

Identifying Inundation Risk Zones on the Southern Coast of the Gulf of Mexico by Groundwater Velocity Tests, Grain-Size Analysis, and Water Table Fluctuations: Coatzacoalcos Paleolagoon

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Abstract

This study presents results from grain-size analyses and apparent groundwater flow velocity tests on 22 sediment samples collected within and outside the Coatzacoalcos paleolagoon to characterize sediment geohydrological dynamics. We determined that the grain-size distribution of the samples correlates with hydraulic conductivity. Furthermore, the sediments filling the paleolagoon (coarse, medium, and fine sand) exhibit a hydraulic conductivity of 13.68 to 55.77 meters/day, which is higher than that of the sediments (fine sand, silt, and clay) in samples collected outside the paleolagoon (0.58 - 8.14 meters/day). Variability in grain-size analysis results indicated that sedimentation conditions varied across depositional sites, thereby influencing hydraulic conductivity. We also observed that clast arrangement within the sediments influences hydraulic conductivity. Estimates of rainfall-driven water-table fluctuations in the paleolagoon area enabled us to characterize its hydrodynamic behavior. For instance, with 132.0 mm of precipitation, the water table rises by 0.081 m, whereas with 390.0 mm, it rises by 0.348 m. If these conditions persist for three days, the rise will be 1.044 m. These estimates allowed us to identify areas vulnerable to flooding in the municipality of Coatzacoalcos.

Keywords

Groundwater Velocity, Water Table, Aquifer, Hydraulic Conductivity, Inundation Risk, Hydrogeology

1. Introduction

Detailed hydrogeological characterization studies in the coastal zone of the State of Veracruz are scarce, and the available information is very general. Hydrogeological research is crucial because it directly affects potable water supply for cities, urban infrastructure development (as seen in the Coatzacoalcos immersed tunnel [1]), and identifying areas vulnerable to flooding.

The agency responsible for characterizing aquifers and groundwater in Mexico is the National Water Commission (CONAGUA). Despite this Mexican government agency's enormous effort, it is necessary to continue collecting new data that reflect the current state of aquifers, groundwater reserves, and their availability for use.

Navigation and maritime trade in the Gulf of Mexico are activities of paramount economic importance. Mexico's maritime activity is considered a matter of national interest. According to the Secretariat of the Navy (SEMAR) and the National Port System Administration (ASIPONA), the most important Mexican ports in the Gulf of Mexico are Altamira, Tampico, Tuxpan, Veracruz, Coatzacoalcos, Dos Bocas, and Progreso [2].

Mexican ports on the Gulf of Mexico maintain trade routes with major U.S. ports in the Gulf of Mexico and along the Atlantic coast, as well as with ports in the Caribbean, South America, and Europe [3] [4].

Currently, Coatzacoalcos is one of the most important ports on the southern coast of the Gulf of Mexico. With the reactivation of the 2025-2030 Institutional Program for the Interoceanic Corridor of the Isthmus of Tehuantepec, the port of Coatzacoalcos has gained significant logistical importance due to its excellent land connectivity via both road and rail, and maritime access; this consolidates its position as a major economic hub at the regional, national, and international levels [5].

This development entails a significant transformation of the city, accompanied by increased human mobility. Among other needs, the city will require a greater supply of high-quality potable water. Furthermore, waste generation will rise, requiring improved infrastructure and services, as well as stronger legislation and monitoring to preserve groundwater quality in the aquifer [5].

This situation highlights the need to understand the geological characteristics of the Coatzacoalcos paleolagoon's sedimentary environment to prevent, or at least minimize, potential impacts on the population, urban infrastructure, and the aquifer.

Likewise, understanding the aquifer's hydrogeological dynamics is important, given that the area experiences extreme precipitation of up to 390 mm/day (mm/d). Consequently, flooding risk persists annually [6] [7].

We use the term "apparent groundwater flow velocity" rather than "groundwater flow velocity" because we used a device developed for this study; therefore, we did not take *in situ* measurements, and the units are in meters/day (m/d).

2. Background

As mentioned in the introduction, hydrogeological information on the southern coast of the Gulf of Mexico is scarce, and what does exist is very general; most studies of the region have focused on the agricultural sector, while fewer have addressed pollution and flood vulnerability along the Coatzacoalcos River. Likewise, analysis from geological, geohydrological, and risk-assessment perspectives has been limited.

[8] used a rainfall simulator to measure water infiltration in soils within agro-systems. [9] conducted a study measuring water infiltration for agricultural purposes. Additionally, [10] developed an R application that simulates, calculates, and forecasts infiltration in real time.

[11] studied how rainfall intensity and soil physical properties influence infiltration and runoff, and [12] investigated the relationship between infiltration and rainwater evaporation in dunes in semi-desert environments.

In contrast, [13] studied the hydrodynamics of the Coatzacoalcos River and estimated potential flooding under climate change scenarios. They considered factors such as rising tides and sea-level rise to generate simulations to identify potential flood zones along the Coatzacoalcos River. Similarly, [14] studied population vulnerability to flooding in low-lying areas along the banks of the Coatzacoalcos and Tuxpan rivers in Veracruz, Mexico.

Some authors measured groundwater velocity using different methods; for example, [15] measured groundwater velocity in discrete rock fractures using point-dilution experiments with an apparatus designed and built specifically for fractured rock systems. [16] used a novel methodology for determining the mean translational velocity of groundwater flow in a karst system using a dye; [17] used an innovative approach to measure groundwater velocity in wells, employing a tool they developed, and [18] used four different tracer methods to estimate groundwater flow velocity at a multiple-well site in a saturated alluvium.

To determine the influence of submarine freshwater discharge from the Veracruz coastal aquifer on coral development within the Veracruz Reef System (VRS) area, the Institute of Marine Sciences and Fisheries of the Universidad Veracruzana has conducted salinity measurements in the region and found evidence of freshwater discharge at the seabed. Salinity readings showed anomalous values lower than the average salinity of Gulf of Mexico seawater [19] [20].

Recently, [21] evaluated the presence of potentially toxic elements in surface sediments along the lower Coatzacoalcos River basin. Pollution in the lower Coatzacoalcos River basin is another source of concern for the inhabitants of the area's two main cities. The study area of [21] is slightly south of ours.

This study provides relevant information through an integrated approach combining geological characterization and groundwater flow dynamics in the shallow Costera de Coatzacoalcos aquifer within the Coatzacoalcos paleolagoon.

3. Study Objective

This study aims to analyze apparent groundwater flow velocity and its relationship

to the grain-size distribution of sediments deposited inside and outside the Coatzacoalcos paleolagoon. It also analyzes the aquifer's daily water recharge volume from significant rainfall events (inflow), the daily discharge volume into the Gulf of Mexico (outflow), and the consequences of water table fluctuations resulting from the difference between recharge and discharge. This water-table fluctuation is crucial for identifying the areas at highest risk of flooding under an extreme rainfall scenario.

4. Location of the Study Area

The study area covers the northern part of the Coatzacoalcos paleolagoon, extending from the southern coast of the Gulf of Mexico in the municipality of Coatzacoalcos to the city of Minatitlán, Veracruz, Mexico.

The Coatzacoalcos paleolagoon lies north of the Isthmus of Tehuantepec in the southern Gulf of Mexico, within an 810 km² area in geographic zone Q15, at UTM coordinates 324,690.0 and 365,190.0 m E; 1,994,700.0 and 2,016,600.0 m N. Coatzacoalcos and Minatitlán are the two largest and most important cities in the study area; however, other small cities, such as Nanchital and Ixhuatlán, also exist (**Figure 1**).

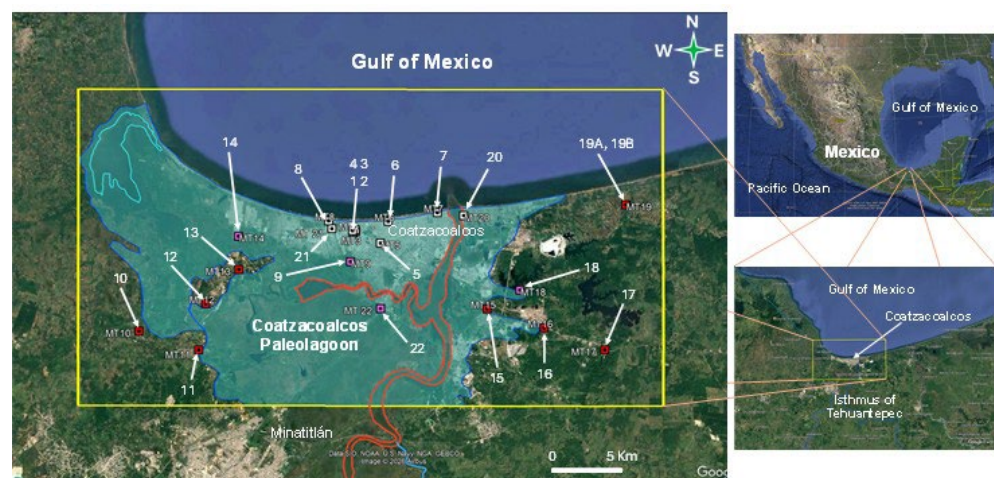


Figure 1. Location of the Coatzacoalcos paleolagoon area on the Isthmus of Tehuantepec, Mexico. Location of the 22 sediment samples collected inside and outside of it (Google Earth, 2026).

5. Geology of the Study Area

In studying apparent groundwater flow velocities, the geological context is essential for understanding the system's functioning. Below, we present the study area's geology based on information from the Mexican Geological Survey [22].

The oldest rocks crop out in the southwestern part of the study area; these belong to the Upper Miocene (11.6 - 5.3 Ma) Filisola Formation (Tmar-Lu), which consists of sand and shale. The Filisola Formation unconformably overlies the Jaltepec Formation (TplCgp-Ar), which is of Pliocene age (5.1 - 1.68 Ma) and composed of polymictic conglomerate and sandstone. The Jaltepec Formation oc-

curs in two locations: the west-central and southeastern parts of the study area (**Figure 2**).

The Pliocene Paraje Solo Formation (5.1 - 2.7 Ma) overlies the Filisola Formation (TplAr-Lu) in a transitional manner. It is composed of sandstones and shales in the eastern and southeastern parts of the study area.

In turn, the Pliocene-Pleistocene (5.1 - 1.5 Ma) Cedral Formation (TplQptAr-Cgp) conformably overlies the Paraje Solo Formation, located in the eastern and northeastern parts of the study area.

Basaltic volcanic breccias and basalts (TplBvB-B) of Pliocene age (2.7 - 0.15 Ma) are in the western and northwestern areas. These basaltic volcanic breccias and basalts are associated with the geological event in the Sierra de Santa Martha within the Los Tuxtlas volcanic field and partially overlie the previously mentioned sedimentary formations.

To the north of the study area, Quaternary aeolian deposits of Holocene age (10,000 - 8000 years old) are composed of quartz sand. These aeolian deposits form the present-day coastline and, in the past, constituted islands and coastal bars that separated the saline waters of the Gulf of Mexico from the waters of the Coatzacoalcos paleolagoon.

Dark-toned Quaternary paludal deposits of Holocene age (10,000 - 8000 years old) are in the central area. These deposits consist primarily of sand, along with silt and clay containing high levels of organic matter derived from decomposing vegetation typical of swampy environments.

During the final sedimentation phase, Quaternary alluvial sediments were deposited in the Holocene (4 - 3 thousand years ago) and consist of fine gravel, sand, and silt (**Figure 2**).

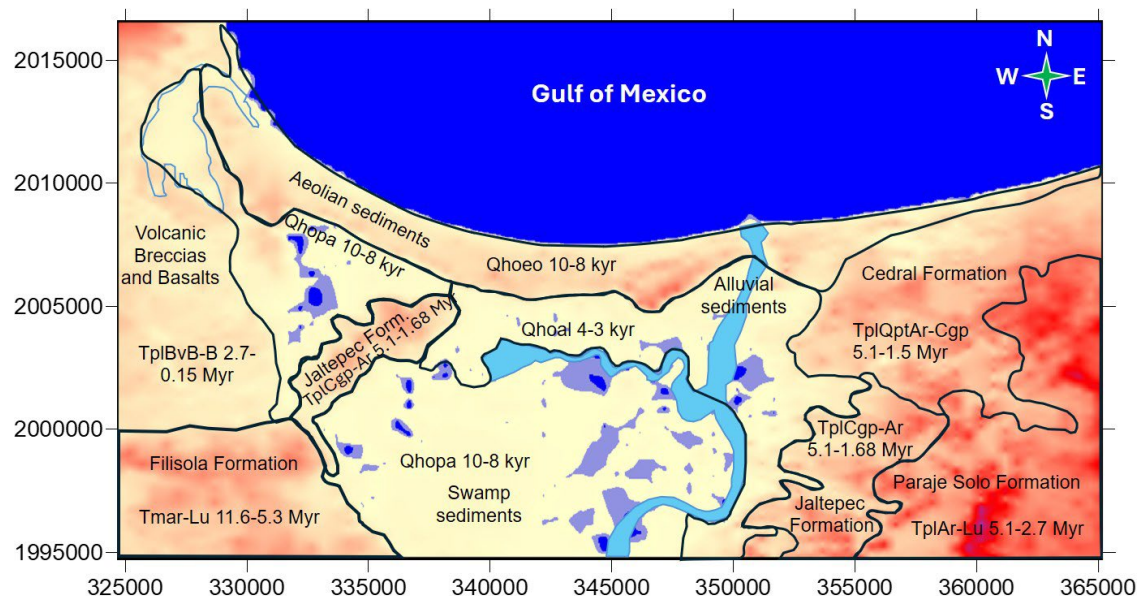


Figure 2. Geology of the study area. Geological formations outcropping within and outside the Coatzacoalcos paleolagoon.

6. Hydrology

The National Water Commission [23] states that two hydrogeological media exist in the study area where the Coatzacoalcos paleolagoon is: one porous and the other fractured. Together, these two media form a heterogeneous, anisotropic, unconfined aquifer with low storage capacity. The porous medium constitutes the uppermost geological unit, composed primarily of alluvial and lacustrine sediments that fill the Coatzacoalcos paleolagoon, with grain sizes ranging from gravel to clay.

These sediments form the riverbeds and floodplains of the Coatzacoalcos, Tonala, Coachapa, and Uxpanapa rivers, as well as the volcanoclastic deposits and conglomerates that form the coastal plain surrounding the paleolagoon area [22].

The lower geological unit is a sequence of sedimentary rocks of interbedded sandstones and shales, with secondary permeability from fracturing. The sandstones act as aquifers under semi-confined or confined conditions because they alternate with shales and siltstones [23].

Information on hydraulic parameters in the study area is scarce; therefore, CONAGUA used data from neighboring aquifers northwest of the Costera de Coatzacoalcos aquifer, which share the same origin, evolution, and geological composition, and assigned them hydraulic conductivities ranging from 4.0 to 11.8 m/d. The highest values correspond to coarser-grained and better-sorted clastic sediments [23].

7. Methodology

The methodology used for the development of this study is below.

A previous study [24] collected 22 sediment samples from both within and outside the Coatzacoalcos paleolagoon. That study determined the granulometry of the samples to determine the grain size of the sediment constituents.

We used the Mexican Geological Service's geological-mining map E15-1-4 (covering Veracruz, Oaxaca, and Tabasco) to locate sediment sampling sites representative of the geological formations, both outside and within the Coatzacoalcos paleolagoon.

We made preliminary trips to verify site access, undisturbed soil, sediment characteristics, and free areas for construction. Initially, the number of samples was undefined and depended on site conditions and visual observations of the sediments. We distributed sampling sites irregularly, based on the factors above and the boundaries of geological formations on the geological-mining map [22]. At each site, we collected 2 kg of sediment samples from cores at 20 to 30 cm of depth.

We collected samples from eolic, swamp, alluvial, and volcanoclastic sediments, as well as transitional alluvial-volcanoclastic environments. At each site, we inspected the area to select a location free of sediment disturbance and recorded the coordinates using GPS. We collected samples from April 15 to 30, 2025, and pre-

served the material in sealed plastic bags for testing. Using the sediment grain-size distribution data, we created graphs showing the material passing through each sieve and quantifying the amount that passed.

To measure the apparent groundwater flow velocity through the sediments, we designed a device in which water passed through a sediment section for each sample. Times were measured using a stopwatch. Below, we describe the procedure for measuring time.

We made a map using the apparent groundwater flow velocity values and the spatial distribution of geological formations from the geological-mining map [22]; additionally, we analyzed the correlation between these elements and the potential risk of flooding affecting the population, using graphs showing the grain-size distribution of the material and the apparent groundwater flow Velocity through the sediments.

8. Development

Sample preparation involved removing organic matter, homogenizing the sample, and oven-drying the sediment at 150 °C to remove moisture. We placed the sediment in a container. Afterward, we placed the container on a vibrating base to allow the sediment particles to settle. To avoid significantly altering sediment porosity, we did not compress any samples. We repeated the sample preparation procedure for all tests.

8.1. Grain-Size Distribution

Because the samples were altered, as the tests were not performed “*in situ*”, we determined apparent porosity from the container volume and the volume of water required to achieve 100% saturation (Table 1). Because we did not control sediment-grain packing during container filling, we assumed the apparent porosity may differ slightly from the true porosity.

We calculated apparent porosity using the container volume and the volume of water added to the sediment collocated in the container. We also recorded the dry and 100% saturated sediment weights to obtain the water weight. To calculate the water volume, we used a water density of 0.99656 g/cm³ at 27.0 °C [25]. The apparent porosity values of samples ranged from 35.95 (S22) to 58.95 (S18) gr/cm³. (Table 1).

Apparent porosity values obtained from the 22 samples (including S19A and S19B) from Table 1 are, in general, consistent with porosity values from [26], which are as follows: Coarse sand with porosity values from 31% - 46%, fine sand with values from 25% - 53%, silt and loess with values from 35% - 50%, clay with porosities of 40% - 70%. From Table 1, S18 showed the highest porosity (58.95%), and S22 the lowest (35.95%).

8.2. Grain-Size Analysis

Sediment samples were collected both within and outside the Coatzacoalcos pale-

olagoon area to quantify and record grain-size percentages for the geological formations at various points within the study area.

[24] presented the specifications of the sieves used, the sample sieving procedure, and the results. Following, we present the sediment volume percentages by grain size for each sample collected in the paleolagoon (**Table 2**).

Table 1. Apparent porosity (%) from the twenty-two sediment samples. * (19A) Upper layer; (19B) lower layer.

Sample	Sample Vol. (cm ³)	Dry sample weight (gr)	Weight of sample 100% Saturated	Water weight (gr)	Water vol. (cm ³)	Apparent porosity (%)
S1	435.60	626.66	824.85	198.19	197.51	45.34
S2	435.60	592.40	784.76	192.36	191.70	44.01
S3	435.60	614.90	802.16	187.26	186.62	42.84
S4	435.60	630.70	834.53	203.83	203.13	46.63
S5	435.60	662.05	844.15	182.1	181.47	41.66
S6	435.60	601.17	803.41	202.24	201.54	46.27
S7	435.60	618.73	802.12	183.39	182.76	41.96
S8	435.60	668.87	879.00	210.13	209.41	48.07
S9	435.60	661.13	842.34	181.21	180.59	41.46
S10	435.60	538.81	760.06	221.25	220.49	50.62
S11	435.60	591.04	768.08	177.04	176.43	40.50
S12	435.60	511.15	721.81	210.66	209.94	48.19
S13	435.60	542.41	738.58	196.17	195.50	44.88
S14	435.60	635.40	814.77	179.37	178.75	41.04
S15	435.60	536.32	762.17	225.85	225.07	51.67
S16	435.60	547.70	758.71	211.01	210.28	48.27
S17	435.60	570.04	782.52	212.48	211.75	48.61
S18	435.60	477.22	734.9	257.68	256.79	58.95
S19A*	261.36	337.78	456.07	118.29	117.88	45.10
S19B*	435.60	512.85	697.74	184.89	184.25	42.30
S20	435.60	644.98	827.52	182.54	181.91	41.76
S21	435.60	641.64	866.4	224.76	223.99	51.42
S22	435.60	641.34	798.46	157.12	156.58	35.95

Table 2. Grain-size results for sediment samples collected in the Coatzacoalcos paleolagoon area. Values in bold represent most of the sample volume.

Retained sample volume (%) according to grain size (mm)										
Sample	>2	2 - 0.85	0.850 - 0.355	0.335 - 0.250	0.250 - 0.180	0.180 - 0.150	0.150 - 0.125	0.125 - 0.090	0.090 - 0.075	<0.075
S1	0.00	0.64	10.18	49.28	23.56	5.90	4.03	2.21	1.23	2.98
S2	0.00	0.78	3.69	45.15	35.00	6.13	4.14	2.56	0.97	1.57
S3	0.00	0.07	8.24	42.85	39.03	4.74	2.65	1.30	0.35	0.76

Continued

S4	0.00	0.08	8.64	36.02	42.15	6.07	3.95	1.90	0.45	0.75
S5	0.00	0.55	8.78	33.35	44.06	8.08	3.44	1.51	0.16	0.07
S6	0.32	0.39	9.60	29.15	44.04	10.00	3.72	1.67	0.48	0.62
S7	0.00	0.02	0.32	33.08	50.28	10.25	3.76	1.91	0.24	0.13
S8	0.00	0.02	22.03	47.00	22.57	4.86	2.24	0.96	0.15	0.16
S9	6.90	7.35	22.88	27.99	24.23	5.34	2.89	1.26	0.68	0.48
S14	0.88	7.69	22.45	28.03	27.83	5.38	3.23	2.60	0.54	1.37
S20	0.17	0.44	22.50	54.92	17.02	3.34	1.09	0.50	0.01	0.00
S21	0.00	1.41	16.27	47.89	20.45	4.86	3.34	1.92	2.02	1.83
S22	0.68	9.15	23.32	26.86	22.86	5.37	4.21	3.84	2.14	1.57

Based on the grain-size analysis results (Table 2), we generated graphs of volume (%) versus grain size passing through each sieve. Figure 3 shows that the bulk of the sample consists of coarse, medium, and fine sands. Additionally, this allowed us to observe slight differences in sediment grain sizes. Note that the percentage values in the graphs are cumulative.

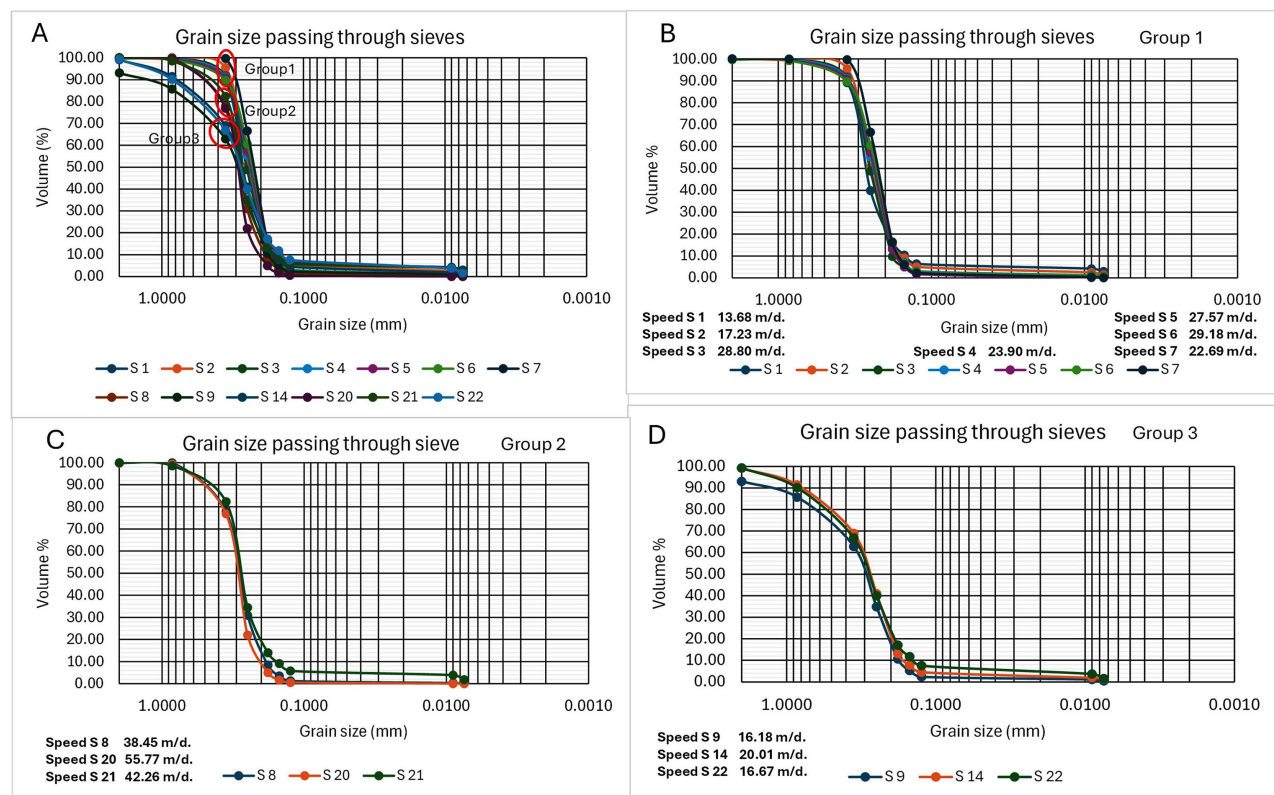


Figure 3. Grain-size characteristics of the sandy sediments from the Coatzacoalcos paleolagoon. The graphs show the percentages of grain sizes passing through each sieve (cumulative values). Graph A shows the results for all samples. Graphs B, C, and D separately show each of the groups appearing in Graph A. Sediments in each graph exhibit similar characteristics.

Graph A in **Figure 3** shows the results for all samples collected from the Coatzacoalcos paleolagoon. It reveals differences that allowed us to classify the sandy sediments into three groups. Later, we will correlate these differences with the hydrodynamic characteristics of the water flowing through these sediments.

Graph B in **Figure 3** shows a similar grain size distribution across samples S1-S7. Most grains ranged from 0.180 to 0.355 mm. Additionally, samples S5, S6, and S7 contained between 8% and 10% of grains in the 0.150 - 0.180 mm range.

Graph C in **Figure 3** shows that samples S8, S20, and S21 have a higher coarse-sand content than those in Graph B.

Finally, Graph D in **Figure 3** shows that samples S9, S14, and S22 exhibit greater size diversity, with more coarse-grained sediment than in Graphs B and C.

Based on the grain-size distribution, we observe that the samples in Graph B are very well-sorted sediments. We classify the samples in Graph C as well-sorted sediments, and those in Graph D as moderately sorted sediments.

Likewise, we determined the grain-size distribution of sediments outcropping around the paleolagoon area (**Table 3**).

Table 3. Grain-size results for sediment samples collected outside the Coatzacoalcos paleolagoon area. Bold values represent the dominant sample volume. * Samples composed of a mixture of gravels, sand, and a small quantity of fine material collected in a transitional paleolagoon boundary.

Sample	Retained sample volume (%) according to the grain size (mm)									
	>2	2 - 0.85	0.850 - 0.355	0.335 - 0.250	0.250 - 0.180	0.180 - 0.150	0.150 - 0.125	0.125 - 0.090	0.090 - 0.075	<0.075
S10*	5.45	25.24	28.43	14.00	10.27	4.82	4.06	4.26	2.23	1.23
S11	21.79	18.18	20.65	8.09	7.47	6.35	3.34	7.69	2.99	3.44
S12	6.59	19.39	27.17	17.00	11.40	5.74	6.13	3.27	2.53	0.77
S13	18.52	23.32	25.01	11.37	8.61	3.12	2.21	2.41	2.86	2.57
S15*	35.89	17.83	20.35	9.41	7.65	3.03	1.95	1.72	0.86	1.32
S16	34.24	9.35	19.43	7.75	7.77	4.94	5.19	3.97	2.98	4.38
S17	7.61	7.37	7.06	18.20	24.40	9.92	13.18	6.40	3.33	2.52
S18	0.00	0.00	8.24	17.32	39.95	12.59	5.10	5.78	5.11	5.90
S19A	2.95	9.00	25.84	17.56	13.04	6.90	6.02	7.94	4.56	6.19
S19B	0.23	15.30	39.77	14.74	9.38	4.91	4.06	4.52	2.89	4.19

Using the values from **Table 2**, we created graphs showing the volume (%) of grain size passing through each sieve (cumulative values). The graphs showed that sediments from samples collected outside the Coatzacoalcos paleolagoon area exhibit a wider grain-size range, from >2.0 mm to 0.090 mm (**Figure 4(A)**).

The grain-size analysis of samples collected outside the Coatzacoalcos paleolagoon revealed greater grain-size diversity. Given this variability, we grouped samples with similar apparent groundwater flow velocity values (graphs B, C, D, and E in **Figure 4**). Below, we describe the procedure for the apparent groundwater flow velocity tests and the correlation between velocity and grain size in detail.

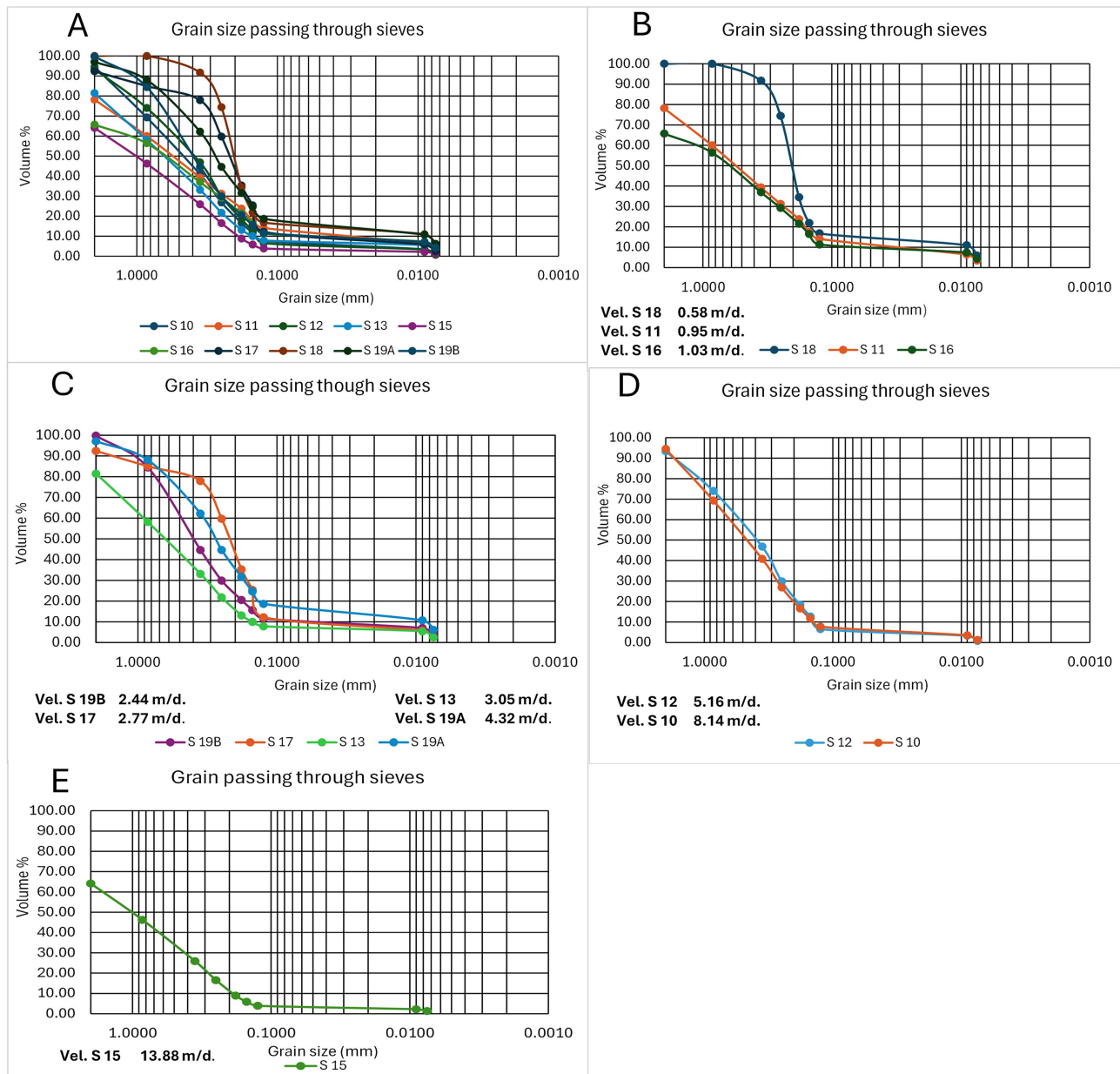


Figure 4. Grain-size characteristics of sediments collected outside the Coatzacoalcos paleolagoon. The graphs show the percentages of grain sizes passing through each sieve (cumulative values). Graph A shows the results for all samples, while graphs B to E show groups of samples with similar ranges of apparent groundwater flow velocity. We collected samples S10 and S15 on the transitional paleolagoon boundary.

8.3. Apparent Groundwater Flow Velocity

To measure the apparent groundwater flow velocity through the sediments, we designed a device to measure the time required for water to pass through a sediment section of a collected sample. We used polymethyl methacrylate, commonly known as acrylic, to construct the device. We placed a fiber filter at the bottom to allow water to pass through with minimal resistance.

To standardize all tests, we measured the side lengths of the rectangular con-

tainer holding the sediments and the water column container. This procedure ensured consistent measurements across tests. We placed sediments from each sample collected at various locations within the study area into the device (**Figure 5**) and reported apparent groundwater flow velocities in meters/day (m/d).

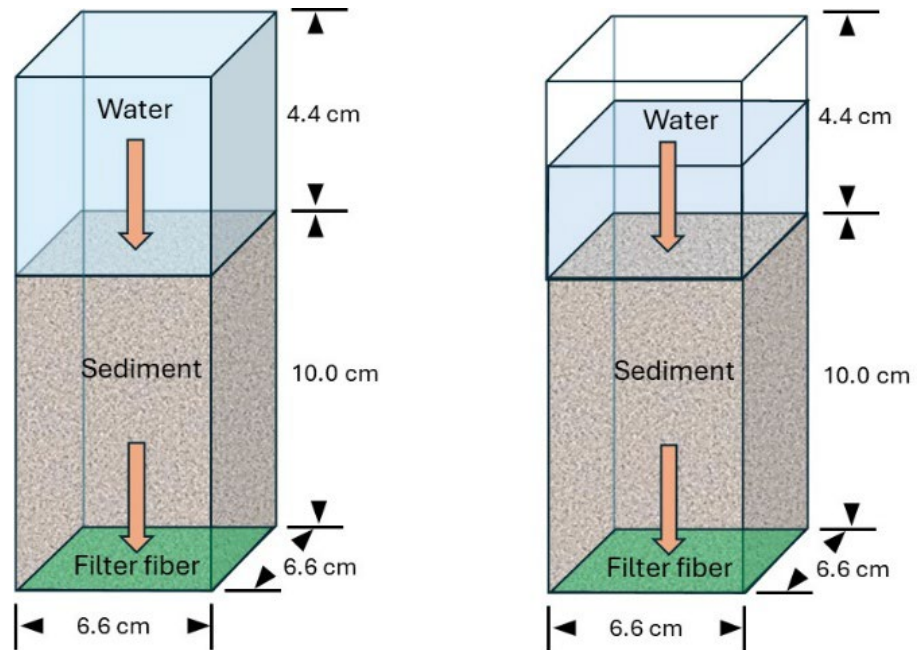


Figure 5. Schematic of the designed device to measure the time it takes for a water column to travel 4.4 cm through the sediments. The figure shows the device's dimensions.

For the tests, we filled a 0.10 m sediment column to 100% saturation with water, then added water until we reached the 0.044 m mark on the device. The water column height was the same for every test. We used a stopwatch to measure the time it took for the water level to drop from 0.044 m to 0.00 m (**Figure 5**). Using the recorded time and distance traveled, we calculated the apparent hydraulic conductivity for each collected sample.

For each apparent groundwater flow velocity test, we took three measurements of the time required for the water column to drop by 0.044 m and averaged them. We replicated the three measurements using the same sediment in the receptacle to avoid altering the grain packing, which could change the results. We also determined the standard deviation of the measured times using Equation (1) (**Table 4** and **Table 5**).

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \mu)^2}{n}} \quad (1)$$

Where: σ is the standard deviation, x_i is the individual measurement value, μ is the mean, and n is the number of measurements.

Based on the grain-size analysis (**Figure 3**) and the apparent groundwater flow velocity tests on samples collected from the Coatzacoalcos paleolagoon area (**Table 4** and **Table 5**).

ble 4), we observed three groups with similar grain-size distributions (Graphs 3B, 3C, and 3D).

The apparent groundwater flow velocity tests yielded values ranging from 13.68 to 29.19 meters per day (m/d) for the seven samples shown in Figure 3(B). For the three samples in Figure 3(C), the apparent groundwater flow velocities ranged from 38.45 to 55.77 m/d. For the three samples in Figure 3(D), the apparent groundwater flow velocities ranged from 16.18 to 20.01 m/d (Figure 3 and Table 4).

To establish a correlation with the grain size distribution of the samples in each graph, we calculated the average apparent groundwater flow Velocity, yielding the following results: an average velocity of 23.31 m/d for the samples in Graph 3B, an average velocity of 45.49 m/d for those in Graph 3C, and an average velocity of 17.62 m/d for those in Graph 3D.

These results indicate that the samples in Graph 3C, which consist of well-sorted sediments, exhibit high hydraulic conductivity in the Coatzacoalcos paleolagoon. Samples in Graph 3B, which consist of very well-sorted sediments, exhibit intermediate hydraulic conductivity. However, sample 1 in Graph 3B had the lowest hydraulic conductivity (13.68 m/d). The grain-size analysis showed more fine material (<0.075 mm) in sample 1 (2.98%) than in the other samples. This factor could explain this difference.

Finally, the moderately sorted sediment samples from Graph 3D exhibit the lowest hydraulic conductivity in the Coatzacoalcos paleolagoon. These results show that sediment grain-size composition is one factor that determines how easily groundwater flows through rock pores.

Table 4. Results of apparent groundwater flow velocity tests on sediment samples collected at various points in the Coatzacoalcos paleolagoon.

Sample	Time1 (s)	Time2 (s)	Time3 (s)	Average time (s)	Distance (m)	Apparent velocity (m/d)	Standard Deviation
S1	275.7	276.8	281.1	277.9	0.044	13.68	2.33
S2	219.2	220.2	222.7	220.7	0.044	17.23	1.47
S3	131.4	130.9	133.7	132.0	0.044	28.80	1.21
S4	155.1	159.1	163.0	159.1	0.044	23.90	3.22
S5	134.2	139.3	140.1	137.9	0.044	27.57	2.61
S6	128.8	132.4	129.7	130.3	0.044	29.18	1.52
S7	162.4	170.3	170.0	167.6	0.044	22.69	3.65
S8	99.0	96.9	100.7	98.9	0.044	38.45	1.55
S9	234.6	237.0	233.4	235.0	0.044	16.18	1.49
S14	185.5	191.3	193.2	190.0	0.044	20.01	3.27
S20	65.8	69.5	69.2	68.2	0.044	55.77	1.67
S21	90.3	88.6	91.0	90.0	0.044	42.26	1.00
S22	225.7	230.0	228.5	228.1	0.044	16.67	1.78

According to [27] and [28], the hydraulic conductivity of fine sand ranges from 1 to 5 m/d, medium sand from 5 to 20 m/d, and coarse sand from 20 to 100 m/d. The apparent hydraulic conductivity values measured for the Coatzacoalcos paleolagoon sediments intercorrelate with the sediment type (coarse and medium sand). However, grain size does not clearly correlate with apparent hydraulic conductivity because the sediments are mixed sand with small quantities of silt and clay.

For samples collected outside the Coatzacoalcos paleolagoon area, the results showed greater diversity in grain-size distribution (Figure 4), preventing their classification into groups based on similar affinities. For that reason, we classified the groups based on the apparent groundwater flow velocity range measured during the tests (Table 5).

Likewise, Figure 4(A) shows the grain-size distribution of all samples collected outside the paleolagoon area. Figure 4(B) shows sediments from samples S18, S11, and S16, which exhibited low apparent velocities (0.58 - 1.03 m/d). Figure 4(C) shows sediments from samples S19B, S17, S13, and S19A, which exhibited higher apparent velocities than the previous group (2.44 - 4.32 m/d).

Sediments from samples S12 (5.16 m/d) and S10 (8.14 m/d) in Figure 4(D) exhibited a notable difference in their velocity. Finally, in Figure 4(E), sediment from sample S15 (13.88 m/d) showed the highest apparent velocity. These values suggest that samples S10 and S15 are from a transitional zone at the boundary of the Coatzacoalcos paleolagoon (Figure 1).

Table 5. Results of apparent groundwater flow velocity tests on sediment samples collected at various points outside the Coatzacoalcos paleolagoon. * Samples located in the transitional paleolagoon boundary. ** Sample 19 with two strata. The upper strata are sand with organic matter; the lower strata are sand with silt and clay.

Sample	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average time (s)	Distance (m)	Velocity (m/d)	Estandar deviation
S10*	472.5	461.7	467.3	467.2	0.044	8.14*	4.410
S11	4032.0	4026.0	4008.0	4022.0	0.044	0.95	10.198
S12	727.0	743.0	740.0	736.7	0.044	5.16	6.944
S13	1238.0	1259.0	1243.0	1246.7	0.044	3.05	8.956
S15*	269.3	278.0	274.5	273.9	0.044	13.88*	3.574
S16	3700.0	3682.0	3690.0	3690.7	0.044	1.03	7.363
S17	1362.0	1376.0	1384.0	1374.0	0.044	2.77	9.092
S18	6590.0	6606.0	6581.0	6592.3	0.044	0.58	10.338
S19A**	877.0	892.0	868.0	879.0	0.044	4.32	9.899
S19B**	1548.3	1570.3	1562.5	1560.4	0.044	2.44	9.107

According to [27] and [28], the hydraulic conductivity of clay soil ranges from 0.01 to 0.2 m/d, that of Loam soil from 0.1 to 1.0 m/d, and that of fine sand with different mixes (silt and clay), from 1.0 to 5.0 m/d. The low apparent hydraulic conductivity measured outside the Coatzacoalcos paleolagoon intercorrelates

with volcanoclastic sediment types (clayed and silty sands, sandy silts, loam soils, and some with fine gravels). However, samples S10 and S15 had higher apparent hydraulic conductivity (8.14 and 13.88 m/d); These samples are from the transitional paleolagoon boundary.

We observed that samples with high apparent groundwater flow velocities showed low uncertainty (green circle); samples with medium apparent groundwater flow velocities showed moderate uncertainty (blue circle); and samples with low apparent groundwater flow velocities showed high uncertainty (red circle) (**Figure 6**).

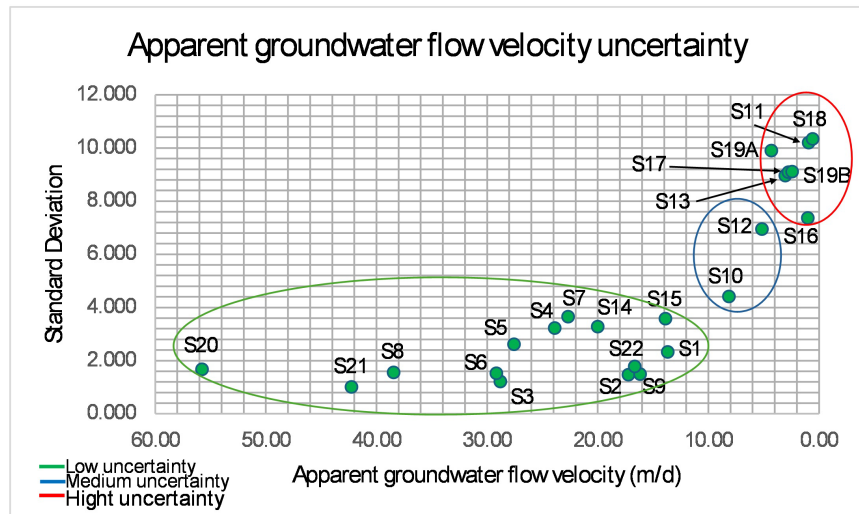


Figure 6. Apparent groundwater flow velocity for the 22 samples collected during this work. Samples with high groundwater flow velocity had a small standard deviation; samples with a moderate groundwater flow velocity had a medium standard deviation; and samples with low groundwater flow velocity had a high standard deviation.

Based on the apparent velocity test results, we observed that sediments collected outside the Coatzacoalcos paleolagoon exhibited lower apparent groundwater flow velocity values than those collected within the paleolagoon area, except for samples S10 and S15 that are located on the transitional boundary of the paleolagoon (**Figure 7**). This parameter (hydraulic conductivity) correlates with rock type and sediment grain size in both the paleolagoon and its surroundings.

8.4. Variability of Apparent Groundwater Flow Velocity

Samples S8 (38.45 m/d), S20 (55.77 m/d), and S21 (42.26 m/d) recorded high apparent groundwater flow velocities in the coastal area (**Figure 1**) and, according to the grain-size analysis, showed higher coarse-sand content.

This coarser grain-size distribution indicates that sediments in samples S8, S20, and S21 originated from former freshwater outflow channels connecting the paleolagoon to the sea, where high-energy fluvial currents drove deposition, distinct from wind-transported (aeolian) sediments. Indeed, we collected sample S20 at the present-day mouth of the Coatzacoalcos River, where high-energy dynamics driven by the river current are observed; these value differences show grain-size

variability within the same geological formation (Figure 7).

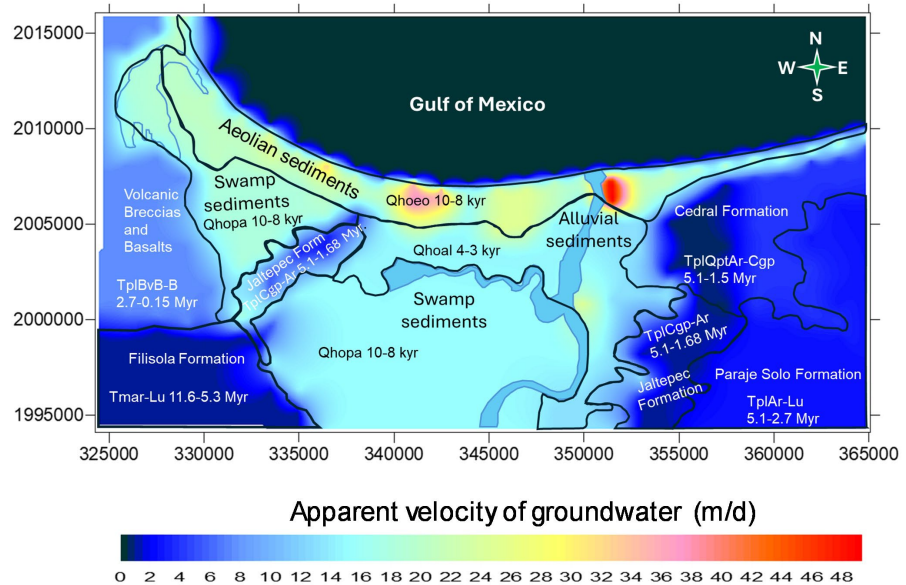


Figure 7. Apparent groundwater flow velocities in the study area. The lowest apparent velocities are outside the paleolagoon area, and the highest apparent velocities are in the aeolian, palustrine, and alluvial sediments filling the paleolagoon.

In other locations, apparent groundwater flow velocity varied considerably between points separated by short distances (Figure 8). We observed this behavior in the samples collected at Universidad Veracruzana. Samples S1, S2, S3, and S4 exhibited very similar grain-size distributions; therefore, we consider that grain arrangement can also influence the apparent groundwater flow Velocity. This behavior demonstrates the heterogeneity of sediment distribution in the Coatzacoalcos paleolagoon.



Figure 8. Location of samples S1 - S4 collected at the Universidad Veracruzana, Coatzacoalcos Campus. The four sampling points are close to one another; however, the apparent groundwater flow velocities differed at each one (13.68, 17.23, 28.80, and 23.90 m/d).

8.5. Scenarios under Constrained Conditions of the Conceptual Model

Simulating an estimation process requires considering many variables, making it highly complex and multifactorial. For this reason, we selected only four scenarios with constrained parameters to calculate the recharge volume, discharge volume, effective recharge, and apparent groundwater flow Velocity from the Coatzacoalcos paleolagoon to determine changes in the aquifer's water table following a rainfall event in the area.

We constrained certain variables to simplify the conceptual model and calculate groundwater flow through the unconfined aquifer of the Coatzacoalcos paleolagoon. We treated rainfall as the only recharge source, omitting runoff, evapotranspiration, moisture, river-stage effects, tidal effects, and spatially variable recharge (**Figure 9**).

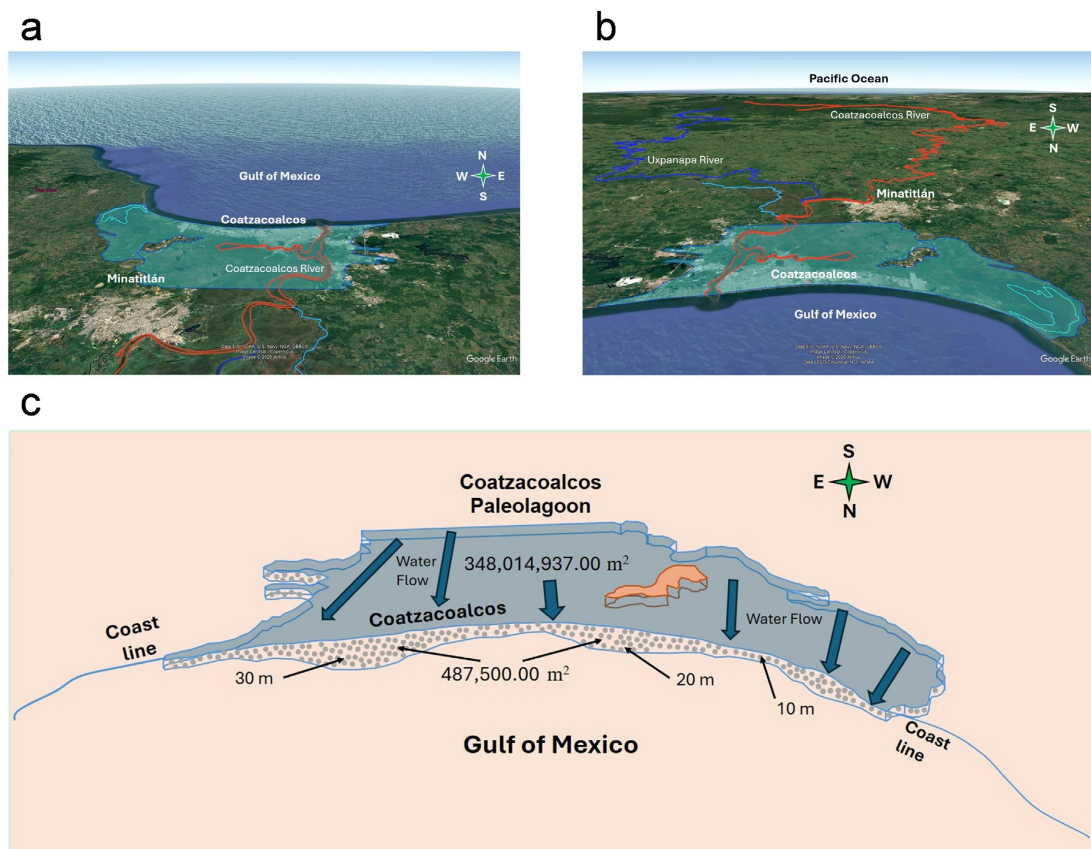


Figure 9. Conceptual model. (a) South-to-north view and (b) north-to-south view of the Coatzacoalcos paleolagoon. (c) Conceptual model of the paleolagoon area with a variable aquifer thickness of 10 to 30 m (no scale).

The stratigraphy of the paleolagoon is complex due to sedimentation processes in this type of geological environment, where fluvial currents, Gulf of Mexico coastal currents, and winds distribute sediments according to the energy of each one at different times.

In [29], geotechnical borehole results (**Table 6**) showed that the stratigraphy

within the Coatzacoalcos paleolagoon is complex and heterogeneous. The unconfined aquifer consists of unconsolidated sediments, primarily medium to fine sand, with small amounts of silt and clay (>5%). However, he identified thin silt and clay lenses (1 - 3 m) in some geotechnical boreholes.

In this type of geological environment, sediment distribution is irregular, resulting in localized deposits with varying grain sizes. Consequently, the deposits consist primarily of sand, silt, and clay layers. However, we observed thin horizons containing angular fragments of older rock alongside younger sand, silt, and clay that filled the paleolagoon, reflecting distinct sedimentation and erosion events over multiple cycles.

Based on geotechnical borehole data (**Table 6**), the maximum aquifer thickness is about 30 m in some areas of the paleolagoon and about 10 m in others.

Additionally, the geotechnical soundings found the water table at depths ranging from 0.5 to 5.8 m below ground level in the geotechnical boreholes.

[29] did not include the ground-level elevation (masl) for each geotechnical sounding site, and the soundings were also conducted intermittently over several years.

In May 2015, during the dry season, a vertical electrical sounding (VES) was conducted on the grounds of the Universidad Veracruzana in Coatzacoalcos, Veracruz. The results indicated that the water table was at a depth of 1.41 m.

In June 2024, after a dry period, manual drilling was carried out on land belonging to the Universidad Veracruzana in Coatzacoalcos, Veracruz, to measure the water table level of the free aquifer. The result showed a depth of 1.30 m. Two weeks later, heavy rainfall occurred, and two days after that, another manual borehole was drilled at the site to determine the groundwater depth; the result was 0.80 m. These two measurements show a 0.50 m variation in the water table.

Table 6. Geotechnical boreholes drilled along the coastline of the Coatzacoalcos paleolagoon. The table shows borehole coordinates, total depth, water table level, and depth intervals for the various sediment strata [29].

Geotechnical Soundings (GS)						
	UTM Coordinates mE mN	Total depth (m)	Freatic Level (m)	Depths Sand (m)	Depths Silt (m)	Depths Clay (m)
GS 01	338533.4	2006596.2	30.5	-3.8	0.0 - 13.0 18.0 - 24.0	13.0 - 15.0 24.0 - 30.0
GS 02	339012.2	2006457.2	15.6	-0.5	0.0 - 15.6	
GS 03	339488.5	2006240.3	40.0	-3.7	0.0 - 21.0	21.0 - 40.0
GS 04	343321.9	2006855.1	10.8	-5.8	0.0 - 10.8	
GS 05	344101.8	2006788.2	20.2	-4.1	0.0 - 15.0	15.0 - 20.2
GS 06	344623.0	2007206.0	25.0	-1.8	0.0 - 9.0 16.0 - 25.0	9.0 - 13.0 13.0 - 16.0
GS 07	345150.4	2007354.0	25.2	-2.3	0.0 - 13.0 18.0 - 25.2	13.0 - 18.0
GS 08	346036.6	2007413.1	38.6	-1.8	0.0 - 14.0 15.0 - 30.0	14.5 - 15.0 30.0 - 34.0 34.0 - 38.6
GS 09	349484.9	2007811.1	14.4	-1.8	0.0 - 14.4	

To simulate water recharge and discharge in the Coatzacoalcos paleolagoon and their influence on aquifer water table fluctuations, we calculated the paleolagoon's area using Google Earth; the result was 348,014,937.00 m². Based on the paleolagoon's surface area and precipitation (mm), we calculated the volume of rainwater (m³/d) falling on it for four precipitation scenarios.

To calculate the daily volume of water flowing from the aquifer into the sea along the coast (discharge), we determined the aquifer's cross-sectional area. We did this by considering the length of the coast and the aquifer's average thickness. In this case, the aquifer thickness ranged from 10 to 30 m; however, most of the range was at 10 m. Consequently, we adopted a general thickness of 15 m. The aquifer cross-sectional area was 487,500.00 m².

We then calculated the average apparent groundwater velocity toward the sea from tests on sediment samples collected near the coastline (Table 7). The average velocity was 29.95 m/d. The daily discharge volume was 13,279,500.00 m³/d. This volume remains constant across the four simulated scenarios.

For simplicity, we used precipitation/day from the Coatzacoalcos and Cangrejera weather station data, assuming 100% infiltration as recharge and effective recharge as recharge minus discharge to the Gulf of Mexico, using an average apparent groundwater velocity along the coastline.

Using data from the Coatzacoalcos and La Cangrejera weather stations, we considered four possible precipitation scenarios for the Coatzacoalcos paleolagoon area, excluding precipitation and runoff in areas located outside its surface.

Table 7. Apparent groundwater flow velocities in sediment samples collected near the shoreline in the discharge zone of the Coatzacoalcos paleolagoon.

Apparent groundwater flow Velocity (m/d)									
S1	S2	S3	S4	S5	S6	S7	S8	S20	S21
13.68	17.23	28.80	23.90	27.57	29.18	22.69	38.45	55.7	42.26

Average apparent Velocity: 29.95 m/d.

Scenario 1. Coatzacoalcos station, date: March 29, 2026, precipitation: 26.0 mm/d.

Based on the precipitation on March 29, 2026 (0.026 m) and the paleolagoon area, we calculated a rainwater recharge volume of 9,048,388.36 m³.

We subtracted the water discharge volume across the coastline (14,600,625.00 m³/d) from the paleolagoon's water recharge volume (9,048,388.36 m³/d), resulting in -5,552,236.64 m³/d. In other words, discharge exceeds aquifer recharge. This result could reflect a 0.016 m/d drop in the water table.

Scenario 2. Coatzacoalcos Station, date: December 30, 2025, precipitation: 123.0 mm/d.

Based on the precipitation recorded on December 30, 2025 (0.123 m), the rainwater volume was 42,805,837.25 m³, recharging the paleolagoon aquifer.

Effective recharge volume equals the recharge volume (42,805,837.25 m³) mi-

nus the aquifer discharge volume ($14,600,625.00 \text{ m}^3$) across the coastline, resulting in $28,205,212.25 \text{ m}^3/\text{day}$. Effective aquifer recharge could raise the water table by 0.081 m/d .

Scenario 3. Coatzacoalcos Station, date: October 2, 2024, precipitation: 258.0 mm/d .

Based on the precipitation recorded on October 2, 2024 (0.258 m), we obtained a rainwater recharge volume of $89,787,853.75 \text{ m}^3/\text{d}$.

That is, we calculated the effective recharge volume as the recharge ($89,787,853.75 \text{ m}^3/\text{day}$) minus the discharge through the aquifer's coastline ($14,600,625.00 \text{ m}^3$), resulting in $75,187,228.75 \text{ m}^3/\text{d}$. Therefore, the effective recharge volume could represent a water-table rise of 0.216 m/d .

Scenario 4. La Cangrejera Station; date: November 20, 2000; precipitation: 390.4 mm/d .

With a precipitation of 0.3904 m on November 20, 2000, we obtained a recharge volume of $135,865,031.40 \text{ m}^3/\text{day}$ for the paleolagoon.

The effective rainwater recharge volume equals the recharge ($135,865,031.40 \text{ m}^3$) minus the aquifer discharge ($14,600,625.00 \text{ m}^3$), resulting in $121,264,406.40 \text{ m}^3/\text{day}$. Therefore, this effective recharge volume corresponds to a water-table rise of 0.348 m/d .

If we consider a daily rainfall event with this volume of precipitation over three days, we could observe a water-table rise of 1.044 m . This fluctuation is significant and could help prevent flooding in vulnerable areas.

9. Vulnerable Areas to Flooding

The first inhabitants established the city center of Coatzacoalcos near the western bank of the Coatzacoalcos River, and the port area was located south of the coastal dunes (aeolian sediments) in alluvial sediment areas; the generally flat topography facilitated the construction of docks for loading and unloading goods transported by ship.

Over time, the city expanded northward, eastward, and westward along the eastern bank of the Coatzacoalcos River, within the coastal dune zone; this entire area constitutes the city's higher ground. The city also expanded southward into low-lying areas near the swamps, making this section most vulnerable to heavy rainfall and flooding (**Figure 10**).

The southern part of the city is generally flat, but its topography is irregular, rising between 1 and 4 meters above sea level. In this area, the water table lies approximately 1 meter above sea level. This ground elevation indicates that a change of just a few meters ($1 - 3 \text{ m}$) could flood extensive low-lying areas in southern Coatzacoalcos.

Based on Scenario 4 data, during a weather event with four consecutive days of heavy rainfall, the water table would rise by approximately 1.39 m . This calculation indicates that all areas below 2.39 meters above sea level could flood.

The estimates in this study used a limited set of variables, including water-table

rise. In contrast, we excluded surface water accumulation resulting from sediment saturation. The results indicate that the sediments in low-lying areas have an apparent hydraulic conductivity of 16.18 m/d, suggesting good water mobility. This condition helps mitigate the impacts of high-precipitation weather events. However, the risk could increase significantly if a large volume of water enters from the south due to the Coatzacoalcos River.

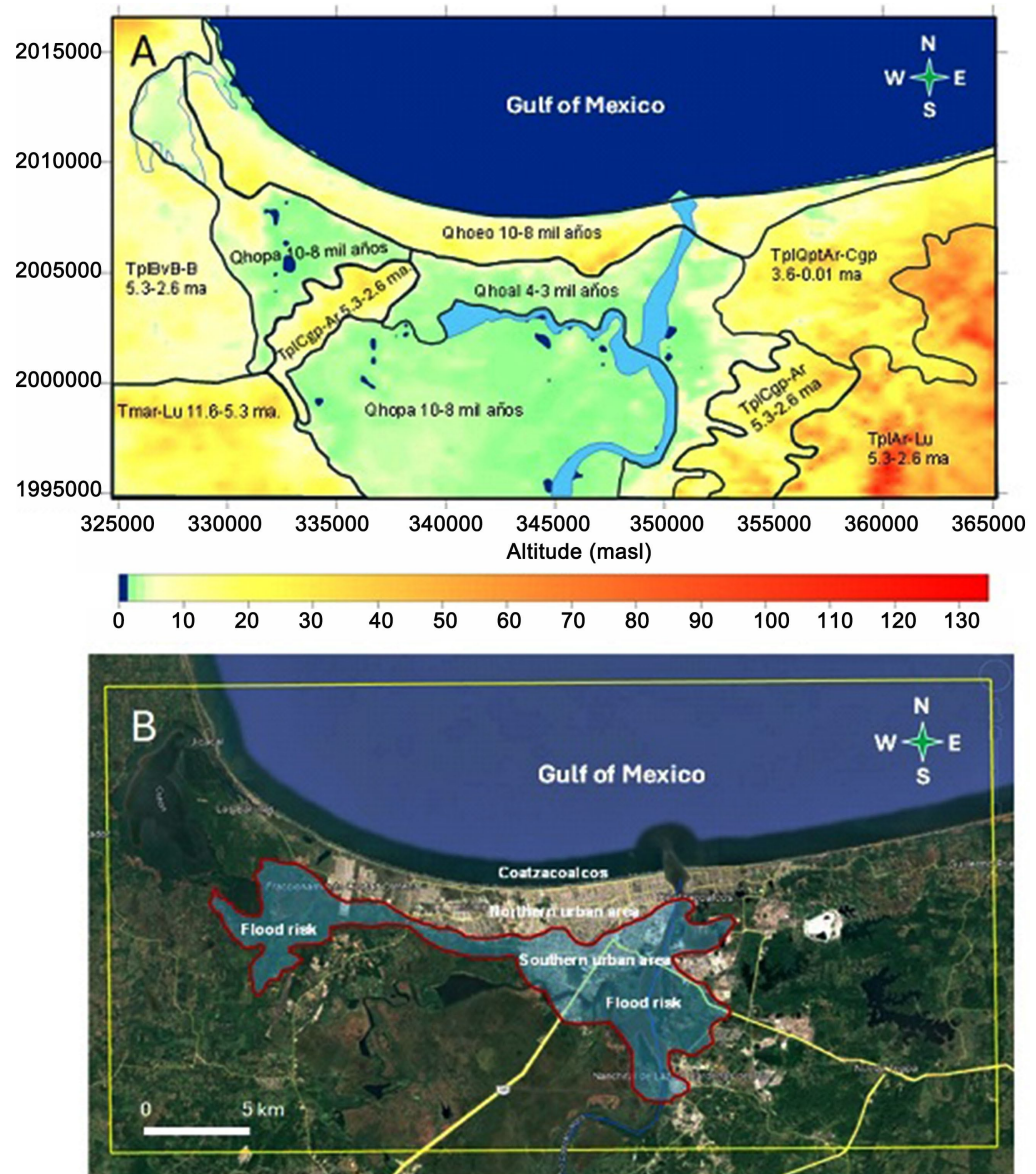


Figure 10. Flood vulnerability in the urban area of Coatzacoalcos. (A) Topographic relief of the study area within the Coatzacoalcos paleolagoon. Green areas are the lowest and have a high flood risk. (B) Southern area of Coatzacoalcos, where ground elevations range from 1 to 4 masl, and the water table is at approximately 1 masl.

10. Discussion

The grain-size analyses and apparent groundwater flow velocity tests reflect the

hydrogeological characteristics of sediments outcropping within and outside the Coatzacoalcos paleolagoon area; at a regional scale, these parameters provide a simple conceptual model for understanding groundwater flow dynamics and behavior (**Figure 7** and **Figure 9**).

However, developing a more detailed geohydrological model requires more samples from less widely dispersed sites; therefore, we limited this study to the samples we could collect.

The results indicated that the sediment type of each geological formation outcropping in the study area correlates with a specific grain-size distribution and with the apparent groundwater flow velocity through the rock (Apparent hydraulic conductivity). However, we also observed some variations depending on the sample location.

Sediments from the same geological unit varied in grain-size distribution and hydraulic conductivity over relatively short distances, indicating distinct sedimentological characteristics within the same unit. These variations resulted from the mode of sediment transport and the energy level involved (wind or fluvial currents). Samples S8, S20, and S21, which correspond to sediments with higher coarse-sand content, illustrate this case. Sample S21 was collected from the eastern bank of the Coatzacoalcos River and indicates a high-energy depositional environment, in contrast to wind-deposited coastal sediments.

For example, samples S1, S2, S3, and S4 are from the Universidad Veracruzana, Coatzacoalcos Campus (**Figure 8**). Their grain-size distributions are very similar; however, the apparent velocities differed: 13.68 m/d for S1, 17.23 m/d for S2, 28.80 m/d for S3, and 23.90 m/d for S4. The distances between sampling sites were small (110 - 195 m). We think that the difference in apparent velocities is due to the arrangement of sediment grains during deposition.

Likewise, another noteworthy result was the grain-size analysis and the findings regarding apparent groundwater flow velocities in samples collected outside the Coatzacoalcos paleolagoon area (**Figure 7**, **Table 5**). Sediments surrounding the paleolagoon are volcanoclastic, distinct from those that fill it.

Based on the grain-size analysis results, samples collected outside the paleolagoon exhibited distinct distributions, making it difficult to form affinity groups (**Figure 4(A)**). Although some samples did not show similar grain-size distributions, they displayed very similar apparent velocities. For instance, samples S18, S11, and S16 showed values ranging from 0.58 to 1.03 m/d (**Figure 4(B)**). Samples S19B, S17, S13, and S19A showed values ranging from 2.44 to 4.32 m/d (**Figure 4(C)**). Samples S12 (5.16 m/d) and S10 (8.14 m/d) showed similar values (**Figure 4(D)**). Only S15 (13.88 m/d) showed a high value, unlike the others (**Figure 4(E)**). We interpreted the apparent velocities in samples S10 and S15 as indicating that they come from the paleolagoon transition boundary, which contains different mixtures of paleolagoon sediments and volcanoclastic sediments from the surrounding area.

The different grain-size distributions and similar apparent velocities suggest

how sediment grains settled during deposition at each location. We submit this observation for discussion.

Finally, estimates of water table fluctuations driven by precipitation events in the paleolagoon area allow us to characterize its behavior under four scenarios using meteorological data from the study area, thereby identifying areas most vulnerable to flooding. For example, with a precipitation of 0.3904 m/d during a weather event with four consecutive days of heavy rainfall, the water table could rise by approximately 1.39 m. Zones below 2.39 masl, where the soil level is between 1 and 3 masl and the water table is at 1 masl, could have a high risk of flooding (**Figure 10**).

We limited the number of variables to use a simple conceptual model; therefore, to strengthen the information and develop a more detailed model, future studies could consider more variables and samples for analysis.

11. Conclusions and Recommendations

Grain-size analyses and apparent groundwater flow velocity tests performed on 22 samples collected in the study area reflect the geohydrological characteristics of sediments both inside and outside the Coatzacoalcos paleolagoon.

The results showed that grain-size distribution controls the hydrodynamic behavior (Apparent hydraulic conductivity) of the sediments. Grain size varies within the same sediment type (geological formation) across sample locations, reflecting variations in sedimentation processes.

Grain-size distribution influences sediment hydrodynamic behavior, and small changes in grain-size distribution can reflect changes in apparent groundwater flow velocity; sediment-grain arrangement during deposition can also modify hydraulic conductivity.

In contrast, apparent velocity tests on the samples indicated that sediments within the paleolagoon area showed high apparent velocities. Those outside it showed low apparent velocities. Except for samples S10 and S15 from the transitional boundary of the paleolagoon.

Estimates of water table changes resulting from heavy precipitation enabled us to identify the most vulnerable areas to flooding in the municipality of Coatzacoalcos.

We recommend that, for future work, more samples be collected for grain-size analysis and apparent groundwater flow velocity tests to generate a more detailed geohydrological model of the area.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] Barousse-Moreno, E. and Olaya-Mira, C.E. (2013) Aspectos Geotécnicos más Relevantes del Túnel Sumergido de Coatzacoalcos. *Geotecnia*, No. 229, 20-28.
<https://smig.org.mx/archivos/pdf/REV229.pdf>
- [2] Gobierno de México (2026) Proyectos México, Oportunidades de inversión, Puertos.
<https://www.proyectosmexico.gob.mx/como-invertir-en-infraestructura-en-mexico/ciclo-inversion/ciclos-puertos/>
- [3] Credlix (2025) Cómo se conecta México con el mundo: las rutas marítimas más importantes.
<https://www.credlix.com/es-mx/blogs/como-se-conecta-mexico-con-el-mundo-las-rutas-maritimas-mas-importantes>
- [4] Multitrans Logistics Solutions (2026) Rutas marítimas clave para el comercio internacional de México.
<https://multitranslogistics.com.mx/rutas-maritimas-comercio-internacional-mexico/>
- [5] Secretaría de Marina (2024) Programa Institucional del Corredor Interoceánico del Istmo de Tehuantepec 2025-2030. Diario Oficial de la Federación, 68 pp.
<https://dof.gob.mx/2025/SEMAR/ProgramaInstitucionalCIIT.pdf>
- [6] Secretaría de Protección Civil (2026) Diagnóstico de las inundaciones en las Cuencas de los Ríos Principales del Estado de Veracruz: Cuenca del Río Coatzacoalcos, Atlas Estatal de Riesgos, Dirección General de Prevención de Riesgos. Gobierno del Estado de Veracruz, 47pp.
https://www.veracruz.gob.mx/proteccioncivil/wp-content/uploads/sites/5/2026/04/Diagnostico_Cuenca_Rio_Coatzacoalcos_2026.pdf
- [7] Sistema Meteorológico Nacional (2026) Registro diario histórico, Base de datos, Estación Meteorológica 30456. La Cangrejera, Coatzacoalcos, CONAGUA.
https://smn.conagua.gob.mx/tools/RESOURCES/Normales_Climatologicas/Diarios/ver/dia30456.txt
- [8] Aoki, A.M. and Sereno, R. (2006) Evaluación de la infiltración como indicador de calidad de suelo mediante un microsimulador de lluvias. *AgriScientia*, **23**, 23-31.
<https://doi.org/10.31047/1668.298x.v23.n1.2688>
- [9] Ávila-Dávila, L., Soler-Méndez, M., Madrona-Sánchez, P., Ruiz-Canales, A., Bautista-Capetillo, C.F., González-Trinidad, J., *et al.* (2019) Análisis de la velocidad de infiltración del agua en el suelo saturados mediante lisímetros de pesada. *Congreso Ibérico de Agroingeniería*, Huesca, 3-6 Septiembre 2019, 642-648.
https://doi.org/10.26754/c_agroing.2019.com.3370
- [10] Méndez-González, J., Flores, A., Zermeno-González, A., Samaniego-Moreno, L. and Sosa-Díaz, L. (2026) InfiltrR: Una Herramienta para Modelar la Infiltración de Agua en el Suelo. *Terra Latinoamericana*, **44**, 1-12.
- [11] Bothma, C.B., van Rensburg, L.D. and le Roux, P.A.L. (2012) Rainfall Intensity and Soil Physical Properties Influence on Infiltration and Runoff under Infield Rainwater Harvesting Conditions. *Irrigation and Drainage*, **61**, 41-49.
<https://doi.org/10.1002/ird.1680>
- [12] Liu, X., He, Y., Zhang, T., Zhao, X., Li, Y., Zhang, L., *et al.* (2015) The Response of Infiltration Depth, Evaporation, and Soil Water Replenishment to Rainfall in Mobile Dunes in the Horqin Sandy Land, Northern China. *Environmental Earth Sciences*,

- 73, 8699-8708. <https://doi.org/10.1007/s12665-015-4125-0>
- [13] Ramírez-León, H., Torres-Bejarano, F., Herrera-Díaz, E. and Rodríguez Cuevas, C. (2010) Hidrodinámica del río Coatzacoalcos y estimación de las posibles inundaciones ante escenarios del cambio climático. In: Botello, A.V., Villanueva-Fragoso, S., Gutiérrez, J. and Rojas Galaviz, J.L., Eds., *Vulnerabilidad de las zonas costeras mexicanas ante el cambio climático*, Semarnat-INE, UNAM-ICMyL, Universidad Autónoma de Campeche, 381-402.
https://www.researchgate.net/profile/Claudia-Agraz-Hernandez/publication/280446616_El_manglar_otros_humedales_costeros_y_el_cambio_climatico/links/55b55b8408ae9289a08a6a68/El-manglar-otros-humedales-costeros-y-el-cambio-climatico.pdf#page=399
- [14] Vergara-Tenorio, M.C., Ellis, E.A., Cruz-Aguilar, J.A., Alarcón Sánchez, L.C. and Galván del Moral, U. (2011) La conceptualización de las inundaciones y la percepción del riesgo Ambiental. *Política y Cultura*, No. 36, 45-69.
<https://polcul.xoc.uam.mx/index.php/polcul/index>
- [15] Novakowski, K., Bickerton, G., Lapcevic, P., Voralek, J. and Ross, N. (2006) Measurements of Groundwater Velocity in Discrete Rock Fractures. *Journal of Contaminant Hydrology*, **82**, 44-60. <https://doi.org/10.1016/j.jconhyd.2005.09.001>
- [16] Matić, N., Vučić, F., Čupić, D. and Maldini, K. (2025) A Novel Methodology of Determination of the Mean Translational Velocity of Groundwater Flow and Its Application in the Karst. *Science of the Total Environment*, **982**, Article ID: 179586.
<https://doi.org/10.1016/j.scitotenv.2025.179586>
- [17] Essouayed, E., Annable, M.D., Momtbrun, M. and Atteia, O. (2019) An Innovative Tool for Groundwater Velocity Measurement Compared with Other Tools in Laboratory and Field Tests. *Journal of Hydrology X*, **2**, Article ID: 100008.
<https://doi.org/10.1016/j.hydroa.2018.100008>
- [18] Reimus, P.W. and Arnold, B.W. (2017) Evaluation of Multiple Tracer Methods to Estimate Low Groundwater Flow Velocities. *Journal of Contaminant Hydrology*, **199**, 1-13. <https://doi.org/10.1016/j.jconhyd.2017.02.003>
- [19] Muñoz-Aldape, A., Montoya-Mendoza, J., Lango Reynoso, F., Castañeda Chávez, M.R., Ortiz-Muñiz, B. and Arenas-Fuentes, V.E. (2024) Acuíferos Costeros: Descarga de Agua Subterránea en el Sistema Arrecifal Veracruzano. *Impluvium, Gestión del Agua Bajo el Enfoque de las Cuencas al Mar*, **11**, 44-50.
<https://www.agua.unam.mx/impluvium.html>
- [20] Arenas-Fuentes, V.E., Muñoz-Aldape, J., Neri-Flores, I. and Hernández, J.L. (2024) Flujos de Agua Subterránea en las Costas y Mares de México. *Impluvium, Gestión del Agua Bajo el Enfoque de las Cuencas al Mar*, **11**, 51-57.
<https://www.agua.unam.mx/impluvium.html>
- [21] Ontiveros-Cuadras, J.F., Olivares-Rubio, H.F., Carnero-Bravo, V., Elías-García, V.G., Salazar-Remigio, L., Santiago-Pérez, S., *et al.* (2026) Assessment of Potentially Toxic Elements in Surface Sediments along the Lower Coatzacoalcos River Basin, Mexico. *Environmental Geochemistry and Health*, **48**, Article No. 129.
<https://doi.org/10.1007/s10653-026-03005-1>
- [22] SGM (2004) Carta Geológico-Minera Coatzacoalcos E15-1-4, Veracruz, Oaxaca y Tabasco. <https://www.sgm.gob.mx/CartasPdf/Inicio.jsp>
- [23] CONAGUA (2024) Actualización de la Disponibilidad Media Anual de Agua en el Acuífero Costero de Coatzacoalcos (3012), Estado de Veracruz. Subdirección General Técnica, Gerencia de Aguas Subterráneas, 1-33.
https://sigagis.conagua.gob.mx/gas1/Edos_Acuiferos_18/veracruz/DR_3012.pdf

- [24] Infante-Pacheco, V.E. (2025) Geological Evolution of the Southern Coast of the Gulf of Mexico: Geomorphological and Sedimentological Evidence from the *Coatzacoalcos paleolagoon*. *International Journal of Geosciences*, **16**, 405-422.
<https://doi.org/10.4236/ijg.2025.167020>
- [25] University of Granada (n.d.) Densidad del agua a diferentes temperaturas. Densidad del agua líquida entre 0 °C y 100 °C.
https://www.ugr.es/~elenasb/teaching/densidadtemperatura_agua_tabla.pdf
- [26] Emeka, A.L. and Samuel, Y.M. (2023) Estimation of Aquifer Hydraulic Parameters Using Electrical Resistivity Method: A Case Study for Damaturu, Northeast Nigeria. *Dutse Journal of Pure and Applied Sciences*, **9**, 191-202.
<https://doi.org/10.4314/dujopas.v9i2a.19>
- [27] Woessner, W.W. and Poeter, E.P. (2020) Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow. The Groundwater Project, 212 p.
<https://doi.org/10.21083/978-1-7770541-2-0>
- [28] Bouwers, H. (1978) Groundwater Hydrology. McGraw-Hill, 402-406.
- [29] García-Ovaldo, A.J. (2028) Contribución a la zonificación geotécnica de la zona urbana de la ciudad de Coatzacoalcos, Ver. Tesis, Universidad Veracruzana, 51 p.