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## Research Article

### Use of Hydraulic Models for the Solution of Sanitary and Pluvial Problems: Case Study Chetumal, Quintana Roo, Mexico

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#### Abstract

The city of Chetumal, located in Quintana Roo state has complex sanitary and pluvial systems that make their improvement and revision difficult, creating a representation of current of current system behavior conditions would allow for the proposal of measures conducive towards a better overall response.

Currently, carrying out a hydraulic analysis requires the use of programs (SWMM, PCSWMM, INFORWKS, CIVIL CAD, ETC) that employ different scenarios in search of the best hydraulic solution. In this article, the case study for the city of Chetumal is described wherein two methodologies for hydraulic analysis are used within a sanitary and pluvial system.

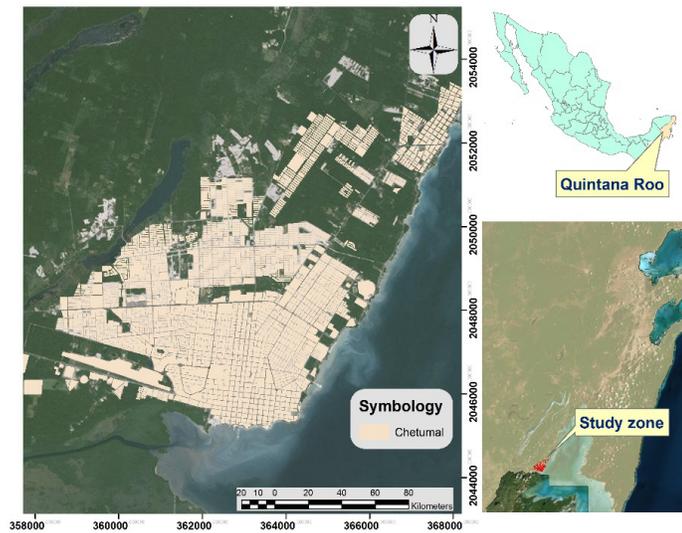
The methodology used for pluvial drainage analysis permits flood studies to be carried out in urban zones, each input is developed to construct a hydraulic model that generates flows and velocities for each rainfall linked to a return period. This information is then used to create hazard maps as well as vulnerability maps for the zone being studied to calculate structural damage costs for different rainfalls linked to a return period.

In the case of sanitary systems, the need for data gathering is described, water flow at each pumping station is calculated with the purpose of discovering how the system works, it is foreseen that in order to discharge the treatment plant, the system requires a regulation tank with a volume of 847 m<sup>3</sup>

**Keywords:** Control works; Hydraulic models; One-dimensional model; Pluvial drainage; Sewer drainage

#### Introduction

The city of Chetumal, Quintana Roo, is the head of the Municipality of Othón P. Blanco located between the coordinates 18° 30' 13" N and 88° 18' 19" (Figure 1), according to data from the INEGI [1] for the year 2015, the municipality has 224,080 inhabitants. Due to its geographical position, it is vulnerable to the arrival of hurricanes and tropical depressions; it has a rainfall problem that has grown in recent years due to the disorderly growth of urban areas.



**Figure 1:** Macrolocalization and Microlocalization.

For this reason, the Mexican Institute of Water Technology (IMTA) has worked with the Drinking Water and Sewerage Commission (CAPA) of Chetumal since 2013 to better understand the pluvial and sanitary problems in the zone and, in turn, propose measures permissive of a better operation of the two systems.

The aforementioned problems are worked on at the IMTA using hydraulic models that describe current operations and proposing measures to improve the operation of the hydraulic-pluvial and sanitary infrastructure.

Regarding these two problems, it has been observed that the city has had an accelerated population growth which has contributed to the construction of homes, roads, public spaces, hotels etc., for residents and visitors. This increased urbanization has given rise to greater impermeability in the zone, which in conjunction with the water table level, contributes to the generation of water logging and flooding in the zone. (Llaguno et al, 2016).

According to the MAPAS manual [2] each hydraulic system can be understood by dividing it according to the type of flow transport, as such, the pluvial system is that which is responsible for the direction of the superficial water, product of the rain, hail, snow, etc., to the point of expulsion. The sanitary sewerage system, on the other hand, has the objective of transporting water used by domestic, commercial or industrial services to a discharge point.

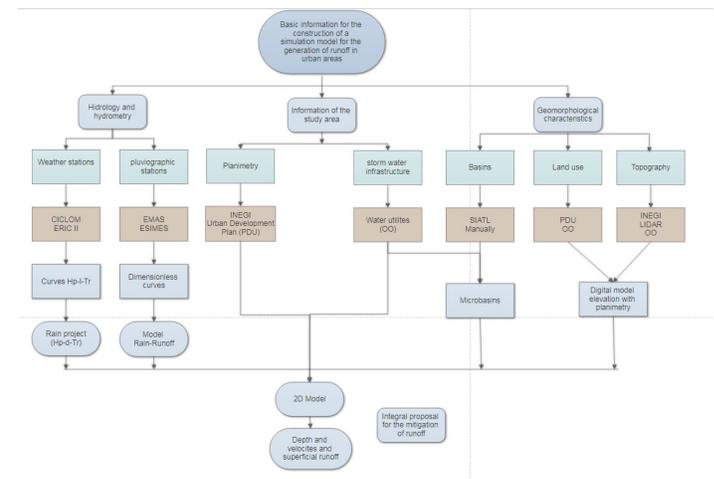
## Materials and Methods

### Rainfall System

The method used for the rainfall analysis in the study is based

on the indications given by Rodríguez et al., [3], where a system is given for flood analysis in urban zones and is adaptable to different geographic zones of the Mexican Republic. The analysis is based on five principal points (Figure 2):

- a) Hydrological and hydrographic analysis.
- b) Physical information of the study area.
- c) Geomorphology of the micro-basins.
- d) Hydraulic modeling (2D model).
- e) Design of urban drainage

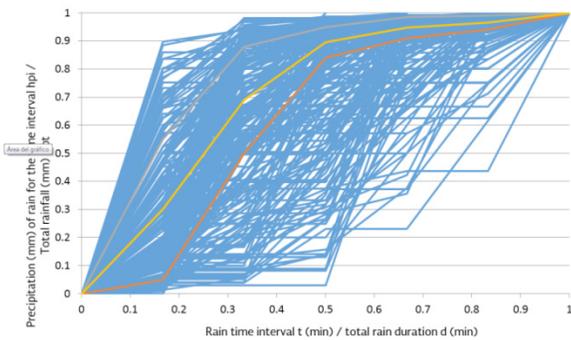


**Figure 2:** Methodology for the proposal of the mitigation of flooding in urban zones [3].

### Hydrological analysis

Nine rain-gauging stations were used for the hydrological analysis of the zone which had a set of data that was more than 12 years old. The rain-intensity graphs were taken based on the data gathered by the IMTA in 2012 using ERIC III V2.0 criteria (Program that provides daily rainfall information from the different weather stations in Mexico), the data missing from the set was corrected to later get a relation between precipitations and return periods through a function analysis of probability distribution.

To know what the temporal distribution of rain is, an Automatic Meteorological Station (AMS) is used to log data every 10 minutes for different parameters, the AMS that was analyzed is located to the south of the airport of Chetumal (Figure 3). Hence, it is necessary to calculate the rainfall average that is more recurrent in Chetumal. This rainfall is used to determine the rainfall designs. The following are extracted from analysis:

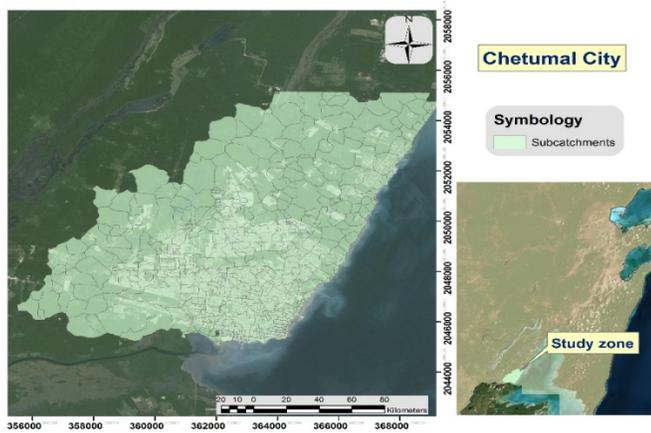


**Figure 3:** Rainfall accumulated for each rainfall (one-dimensional) with duration of less than 60 minutes and more than 30 minutes (IMTA, 2013).

### Hydrographic analysis

It is important to know and plot the tributary micro-basins to characterize the study zone, for this, the Rodríguez et al [4] methodology is taken as a reference in which the systemization of the procedure for the generation of micro-basins is described. These are determined through the construction of a Digital Elevation Model, an urban zone planimetry that will give the core lines of the current through a process that will be described shortly.

Ultimately, 674 tributary micro-basins were identified (Figure 4).



**Figure 4:** Tributary Micro-basins.

### Physical information of the study zone

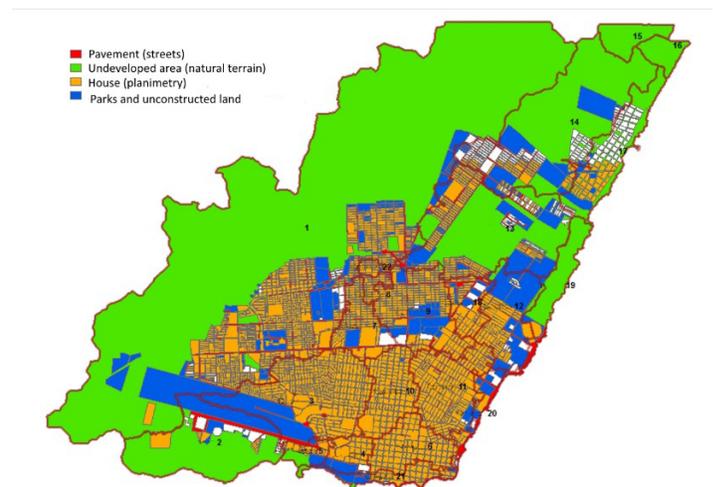
Understanding Chetumal's surrounding area requires knowledge of key sites, which can be generated using the data found in the AGEBA (Geostatistical Base Area) from the National Institute for Statistics and Geography (INEGI); this data helps to identify such sites as well as establish the names of channels (Figure 5) along with the boundaries neighborhood with which 139 neighborhoods were identified.



**Figure 5:** Streets in the city of Cancún, Quintana Roo.

### Geomorphology of the sub-basins and micro-basins

A study carried out by the IMTA (2013) identified the land use in the zone, which is divided into 4 categories, street pavement, undeveloped areas made up of natural land, the homes indicated in the planimetry blueprint and the parks and undeveloped lots without construction within the urban area indicated as Parks and Fallow land (Figure 6).

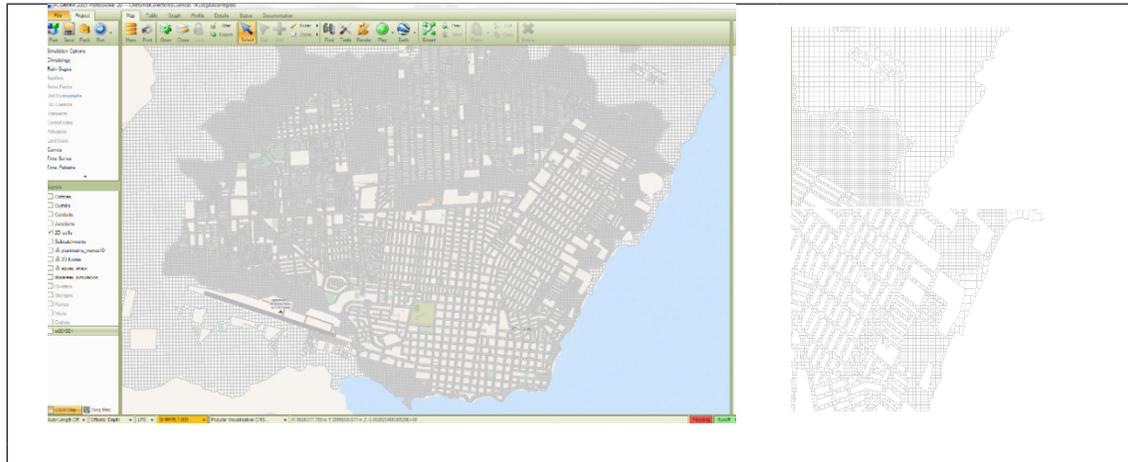


**Figure 6:** Land Use (IMTA, 2013).

### Hydraulic modeling (2D modeling)

Hydrological and hydrographical data derived from the physical information of the study zone and the profiling of the sub-basins and micro-basins are vital components for the construction of a two-dimensional drainage model. An irregular calculation net was used outside of the study area to make processing time more

efficient in places where specific details were not required, a rectangular net was used for the urban zone and, hexagonal nets of 50 by 100 meters (Figure 7) were used for the other zones of the two-dimensional model with the results (flow and flow depths) plotted for different return periods to make hazard maps. Obstructions (housing areas) were taken into account.

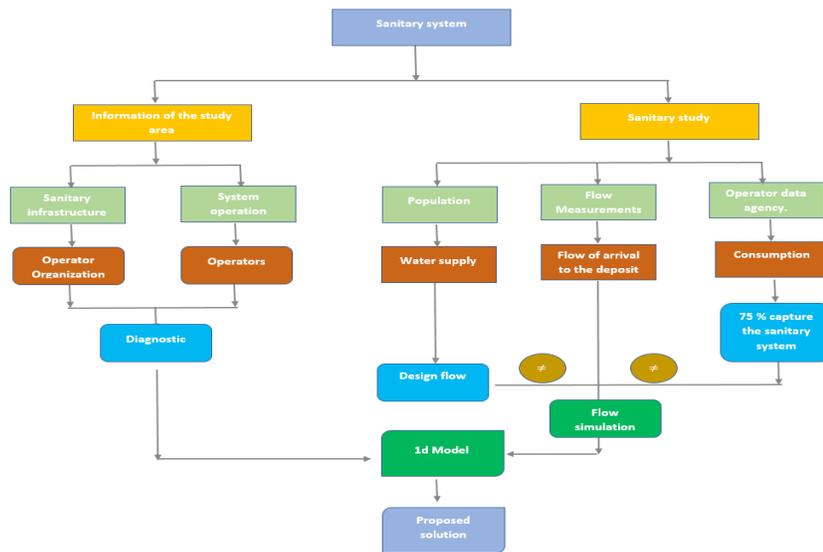


**Figure 7:** Cell forms used in the mathematical model.

In knowing the flow depth and velocities that will arise in the study zone, current conditions are represented under different scenarios (rains for a return period of 10, 25, 50 and 100 years) which, afterward, will suggest an alternative solution.

### Sanitary Drainage Design

For the year 2015, Rodríguez et al. [4], proposes a way to deal with the problem of the sanitary drainage system through two principal precepts:



**Figure 8:** Development for a hydraulic model of a sanitary drainage.

### Physical of the study zone

The sewerage system of the city of Chetumal consists of two types of sewerage, one is of the conventional pressurized type and the other is of the vacuum type (Figure 9). Fifteen pumping stations are used for the conventional system and the remaining 3 are used for the pressure system. The flow of wastewater goes through pumping stations and pressure emitters until arriving to the treatment plant.

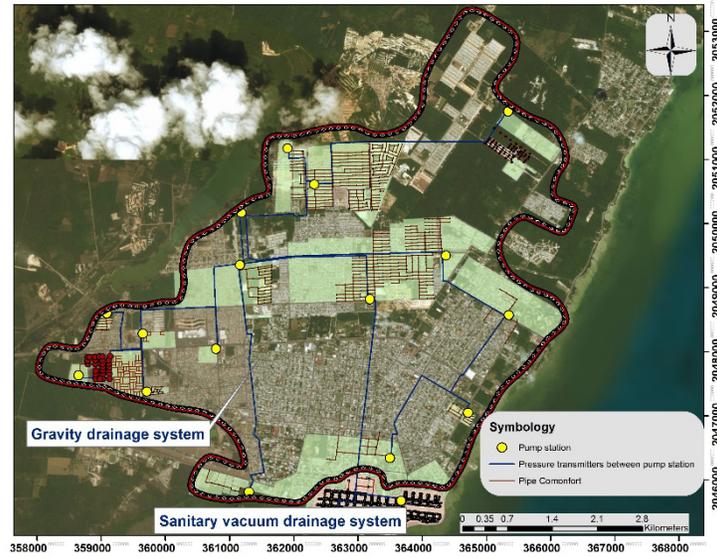


Figure 9: The Chetumal sanitary drainage system.

Field trips were organized to better know the form and dimension of pumping sumps which helped determine their storage volume. (Figure 10).

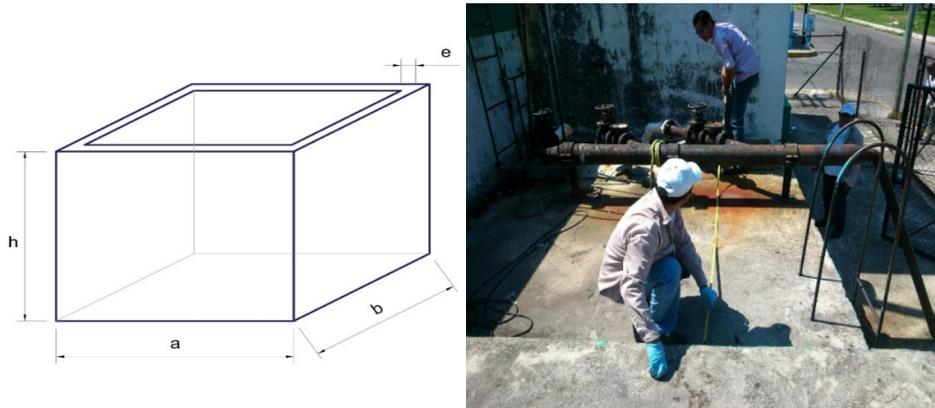


Figure 10: Measurement of the pumping sumps in the city of Chetumal.

Upon exploring each pumping sump, the number of sumps and brand type of the pumping equipment was documented with the idea of assigning a pump curve from the provider data (Figure 11).

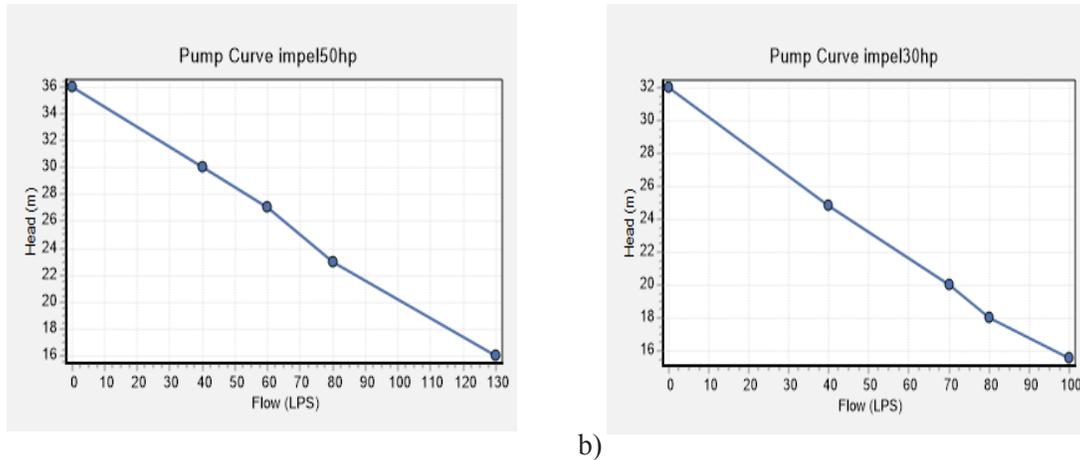


Figure 11: Pump Curves from pumping sump no. 4.

Moreover, a field trip was arranged to know the diameter, material, height of the sewer manholes, and the general conditions in some neighborhoods that have a sanitary network.

### Operating schedule for pumping sumps

As part of knowing the workings of the integral system, inspections were carried out at each pumping sump to determine the schedule in which the pump is on (active) and off (inactive) and the daily intervals with which this work program is carried out. Some pumping sumps like the “Comonfort” operate based on these levels, that is to say, after a certain level is reached, the pump is activated and when the flow depth drops below a certain point, the wastewater pump turns off.

For example, to drain the wastewater in pumping sump no. 8 there are two sets of pumping equipment, of which, one is in service. The brand of the equipment is “Impel” and it has 60hp. It operates in manual mode and there are three operation shifts, Table 1 shows the operating hours for the equipment according to shift. On sunny days the pumping is done during 15 to 20 minutes when the pumping sump reaches 80% capacity.

1	12:00 a. m.	12:20 a. m.
2	02:00 a. m.	02:10 a. m.
3	05:30 a. m.	05:50 a. m.

Table 1: Manual operation mode for pumping sump no. 8.

- Calculation of sanitary outputs

### Design outputs according to the MAPAS

According to the Drinking Water and Sanitation Manual (MAPAS, 2015) there is a process with certain guidelines to determine the design output, through population projects, areas of influence, average costs, minimum, instant maximum and extraordinary maximum.

Where:

$Q_{Max}$  = Maximum extraordinary wastewater cost in L/s

$Q_{Minst}$  = Maximum instantaneous wastewater cost in L/s

CS = Safety coefficient

### Measurements

Measurements were done with an ultrasonic measuring device that establishes the flow that discharges into each of the emission points of the sumps in order to know the behavior of each sump.

### Outputs by area of influence

Through the intakes of the zones where logs are kept in the city of Chetumal, a contributing output of wastewater per sump was derived with the support of the CAPA personnel. The National Water Commission (MAPAS, 2015) states that the contributing value can be attained multiplying the allocation data by 0.75,

No.	(Activation) On time	Shut-Off time
<b>First shift</b>		
1	08:00 a. m.	08:30 a. m.
2	12:00 p. m.	12:30 p. m.
3	02:00 p. m.	02:15 p. m.
<b>Second shift</b>		
1	05:00 p. m.	05:45 p. m.
2	07:00 p. m.	07:20 p. m.
3	09:00 p. m.	09:20 p. m.
<b>Third shift</b>		

which can give the volume per inhabitant, per day, which is deposited in the sewerage network. (Table 2).

No.	Pumping Sumps	No. of Users	Consumption		Sewerage	
			(m <sup>3</sup> /month)	(m <sup>3</sup> /day)	(m <sup>3</sup> /day)	(l/s)
1	Bachilleres II	5741	51886.33	1729.54	1297.16	15.01
2	Caribe	5168	45199.33	1506.64	1129.98	13.08
3	Comonfort	1133	13973	465.77	349.32	4.04
4	Forjadores	1615	16194.33	539.81	404.86	4.69
5	Fovissste IV etapa	173	1663	55.43	41.58	0.48
6	No. 1	860	13527.5	450.92	338.19	3.91
7	No. 4	465	4988	166.27	124.70	1.44
8	No. 8	2266	20231	674.37	505.77	5.85
9	Nueva generación	101	992.33	33.08	24.81	0.29
10	PactoObrero	6673	6763	225.43	169.08	1.96
11	Tampico	209	1859.33	61.98	46.48	0.54
12	Bosques del lago	-	-	-	-	1.04
13	Final	1838	18681.66	622.72	467.04	5.41
14	Fovissste III etapa	194	2102	70.07	52.55	0.61
15	Millennium	206	2256.66	75.22	56.42	0.65
16	Planta de vacío A	1133	20973.33	699.11	524.33	6.07
17	Planta de vacío B	1421	17925.66	597.52	448.14	5.19

Table 2: Water Bill data analysis.

- Hydraulic simulation model

Several values were taken from the variation curve of drinking water demand for different parts of the city for the hydraulic-simulation model; the results are shown in table 4. The variations in average consumption are expressed as mean-cost hourly percentages [5].

To plot the simulation model, curves were generated that represent the area-height relation in all of the pumping sumps. (Figure 12).

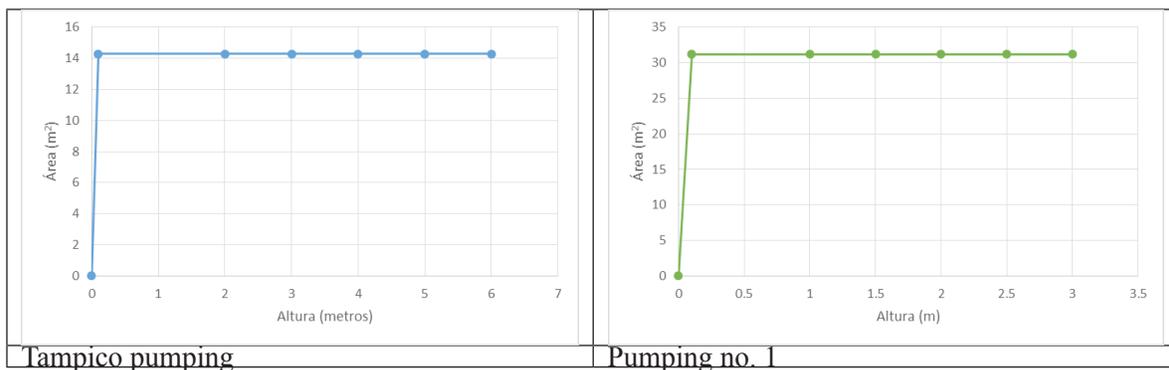


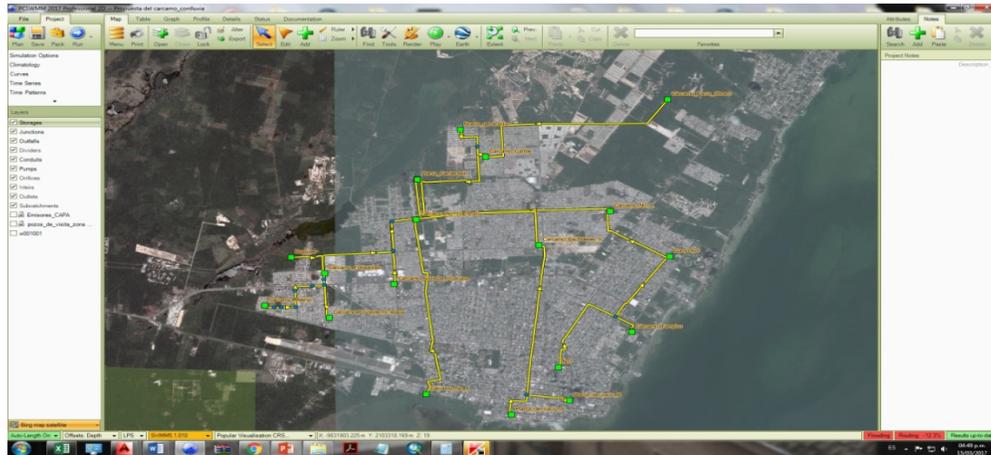
Figure 12: Capacity-height curve for pumping sumps.

### Simulation model

Summing up, to configure the output that transits through the emission points and that arrives at each one of the storage systems, a variation curve was used for the demand and outputs per area of influence since upon comparing these with the measurement data, there was not a big difference and what little difference existed could be attributed to broken piping that permitted the entry of groundwater which increased the output.

Sumps were sized, afterwards an elevation-capacity curve was generated, and each pump was assigned its characteristic curve.

For the tracing part, emitter dimensions and material type were given; field trips were carried out to know if the CAPA data was consistent with field observations. There are 38 km of emitters; Figure 13 presents the hydraulic simulation model for the sanitary system of Chetumal.



**Figure 13:** Hydraulic simulation model for the sanitary system of the city Chetumal.

## Results

### Structural damage cost

- Hydraulic model

From the construction of the hydraulic model, 6 scenarios were performed (2, 5, 10, 25, 50 and 100 years), in order to know the behavior of the suspenders and the speed that occurs in the city. In Table 3, simulated rain is presented.

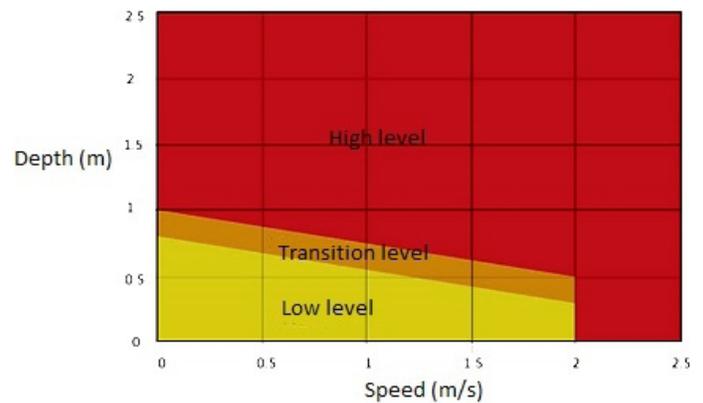
Tr (years)	Duration 90 minutes (mm)
2	65.5
5	86.4
10	102.3
20	118.1
25	123.2
50	139.1
100	154.9
200	170.8

**Table 3:** Lluvias vinculadas a diferentes periodos de retorno.

- Hazard criteria

The place where this criteria was applied is in the city of

Dórrigo, Australia, where hazard maps were created based on the depth and velocity criterion of water as shown in Figure 14, in which the three hazard ranges are defined [6].



**Figure 14:** Hazard levels applied in the city Dórrigo, Australia (NSW, 2005).

This hazard classification applied to Dórrigo, Australia, was used for each of the posited scenarios (2, 5, 10, 25, 50 and 100 years), Figure 15.

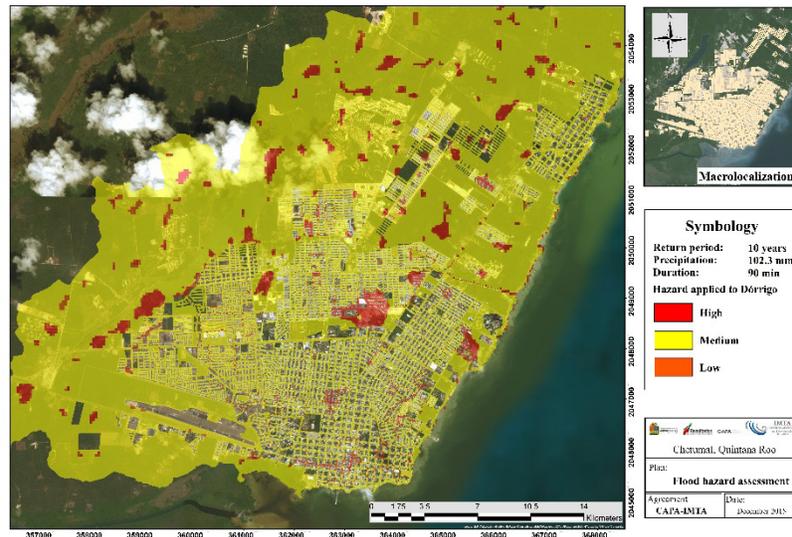


Figure 15: Hazard evaluation for a return period of 10 years.

### Vulnerability map according to housing type

The methodology set forth by Rodríguez et al [4], uses information according to housing areas: the number of homes with one room only, homes with two rooms, home three rooms or more, as well as the economically active population. This information can give us the housing type and degree of vulnerability of the constructions in the city of Chetumal, Quintana Roo (Figure 16).

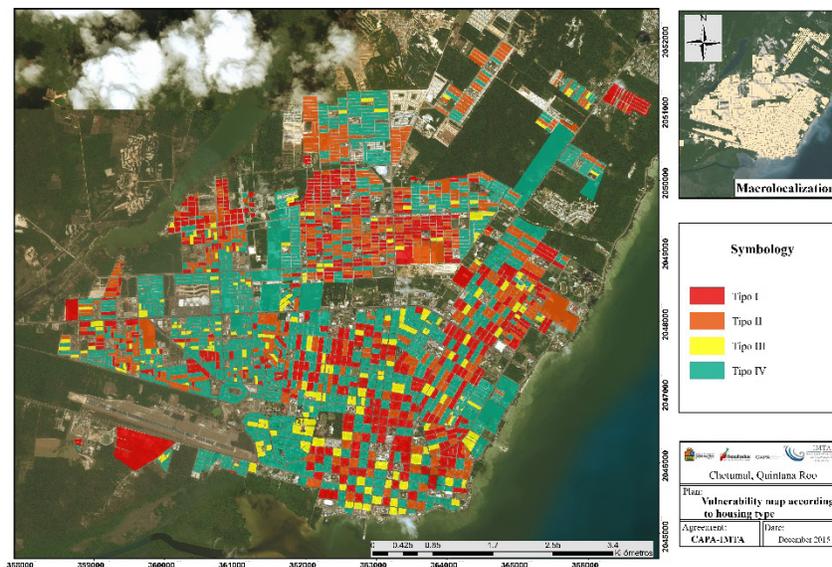


Figure 16: Vulnerability Map according to housing type.

According to Vélez et al., (2014) a damage curve is generated in relation to the depth flow, where a value of \$85,000 pesos is given to housing type 1. Table 4 contains the values derived from structural damage, depending on the type of housing and vulnerability.

Vulnerability	Type of housing	Structural damage cost
Very High	I	\$ 85 000
High	II	\$ 77 000
Medium	III	\$ 69 000
Low	IV	\$ 61 000
Very Low	V	\$ 53 000

Table 4: Structural damage cost according to housing type [7].

Overlapping the hazard map with rain linked to a return period that goes from 2 to 100 years, a total cost for structural damage failure can be derived (Table 5).

Return period (years)	Cost per structural damage (pesos)
2	\$26,659,050.00
5	\$30,156,950.00
10	\$34,767,060.00
25	\$37,412,900.00
50	\$40,141,370.00
100	\$67,990,250.00

Table 5: Cost per structural damage for different analyzed scenarios.

### Flood Index Calculation (FIC)

Using the maps for flood-risk zones in accordance to the topography of the city, a flood vulnerability index calculation was done using the following expression:

$$FIC (\%) = \frac{\text{Urban population with little or no risk of flooding during the rainy season}}{\text{Total population of the city (inhabitants)}}$$

The FIC was calculated and it turns out that, for a return period of ten years, 8.80% of the population is at risk of flooding during the rainy season. For the sanitary part, 3 scenarios were simulated, current conditions and two solution alternatives:

#### Current conditions scenario

Illustration 6.72 shows a blue line that represents the coming together of the outputs that proceed from the three emitters, with this it can be said that according to the design of the 120 l/s plant, this figure is surpassed on repeated occasions due to the arrival of simultaneous flows, this provokes excesses at different times of the day. To be precise, during 6.58 hours of the day the project output is surpassed, with outputs that are maximum 235 l/s maximum and an average of 142 l/s.

#### Considering a regulation tank

According to the water quality analysis of the plant, there is a problem due to the absence of homogeneity at the moment of the arrival of the discharge of the three emitters that converge in the PTAR. For that reason, the use of a regulating sump is suggested that will allow for homogeneity in the wastewater mixture, which will damper the output peaks, and allow work on the plant with the design output (120 l/s), Figure 17.

This result reveals a deficit of 847 m<sup>3</sup>, that need to be regulated, then, a scenario is created with a regulating sump that can hold 847m<sup>3</sup>. For that reason, a pumping sump of that capacity is recommended.

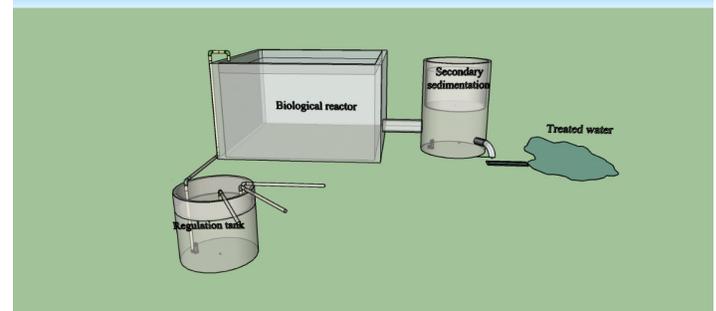


Figure 17: System configuration of the PTAR Centenary through a tank.

## Conclusion and Recommendations

### Sanitary

- Field trips to review the sanitary network infrastructure revealed the absence of preventative maintenance Problems are given short-term solutions in lieu of the proper mid and long-term planning required in order to contribute substantially to the improvement of the service.
- A sewer drainage network has to be pulled up from cadastre, due to the fact that that less than 50% of the total network is available and what is available can have inconsistencies upon revision, this will allow for the creation of hydraulic simulations for specific zones (neighborhoods, sectors, etc.) and permit the generation of the service conditions for the dispelling of wastewater all the way down to the individual inhabitant level.
- For the construction of the hydraulic simulation model that represents the workings of the sewerage system for the city of Chetumal, pumping sumps, pumping equipment, emitters and manholes were identified along with their contributions according to area of influence and pumping sump, which were then distributed temporally through a characteristic demand curve of drinking water established for different parts of the country. Simulating 24 hours.

Based on the sanitation network, which considers the output calculated in double (taking breaches, rainfall or other factors into account), excess volume that the PTAR received is calculated, resulting in 847 m<sup>3</sup> that must be regulated.

The volume dimension of the regulating tank (847 m<sup>3</sup>), requires that it be elevated. Under this proposal there would be no problem at all in the event of a flood, moreover, maintenance costs would go down and the operation of pumping equipment would be through a gravity flow operation to be later processed in pretreatment. The scenario resulted in there being no problem with overflow in any pumping sump and the way the PTAR receive sits design flow.

Having the regulation tank buried, a scenario was generated considering double the output as well, with this condition, the pumping sump went on to reach 84% of storage capacity installing equipment that permits the evacuation of water at the rate of 120 l/s.

### Rainfall system

- The superficial flow model was constructed based on an MDE, the planimetry of the city, the geomorphological plotting of the micro-basins and rainfall drainage taking as the initial condition, project rains that go from 2 to 100 years return period.
- The CONAGUA recommends a return period of 10 years for the construction of rainfall works, then a cost-benefit analysis is needed to know what could be more feasible, building a new infrastructure or repairing the damage sustained. The structural damage of the homes goes up to 34.76 million pesos.
- With the Flood Vulnerability Index (FVI) it can be stated that for a return period of 10 years, the population that is at risk in the city of Chetumal is 13,309 inhabitants.
- One of the recurring problems in times of intense precipitation is traffic repercussions, according to the hydraulic simulation model for a return period of 10 years there are problems in 11.8% of the city's roads, this can reach almost double that amount (Tr 100 years).
- According to the map, maximum flow depths are reached for rainfall linked to a return period of 10 years, in the city of Chetumal there are depth flows between 0.27 and 2.02 m.

- Flood areas were calculated for rainfall linked to a return period of 10 years, with this, the number of neighborhoods identified that require structural attention for the mitigation of floods totals 15.

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