046-2065, and 2081-2100 reported in the latest IPCC assessment report. Damage to people's property and goods was analyzed using the CENAPRED methodology based on the type of housing. The results allow identifying that the area of the old neighborhood of San Román, Colonia Miramar, Pedro Sainz de Baranda, Adolfo Ruiz Cortinez, Resurgimiento avenues, and the Campeche-Merida and Campeche-Champoton coastal highway, as well as the federal and state government offices they will be the most affected areas by sea level rise with economic damages exceeding $13,860,322 Mexican pesos ($USD 805,832.67) under the 2031-2050 scenario, $14,706,754 Mexican pesos ($USD 855,043.83) in the 2046-2065 scenario and $22,536,250 Mexican pesos ($USD 1,310,247.09) in the 2081-2100 scenario; and the Los Petenes Biosphere Reserve as one of the ecological zones with the greatest extension of flooding; as well as downtown areas of the city that currently have residential, commercial, recreational, and port uses. Considering the three scenarios and effects on the population and housing, the 2081-2100 scenario is the one that generates the greatest flooding and with it a greater economic loss that exceeds 12 million dollars compared to the 2046-2050 scenario.

Keywords: flood risk and damage, sea level rise, numerical model, San Francisco de Campeche

Evaluación de daños e inundaciones costeras bajo proyecciones de aumento del nivel del mar: un estudio de caso en San Francisco de Campeche, México

RESUMEN

La ciudad de San Francisco de Campeche, ubicada en la Península de Yucatán, México; es vulnerable a inundaciones costeras debido a su ubicación geográfica y terreno de baja altitud. Bajo estas condiciones inherentes al sitio, el aumento del nivel del mar asociado con el cambio climático representa una amenaza potencial a las propiedades y bienes de las personas en las próximas décadas. En este trabajo se evaluaron tres escenarios de aumento del nivel del mar en la zona costera de la ciudad de San Francisco de Campeche mediante simulación numérica y utilizando como insumos datos de oleaje y viento obtenidos del modelo de reanálisis ERA5, datos de mareas astronómicos y un modelo topobatimétrico de alta resolución. Los escenarios evaluados corresponden a los períodos 2031-2050, 2046-2065 y 2081-2100 reportados en el último informe de evaluación del IPCC. Los daños a las propiedades y bienes de las personas se analizaron mediante la metodología del CENAPRED según el tipo de vivienda. Los resultados permiten identificar que el área del antiguo barrio de San Román, la Colonia Miramar, las avenidas Pedro Sainz de Baranda, Adolfo Ruiz Cortínez, Resurgimiento y la carretera costera Campeche-Mérida y Campeche-Champotón, así como las oficinas del gobierno federal y estatal serán las zonas más afectadas por el aumento del nivel del mar con daños económicos superiores a los $13,860,322 pesos mexicanos ($USD 805,832.67) en el escenario 2031-2050, $14,706,754 pesos mexicanos ($USD 855,043.83) en el escenario 2046-2065 y $22,536,250 pesos mexicanos ($USD 1.310.247,09) en el escenario 2081-2100; y la Reserva de la Biosfera Los Petenes como una de las zonas ecológicas con mayor extensión de inundaciones; así como zonas céntricas de la ciudad que actualmente tienen usos residenciales, comerciales, recreativos y portuarios. Considerando los tres escenarios y efectos sobre la población y la vivienda, el escenario 2081-2100 es el que genera mayores inundaciones y con ello una mayor pérdida económica que supera los 12 millones de dólares respecto al escenario 2046-2050.

Palabras clave: riesgo y daños por inundaciones; aumento del nivel del mar; modelo numérico; San Francisco de Campeche

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1. Introduction

In statistical terms, coastal flooding is one of the world's most common and widely distributed natural hazards that causes serious natural disasters (Balica, 2012; Peterson et al., 2013; Fernández et al., 2018; Bakkensen & Blair, 2020). Since most coastal areas are exposed to extreme hydrometeorological phenomena and the pressure exerted by anthropic developments on them, with low-lying coastal areas being the most vulnerable to negative effects (Church et al., 2014; IPCC, 2019; Losada et al., 2020; Fernández et al., 2022).

Under the context of climate change, sea level rise exacerbates the danger of flooding that extreme hydrometeorological events represent for coastal areas, so it is expected that, in the coming decades, coastal floods will be more devastating and costly (IPCC, 2021). From the Special Report on the Ocean and the Cryosphere in a Changing Climate (IPCC, 2019) it was established that if the current rate of greenhouse gas emissions is not reversed, the collapse of the ice masses will be inevitable and the increase in the level of the sea will affect more than 680 million people who live in coastal areas of the world. Although the IPCC Report (2019) highlights Asian countries such as Thailand, Indonesia or Bangladesh as those most affected by sea level rise; In Mexico, the latest Intercensal Survey of the National Institute of Statistics and Geography (INEGI) estimates that approximately 55 million people living on the coastal zone of the country will be affected by the rise in sea level in the coming decades, being The Campeche coastline is one of the most compromised (Climate Central, 2021) due to its low altitude, the physical conditions of its coast and the potential damage.

In this sense, floods associated with sea level rise represent a strong threat to the exposed coastal population, housing and service infrastructure, related economic activities, coastal ecosystems, and the loss of their environmental services (Kopp et al., 2016; Adeel et al., 2020; Fernández et al., 2022). Therefore, the assessment of potential flood-related damage is a key requirement in coastal zone planning and management (Bates et al., 2005; Hallegatte et al., 2011; Gallient et al., 2014; Seenath, 2015; Seenath et al., 2016; Gallient, 2016; Rey et al., 2020), and takes special relevance to establish plans for urban development, disaster prevention, emergency response and management and recovery strategies, especially in areas with strong environmental and economic importance, such as Campeche. However, first, it is necessary to identify the potential areas to be flooded and characterize them based on the population, type of infrastructure, economic activities, present ecosystems, loss of environmental services, etc., depending on the approach (environmental or socioeconomic). This allows us to better understand the possible consequences of floods on local and regional economies, estimate the comprehensive cost of such disasters, and provide baseline information that contributes to the development of prevention and action strategies.

Therefore, this work presents the results obtained from the identification, quantification, and evaluation of flood-prone areas and damage caused to homes and household goods in the City of San Francisco de Campeche (CSFC), capital of the state of Campeche and a city which has had economic growth due to activities related to its coastal area, which have historically demanded modifications on the beachfront, such as filling land reclaimed from the sea and port, tourist and housing development that has been established at topographical levels. low and prone to flooding. The results represent three sea level rise scenarios coupled with predominant sea states simulated with a two-dimensional numerical model and the potential economic damages in the areas identified as flood-prone.

Although previous studies have been carried out that address the issue of flooding in the coastal area of Campeche (Palacio et al., 2005; Posada et al., 2012, 2013), the quantification and evaluation of areas prone to flooding and the economic loss due to damage to homes and household items under scenarios of sea level rise is non-existent at the moment, so this work contributes to the generation of said base knowledge for decision making.

2. Materials and Methods

Study Area

The city of San Francisco de Campeche (CSFC), capital of the state of Campeche, is located in southeastern Mexico, in the western portion of the Yucatan Peninsula (Figure 1). Given the geographical location of Campeche in the Yucatan Peninsula, it is under the imminent threat of flooding, especially during the passage of high-pressure cold fronts, locally called "Nortes", as well as tropical cyclones (Rey et al., 2020). ; since during the passage of these hydrometeorological phenomena, the disturbances in atmospheric pressure and the stress of the wind on the sea surface cause extreme waves and rises in sea level along the coast; the above, combined with the low topography and very gentle slope that induces an increase in exposure and physical vulnerability of the system (Enríquez et al., 2010).

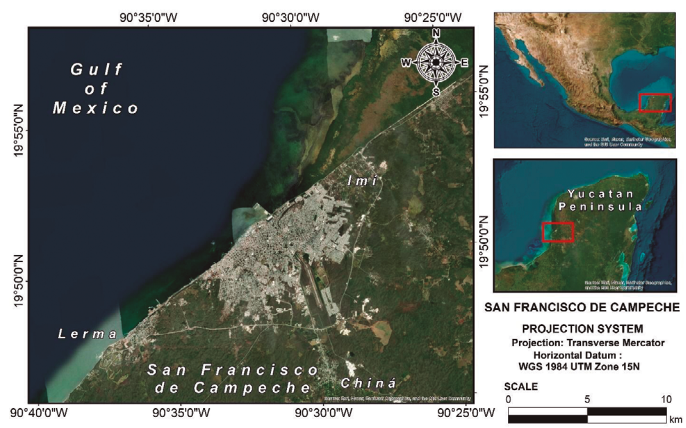

Figure 1. San Francisco de Campeche localization

The CSFC has a territorial area of 3,410.64 km^2, which represents 6% of the state (INEGI, 2020). According to the 2020 population and housing census (INEGI, 2020), the city has 86,048 homes and 294,077 people who carry out activities related to its coastal areas, such as tourism, food services, and fishing. This city has a port terminal (dock) oriented towards recreational activities, nautical tourism, and commercial and sport fishing in which a large part of the population works. Along the city's coast, there are various beaches, fishing ports, and arrival docks, such as Playa Bonita, San Román port, and the arrival dock to the city's water park, as well as the arrival port of the Secretary of the Navy VII Naval Region, the Lerma fishing industrial unit and the port of the Country Club and Nautical and Sports Club, to mention a few (Figure 2). In addition, the city has infrastructure of great historical importance that is located in a coastal area, since the CSFC was a walled city that, currently, has historical buildings that represent economic income for locals through tourist activities. Most of the main economic activities carried out in the CSFC depend on the coastal zone, which is why the various sectors of the city's coastal zone gain social and economic relevance.

a) Campeche Nautical and Sports Club, San Francisco de Campeche, Campeche.

b) Campeche Country Club, San Francisco de Campeche, Campeche.

c) Playa Bonita, San Francisco de Campeche, Campeche.

d) San Francisco de Campeche Dock, Campeche.

Figure 2. Representative sites of the CSFS coast.

Historical wave and wind data and tide

To characterize the prevailing wave and wind conditions in the CSFC coastal zone, historical and robust time series of waves and wind were analyzed for the period from January 1979 to December 2021 taken from the ECMWF v5 (ERA5) reanalysis model, a 5th-generation model that provides hourly estimates of various atmospheric variables. The time series is composed of hourly data for a point in deep waters at 20 km from the analyzed coast (19.97° N -90.69°W). Figure 3 shows the data of the wave parameters (significant height (a), peak period (b), and direction of incidence (c)) obtained for the mentioned period. These data were analyzed using statistical methods focused on establishing the average annual and extreme (storm) conditions (regime). The above allowed us to establish a value of 1.5 m wave height as the storm threshold in the region (Figure 3e). The wave parameters selected as predominant in the medium regime are a wave height of 0.5 m, a peak period of 6 seconds, and an incidence direction of 22.5° (Figure 3d). In the case of wind, the predominant values in the medium regime are a speed of 6.5 m/s and a direction of 292.5° (towards where the wind is directed) (Figure 4c), and in storm conditions speed of 10.65 m/s and direction 292.5° (Figure 4d).

Tidal conditions were obtained from data records of the global tidal model development by DTU Space (DTU10) representing the main diurnal currents (K1, O1, P1, and Q1) and semidiurnal tidal components (M2, S2, N2, and K2) with a spatial distribution of 0.125° x 0.125° resolution based on TOPEX/POSEIDON altimetry data (data applied at 20 m depth). The Admiralty Method was used, which explicitly considers the four principal components M2, S2, 01, and K1 and allows corrective factors to consider the effects of a series of astronomical components generated in shallow water.

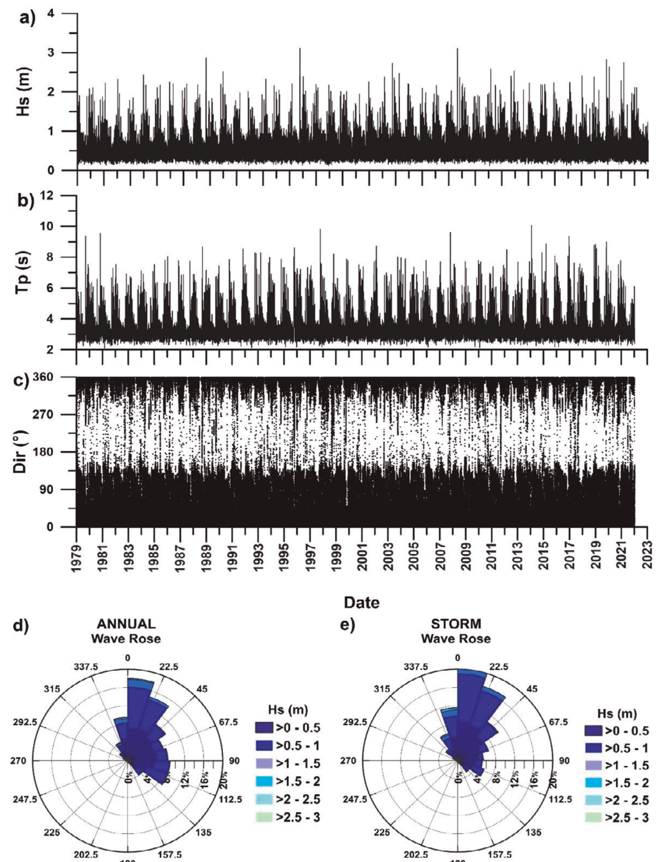

Figure 3. Wave characterization on the coast of Campeche, period 1979-2021.

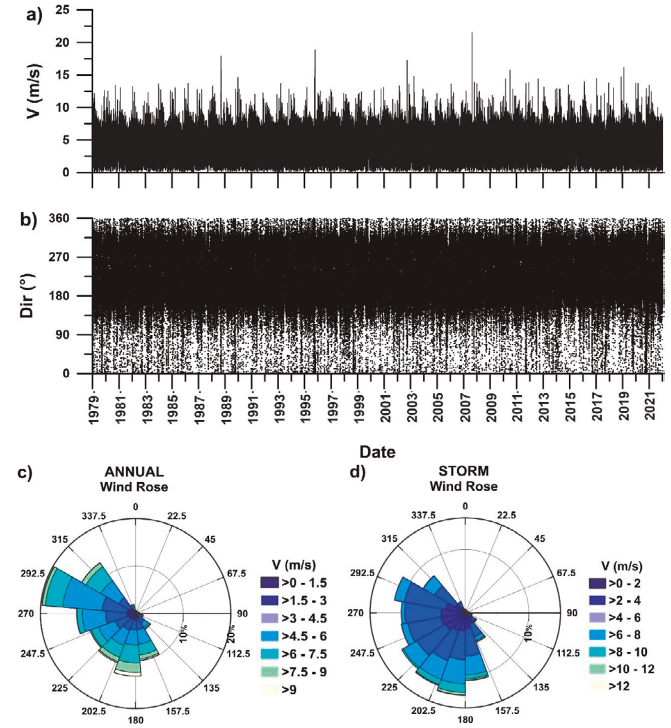

Figure 4. Characterization of the wind on the coast of Campeche, period 1979-2021.

Topo-bathymetric survey and Numerical Modelling

To represent the topographic and bathymetric terrain of the study area, a digital topobathymetric model was generated from the union of LiDAR data with a horizontal resolution of 5 m obtained from official INEGI bases and digitized data from a nautical chart obtained from the base world C-Map. Data joining was performed using geoprocessing tools (Figure 5a). From this model, a flexible mesh was generated with three open borders and one land border. The mesh is composed of 177,956 elements and 89,270 nodes, where the minimum cell resolution is 7 m^2 and the maximum is 72,262 m^2 (Figure 5b).

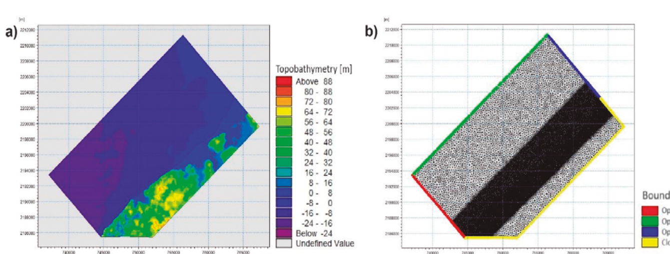

Figure 5. Topobathymetric model (a) and flexible simulation mesh (b).

The Sixth Assessment Report on Climate Change of IPCC (AR6) assumes that sea level rise scenarios worsen the threat of flooding in coastal areas around the world. The AR6 is based on five shared socioeconomic pathways (SSP), which are scenarios of global socioeconomic changes projected until the year 2100 and that are related to greenhouse gas emissions under different climate policies. The scenarios are named SSP1, SSP2, SSP3, SSP4 and SSP5; the latter is the most unfavorable scenario since it assumes that markets are very competitive and integrated, with enormous exploitation of fossil fuels and the adoption of resource and energy intensive lifestyles. Here we use the SSP5 scenario under three-time horizons 2031-2050, 2046-2065 and 2081-2100 (called scenarios), for each scenario the projected increase in sea level was identified (Table 1). Hydrodynamic numerical simulations were carried out to understand the behavior resulting from the coupling of the established wave, wind and tide conditions that are the main forcing in the numerical model, and each of the three projected sea level rise scenarios.

Table 1. Sea level rise scenarios considered in numerical simulations.

Horizons	Sea level rise projection (m) SSP 8.5
2031-2050	0.26
2046-2065	0.4
2081-2100	0.92

The topobathymetric model and sea level rise scenarios, in conjunction with the predominant states of waves, wind, and tidal data described in the previous section, were used to feed a state-of-the-art two-dimensional numerical model that solves the equations of conservation of mass and momentum; allowing to specify the variety of boundary conditions, initial conditions and forcing (tide, wind, and waves), which allows simulating variable flows in two horizontal dimensions and a single vertical layer and reproducing flooding conditions on the coast. Simulations were carried out for each scenario established for each time horizon. Subsequently, the results of the numerical simulations were migrated to a geographic information system that made it possible to identify flood zones. From the results of the numerical simulations, the minimum, average, and maximum values for the surface variables of elevation, direction, and current speed were obtained. The maximum values obtained were considered the most unfavorable conditions that may occur in the area and with them, maximum flood maps were generated for each scenario.

For this work, the increase in sea level was considered as a constant value of increase with which the tide height was affected, likewise for the wind and wave data, the data projected for the years 2050, 2065, and 2100 were used, extreme years of the periods considered.

Flooded areas and Loss quantification

An approximation was made to the number of inhabitants directly affected, as well as the quantification of the loss due to household goods in the flooded areas for each simulated scenario.

For this, the floodable areas resulting from the numerical simulations were identified, and taking information from the AGEB (INEGI, 2020) in the study area, the flood area was quantified in hectares by applying geoprocessing tools. An AGEB is defined as a geographical area occupied by a set of blocks (minimum unit) perfectly delimited by streets, avenues, walkways, or any other easily identifiable feature on the land and whose land use is mainly residential, industrial, services, businesses, among others, and are only assigned to the interior of urban areas, identified as those with a population greater than or equal to 2,500 inhabitants (INEGI, 2020).

In the AGEB identified as flood-prone, based on data from the Population and Housing Census (INEGI, 2020), the number of homes and people living in each affected AGEB was quantified. The information was analyzed using geoprocessing tools that made it possible to characterize the flood zones at the block level and the total number of people and homes exposed.

The approach to damage to household items was quantified based on the study carried out by the Autonomous University of Campeche (UACam) together with the State Emergency Center (CENECAM) in 2015; in this study, the average costs of damage to household goods caused by floods were obtained for different housing models classified based on the material used for the construction of walls and roofs. Table 2 presents the characteristic housing models for the entire state of Campeche; specifically for the coastal area of San Francisco de Campeche, the characteristic type of housing is type No. 1, in which the wall and roof are made of partition due to the type of economic activity and capital gains in the area (Posada et al., 2015).

Because the values of the cost of damage to household items presented in Table 2 are adjusted to the year 2015, in this work they were updated for the year 2022; for each year, annualized inflation was used, the cost of the previous year was considered and the inflationary increase in the cost was added, thus obtaining the cost of household items for the current year (Table 3). For the year 2022 amounts to 112,505.60 Mexican pesos (which is equivalent to $USD 5,625.28) for the housing model characteristic of the coastal area of the city.

Table 2. Housing models for Campeche (derived from CENECAM, 2015)

Model No.	Wall	Ceiling	Cost for 2015 (mexican pesos)
1	Partition	Concrete	$80,312.50
2	Partition	Roof tile	$48,677.50
3	Partition	Galvanized sheet	$48677.50
4	Partition	Wood	$106,130.00
5	Wood	Roof tile	$39,682.50
6	Wood	Galvanized sheet	$34,107.50
7	Wood	Wood	$21,377.50
8	Wood	Straw	$19,932.50
9	Galvanized sheet	Galvanized sheet	$38,075.00
10	Galvanized sheet	Wood	$3,770.00

It is important to mention that, in this work, only direct damage to household goods is considered for model No. 1 and the damage or indirect losses caused by the closure of roads, stoppage of economic activities, deaths, and damages are not quantified psychological, etc.

Table 3. Update of the cost of damage affected by annual inflation

Year	Annual inflation	Cost mexican pesos	Cost Dollar (exchange of 17.2 pesos per dollar)
2015		$80,312.50	$4,669.33
2016	2.82	$82,577.31	$4,801.00
2017	6.04	$87,564.98	$5,090.98
2018	4.9	$91,855.67	$5,340.44
2019	3.64	$95,199.21	$5,534.83
2020	3.4	$98,435.99	$5,723.02
2021	5.69	$104,036.99	$6,048.66
2022	8.14	$112,505.60	$6,541.02

3. Results

The coastal zone of the city of San Francisco de Campeche was divided into three zones to represent the flood results for each scenario. These areas correspond to: Petenes – Imi (northeast), Historic Center – August 7 (center) and Lerma (southwest).

For the 2031 – 2050 scenario, the maximum flood depth reaches 2 m, mainly in the area northwest of the city, known as Los Petenes; In this area, a portion of the Biosphere Reserve of the same name is identified, as well as housing units; while in the area of the boardwalk, which is tourist, the flood depth does not exceed 50 cm; with the exception of the area known as August 7, an area with commercial and residential activity, where the flood depth reaches values close to 1.5 m (Figure 6c). In the Lerma area the flood does not exceed 20 cm.

For the 2046 – 2065 scenario, the maximum flood height corresponds to 2.5 m. The difference with the previous scenario is that the extent of flooding increases, presenting greater impact in the mangrove area of Los Petenes and the first square of the residential area Imi (Figure 7b). Under this scenario, in the seawall area the depth is increased in the range of 0.5 m to 1.0 m; likewise, the extension of the flooded area increases and moves to the area known as "El Nuevo Campeche", which corresponds to the area of the historic center bordering the sea, where a depth of up to 0.5 m of flooding is observed. The natural drainage "La Ría" overflows and the water move between the Francisco I. Madero roundabout and the so-called "Puente", very close to the August 7 area. In the Lerma area the water column increases up to 0.50 m, due to the high terrain (Figure 4d).

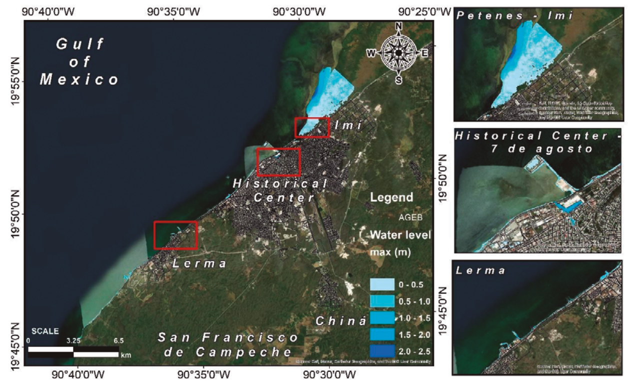

Figure 6. Surface elevation 2031 -2050 scenario. a) General map of the city, b) Petenes - Imí area, c) Historic Center area and part of August 7 and d) Lerma area.

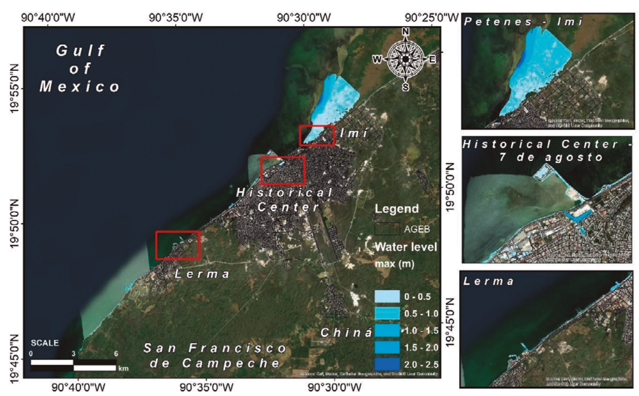

Figure 7. Surface elevation 2046 - 2065 scenario. a) General map of the city, b) Petenes - Imí area, c) Historic Center area and part of August 7 and d) Lerma area.

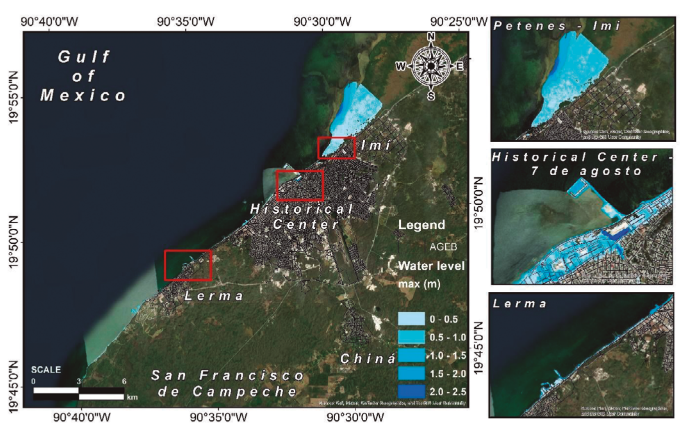

Figure 8. Surface elevation 2081 - 2100 scenario. a) General map of the city, b) Petenes - Imí area, c) Historic Center area and part of August 7 and d) Lerma area.

While for the 2081 – 2100 scenario the flood height is greater than the 2.5 m predominant in the Los Petenes area, here a greater intrusion of the sea is observed. The average height of the tie ranges from 2.0 m. It is in this area where a flood of the population center called Imí (Figure 8b), Fidel Velázquez and Palmas can be seen with heights of up to 1.5 m; likewise, federal highway

180 (the only access to the city through this quadrant) is flooded with heights of up to 1.0 m. With respect to the boardwalk area, a height of up to 1.0 m is observed. The area of August 7 and the so-called "La Ría" presents flood levels above 3.0 m. The flooding in the city occurs in the so-called "Campeche Nuevo" with flood heights ranging in some areas from 0.5 m to 1.5 m (Historic Center); likewise, it is observed that the structure of the Dock is completely flooded due to a level of 1.5 m. At the other end of the city, in the population center of Lerma, the port infrastructure is affected due to the flooding of the docks, with heights close to 0.65 m. Likewise, the Campeche Country Club tourist complex is affected coastal zone due to flood levels that range between 0.80 and 1.0 m.

Of the 3 scenarios analyzed, it stands out that the 2018 – 2100 scenario is the one that represents the greatest amount of economic losses directly. For the first scenario (2031 – 2050) the number of affected houses amounts to 131, which is equivalent to an area of 323 hectares flooded and damage to household goods in the amount of $13,860,322 Mexican pesos (which is equivalent to $USD 805,832.67).

The 2046 – 2065 scenario generates a direct economic loss of $14,706,754 Mexican pesos (which is equivalent to $USD 855,043.83), affecting 139 homes that represent an affected area of 330.73 hectares. The 2081 – 2100 scenario affects an area of 376.30 hectares with damage to 213 homes that represents an economic loss of $22,536,250 Mexican pesos (which is equivalent to $USD 1,310,247.09).

Another important parameter in the analysis of floods is related to speed; Indirectly, the speed influences the flooding speed. Regarding speed, it is observed that the 2081 - 2100 scenario is the one with the highest current speed; however, occasionally in the 2031 - 2046 scenario there is an area that reaches up to 2.5 m/s (area with a large slope in which a valley is formed), while in the 2031 - 2050 scenarios the average speed oscillates between 0.36 to 0.40 m/s in the dock area (green color) and for the 2046-2065 scenario the current speed increases slightly in the same area, reaching values between 0.40 and 0.44 m/s. Compared to the 2031 - 2046 scenario, in 2056 - 2065 a larger area is identified with speeds greater than 0.50 m/s and predominates in the dock area, towards the northeast (Figure 9b). For the 2081 - 2100 scenario, the speed reaches maximum values of 0.60 m/s and the highest values occur from the Los Petenes area to the so-called Aquatic Park following the coastline to the southwest (Figure 9c).

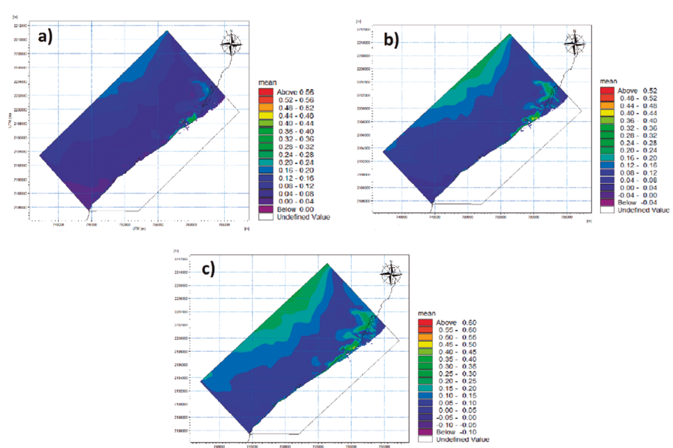

Figure 9. Current speed: a) 2031 - 2050 scenario; b) 2046 - 2065 scenario; c) 2081 - 2100 scenario.

4. Discussion

Over the years, the coastal area of the city of San Francisco de Campeche has gone from residential to commercial use; Currently, the city's boardwalk represents the focal point not only in terms of real estate but also for the commercial, tourist and recreational activity of the city. During the 20th century there was a substantial change in the infrastructure of the coastal area, around 1962 a process of filling in the coastal area began (in front of the old seawall) whose main land use was focused on the commercial and tourist sphere; and the housing area expands to the west (town of Lerma).

Towards the east of the city, an expansion of the urban area begins, currently called the Palmas e Imi housing unit. By 1977, the filling continued in front of the area called the Historic Center in the "Puerta de Mar" section and the area near the town of Lerma.

By the 90s, the infill areas continued urban development, increasing the commercial area and the development of residential areas, such as the expansion of the Palmas and Imi areas.

This urban expansion has generated a development of the CSFC whose economy depends directly on the coastal zone; The loss of this area due to flooding must be studied in greater detail and incorporate other variables such as soil type and include among the analyzes the indirect damages generated by flooding, that is, those damages that could be generated indirectly by the stoppage of activities, closure of roads, among others, and which can be much greater than the direct damage. The methodology used here has been replicated in other coastal areas worldwide, since the strategy of building scenarios defined by factors of change in sea level applied to simulation models is applied, as indicated by Wang et al., 2018.

Numerical simulations have been performed in many coastal areas of the world evaluating changes in hydrodynamics and other factors such as those performed by Ranjbar et al. 2018 y Ranjbar et al. 2020 in Gorgan Bay, Iran and Hong et al., 2020 in Pearl River Estuary, China. These studies have shown that sea level rise will increase the frequency and intensity of coastal flooding as noted Wang et al., 2021; Hunter et al., 2013; Marsooli et al., 2019; Marsooli et al., 2020 and Rasmussen et al., 2018. In San Francisco de Campeche, a study that includes numerical models and sea level rise has not been developed; the above is consistent with what was reported by Mohd et al., 2018 who points out that in tropical countries little attention has been paid to the possible hydrodynamic changes due to the effects of the SLR.

Identifying the number of inhabitants that could be affected, the number of homes that could be damaged and the cost of this damage, is basic information that is required to understand the effects of changes due to flooding associated with sea level rise and is essential to formulate strategic risk reduction plans for coastal flooding as indicated Wang et al., 2018. Considering both the demographic explosion and the indirect damages would increase the cost of the damages generated, this analysis must be more robust, being able to adapt the integrated flood risk analysis framework to calculate the total economic damages (direct and indirect) with different socioeconomic developments proposed by Yin et al., 2021.

On the other hand, different methods could be applied to evaluate the risk of flooding and the damage caused in a coastal area, as carried out by Rey et al., 2020 in Progreso, Yucatan; in their study they applies the method proposed by the National Center for Disaster Prevention (CENAPRED) of Mexico and used by the Mexican government, based on the values of economic assets (household goods) and flood impacts (similar to the method used here); the CENAPREDv2 method and the FRI method, which are methods to evaluate risk that include 17 socioeconomic indicators. The application of the methods will depend on the specific interest of the risk assessment; for example, identifying where the greatest economic impacts will occur, knowing both economic damages and socioeconomic aspects or mapping the most vulnerable population considering important elements such as mobility, communications or others.

The affected area ranges from 322.91 ha, 330.73 ha and 376.30 ha for each scenario respectively. The Los Petenes area, the 7 de Agosto Pier and the boardwalk near the San Román neighborhood are among the most affected in the third scenario; these areas belong to the filling area that was carried out between 1960 and 1970. Around 2018, the modernization of the boardwalk of the City of San Francisco de Campeche began, so filling was carried out in various sectors where playgrounds, water parks, light sources, as well as statues and monuments and commercial areas of the food industry; all these works should consider the effects of sea level rise, as well as the impact of hydrometeorological phenomena.

Special attention should be dedicated to the Los Petenes area, since being a Biosphere Reserve, the loss of this coastal ecosystem would negatively impact others, which could start a domino effect, putting at risk the loss of different coastal ecosystems, increasing the risk of coastal erosion, the loss of socio-ecosystem services and the increase in flooding as indicated Keyzer et al., 2020.

5. Conclusions

Floods due to an increase in the average sea level in the City of San Francisco de Campeche are imminent. The number of homes and population directly affected by the flood is low compared to the entire city. However, due to the economic activities carried out in the area, economic losses will increase considerably.

The "Los Petenes" Protected Natural Area will be considerably affected by direct contact with the sea, altering its dynamics and the ecosystem services it offers; the loss of these services and its impact on the local and regional economy must be quantified; likewise, changes in dynamics must be evaluated to determine the impact on the ecosystem.

San Francisco de Campeche, due to its topography, is vulnerable to changes in the elevation of the sea level surface; however, actions can be carried out that allow adaptation to these future modifications that may occur in the coastal zone.

The greatest economic loss occurs in the 2081 – 2100 scenario with a value of $22,536,250 Mexican pesos.

Finally, it is necessary to carry out multivariate analyzes where conditions of meteorological events such as storms and hurricanes are implemented, as well as their effects, such as storm surge; since these conditions will generate even more unfavorable scenarios that will increase flood spots and thus greater direct and indirect economic loss; as well as a greater alteration to the coastal dynamics and the mangrove ecosystem. Likewise, form multidisciplinary groups that allow specialized studies to be carried out to analyze ecosystem and biodiversity changes.

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