Article

Not peer-reviewed version

Evaluation of Wastewater Discharge Reduction Scenarios in the Buenaventura Bay

Francisco Fernando Garcia * , Gustavo Chang , Gustavo Hernandez

Posted Date: 7 February 2023

doi: 10.20944/preprints202302.0109.v1

Keywords: Hydrodynamic model; Water quality model; Colombian Pacific coast; Marine pollution; Fecal coliforms

Article

Evaluation of Wastewater Discharge Reduction Scenarios in the Buenaventura Bay

Francisco Garcia. [1,*], Gustavo Chang. [2] and Gustavo Hernandez. [2,]

[1] Gestión Evaluación y Monitoreo Ambiental - GEMA, Santa Marta 470004, Colombia; fcofdogarcia@gmail.com

[2] Department of Civil Engineering, Magdalena University, Santa Marta 470004, Colombia; gchang@unimagdalena.edu.co (GC)) ghernandez@unimagdalena.edu.co (GH)

* Correspondence: fcofdogarcia@gmail.com

Abstract: The RMA11 water quality model, which has been previously calibrated and validated, was coupled with the RMA10 3D hydrodynamic model to evaluate sanitation scenarios in Buenaventura Bay. The bay receives direct discharge of untreated wastewater from 500,000 people through 695 outlets along the coast. Five different effluent reduction scenarios were proposed and compared based on fecal coliform concentration as an indicator. The areas where values exceed the standard for primary contact were also used to evaluate the scenarios. The model results indicate poor water quality in the bay and how that the situation will become even more severe if immediate action is not taken. The proposed reduction in discharges in stages will have temporarily more severe effects than the current situation, but these will end when the treatment plant becomes operational. However, even with the plant in operation, complete sanitation of the bay cannot be achieved, and further measures must be considered.

Keywords: Hydrodynamic model; Water quality model; Colombian Pacific coast; Marine pollution; Fecal coliforms

1. Introduction

In Buenaventura Bay (Figure 1), the second most important container port terminal in Colombia operates due to the volume of cargo moved. Nearly 45% of Colombia's international maritime cargo is moved through this logistics hub. In 2020, Colombia mobilized more than 99 million tons of cargo and received around 35 tons and 61 thousand ships on both the Atlantic and Pacific coasts, reaching 2 million containers for the year. Buenaventura was positioned as the second regional port company with the largest participation in the country's maritime export routes [1].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

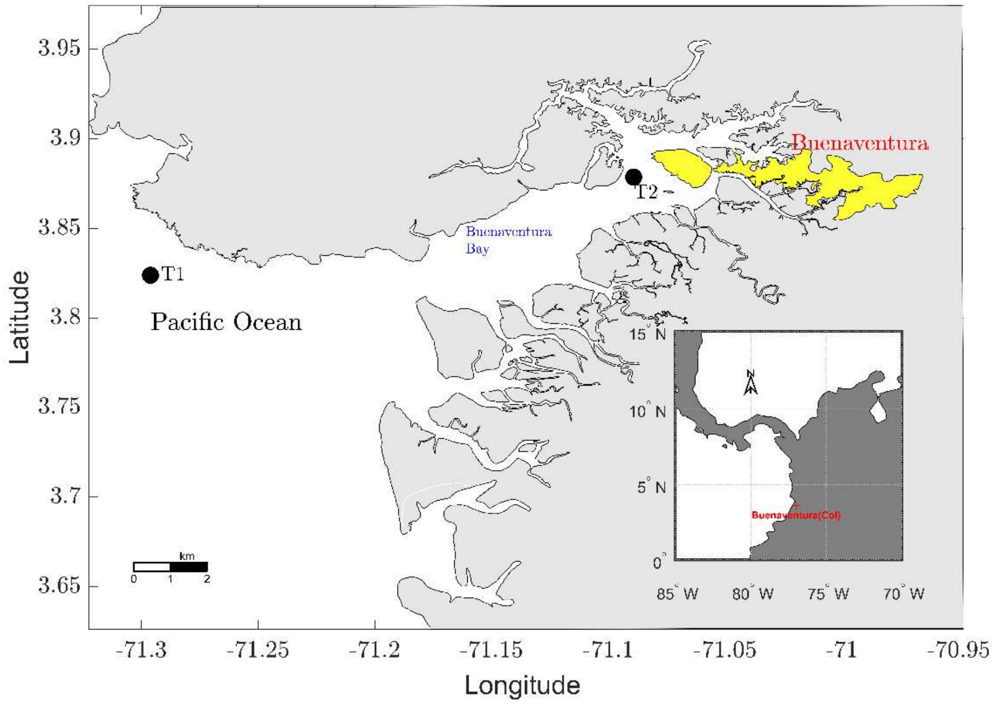

Figure 1. Buenaventura bay localization.

Despite having Colombia's most important port on the Pacific, Buenaventura is currently considered a municipality with the highest levels of monetary poverty and multidimensional poverty, with a poor level of development and socioeconomic conditions for its inhabitants. According to the results of the Continuous Household Survey (ECH) conducted by the National Administrative Department of Statistics (DANE), 62,7% of the population lives in poverty and 20,9% are considered indigent. The coverage of basic services, particularly water, is 73,2%, and sanitation is 61,0% [2]. It is the most important population settlement on the Colombian Pacific coast with 500.000 inhabitants, with a varied ethnic composition including indigenous and mestizo Afro-descendants. 30% of the population lives in stilt houses and palafitic dwellings located in low tide areas, which are classified as public property under Colombian law [3,4].

The Bay of Buenaventura is considered a true estuary due to its semi-enclosed body of water with a connection to the sea and contributions of fresh water from the rivers Dagua and Anchicaya. Chemical substances from economic and domestic activities carried out in the basins and bay have caused deterioration in the quality of water and the ecosystems, as evidenced by contamination indicator organisms in the communities above the water column (planktonic and benthic) and in the mangroves [5]. This body of water has an average temperature of 26,4 °C, with a range between 23,3°C and 33,5°C. The general average salinity varies slightly between climatic seasons, being slightly higher in low rainfall seasons (13,0±8,3 Units Practical Salinity-UPS) compared to high rainfall seasons (11,0±5,8 UPS), confirming its estuarine characteristics. The historical average of dissolved oxygen was 6,08 ± 1,09 mg/L. Biochemical Oxygen Demand (BOD) is an average of 1,58 ± 1,75 mg/L. The bay shows contamination from domestic wastewater with thermotolerant coliforms (> 200 MPN/100mL) and Total Coliforms (>5000 MPN/100mL) [6].

The discharge of untreated wastewater is becoming a growing problem of environmental and sanitary contamination. This issue is not only limited to rivers and streams but also affects coastal areas, reducing the availability of water resources and restricting their use. It is estimated that 95% of domestic and 85% of industrial wastewater in Colombia are discharged without proper treatment, and 95% of agricultural wastewater is released without treatment [7]. The sewage system of Buenaventura has 695 discharges into the natural environment without any prior treatment, with an estimated daily domestic wastewater production of 61.164 m^3 being discharged into Buenaventura Bay [8]. The estimated pollutant load of the untreated wastewater discharged into Buenaventura Bay

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

was 2.925 t/year of organic matter in the form of BOD, 702 t/year of dissolved inorganic nitrogen, 47 t/year of dissolved inorganic phosphorus, 2.925 t/year of Total Suspended Solids (TSS), and 1,2 $x10^{19}$ t/year of coliform bacteria. The main tributaries provide a flow of 330 m^3/s to the bay, carrying 6.734 t/year of dissolved inorganic nitrogen, 12.298 t/year of BOD, and $5{,}81x10^{19}$ t/year of thermotolerant coliform bacteria [9].

A plan for managing and sanitizing wastewater discharge (PSMV) has been proposed to reduce and eliminate the 695 untreated discharges in Buenaventura. The plan is expected to take 30 years. To achieve this reduction, a new sewage infrastructure and a wastewater treatment plant will need to be constructed. As this infrastructure is being built and the number of discharges decreases, there will be a temporary concentration of the discharged flow in certain areas before the treatment plant becomes operational. This article assesses the impact of these temporary discharges on the water quality of Buenaventura Bay.

2. Materials and Methods

2.1. Study Area

Buenaventura Bay is located on the Colombian Pacific coast and its geographic coordinates range from 77,26 to 77,35 degrees west longitude and from 3,71 to 3,92 degrees north latitude (Figure 1). With an elongated, narrow configuration, the bay is approximately 21 kilometers long, with a width that varies between 3 and 11 kilometers. It has a single entrance called La Bocana, formed by a strait approximately 1,6 kilometers wide. The bay has an outer section that connects directly to the open sea and receives the influence of tides and currents, and an inner section with the characteristics of an estuary, with the discharge of fresh water from various tributaries. This provides an average flow of 345 m^3/s, mainly from the Dagua and Anchicayá rivers and the Pichidó, San Joaquín, Aguadulce, Gamboa, San Antonio, and Aguacate estuaries.

2.2. Wastewater Characterization

To determine the quality of wastewater discharged into Buenaventura Bay, a characterization campaign was conducted. The Fecal Coliforms (FC) were determined according to the Standard Methods for the Examination of Water and Wastewater [10]. The 695 wastewater discharge locations were georeferenced, and 100 (14,39%) of these were selected as a sample for characterization. Figure 2 shows the location of the sampled wastewater discharges.

Based on the characterization data, the discharges were categorized into three groups based on low, medium, and high flow. An average flow was calculated for each category. An estimated total wastewater discharge flow of 694 L/s was determined to flow into Buenaventura Bay. Table 1 displays the flows used for the categories of wastewater discharges in the simulations.

Table 1. Discharge flows were considered in the simulations.

Discharge Type	Flow (L/S)	Amount Discharges	Total Flow (L/s)
Low	0,74	316	233,84
Medium	1,01	252	254,52
High	1,62	127	205,74

2.2. Hydrodynamic and Water Quality Models Description

A coupling scheme combining the RMA10 3D hydrodynamic and RMA11 water quality models was used to simulate the hydrodynamic and water quality conditions in Buenaventura Bay. The RMA10 model simulates the velocity, pressure, and sediment fields in three dimensions [11–14]. The system of equations that the model solves is described from equations (1) to (6).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

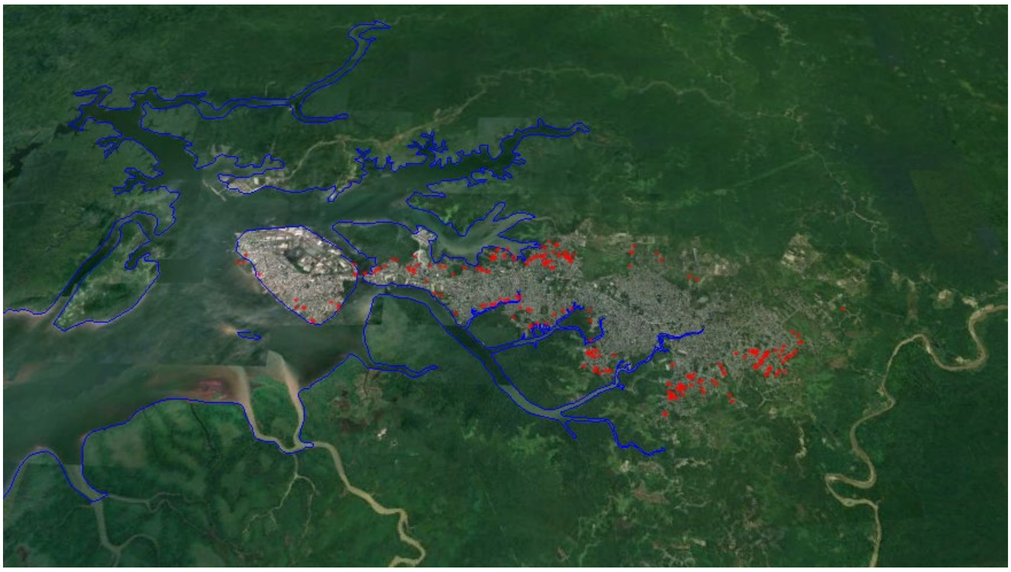

Figure 2. Location of wastewater discharges (red dots), blue line represents the coastline, Google Earth image.

The equations of movement in the three components of the cartesian field are shown by equations (1)–(3):

$$\rho.\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)-\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{xy}\frac{\partial u}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_{xz}\frac{\partial u}{\partial z}\right)+\frac{\partial p}{\partial x}-\Gamma_x=0, \quad (1$$

$$\rho.\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)-\frac{\partial}{\partial x}\left(\varepsilon_{yx}\frac{\partial v}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{yy}\frac{\partial v}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_{yz}\frac{\partial v}{\partial z}\right)+\frac{\partial p}{\partial y}-\Gamma_y=0, \quad (2$$

$$\rho.\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)-\frac{\partial}{\partial x}\left(\varepsilon_{zx}\frac{\partial w}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{zy}\frac{\partial w}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_{zz}\frac{\partial w}{\partial z}\right)+\frac{\partial p}{\partial z}+\rho.g-\Gamma_z=0 \quad (3$$

The continuity equation is presented in equation (4):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4$$

Advection–diffusion processes are presented in equation (5):

$$\frac{\partial s}{\partial t}+u\frac{\partial s}{\partial x}+v\frac{\partial s}{\partial y}+w\frac{\partial s}{\partial z}-\frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right)-\frac{\partial}{\partial y}\left(D_Y\frac{\partial s}{\partial y}\right)-\frac{\partial}{\partial z}\left(D_z\frac{\partial s}{\partial z}\right)-\theta s=0, \quad (5$$

And the equation of state is presented in equation (6):

$$\rho = F(s),\ (6) \quad (6$$

Where x, y, and z are the coordinates of the Cartesian system; u, v, and w are the velocities in the directions of the Cartesian system, p is the water pressure, t is time, ε_{xx}, ε_{xy}, ε_{xz}, ε_{yx}, ε_{yy}, ε_{yz}, ε_{zx}, ε_{zy}, ε_{zz} are the eddy turbulence coefficients, g is the acceleration due to gravity, D_x, D_Y, and D_z are the eddy diffusion coefficients, ρ is the density of water, Γ_x, Γ_y, and Γ_z are the external forces; s is the salinity, and θs is the salinity source/sink.

The RMA11 model, which uses the finite element method, has been used successfully to model water quality in estuaries, bays, lakes, and rivers [15–18]. It receives the velocity, temperature, and salinity fields from the RMA10 model and uses them to solve the advection-diffusion constituent transport equations [15]. The water quality relationships implemented in RMA11 are derived from QUAL2E, and for more information, the reader is referred to Brown and Barnwell [19]. In RMA11, coliform transport is modeled using three loss parameters: settling, decay in darkness, and light–sensitive decay. The equation for coliform growth (GC) is given by:"

$$GC = -(K_{C1} + K_{C2} + K_{C3}/d) * C_C \quad (7)$$

where C_C is the concentration of the coliform, (MPN/100mL), K_{C1} is the coliform die–off rate in darkness – temperature adjusted (1/day), K_{C2} is the coliform die–off rate due to light - temperature adjusted (1/day), K_{C3} is the coliform settling rate–temperature adjusted (m/day) and d is the water depth (m).

The temperature values computed in RMA11 were used to adjust the rate coefficients in the source/sink terms. These coefficients are input at 20°C and then corrected to the actual temperature (T) using Equation (8):

$$X_t = X_{20}\theta^{(T-20)} \quad (8)$$

where, X_t is the value of the coefficient at the local computed temperature X_{20} is the value of the coefficient at 20°C, θ is a dimensionless constant coefficient usually set to be 1,07 [20]. This correction was applied to K_{C1} and, K_{C3} , While K_{C2} dependent on the light intensity and is given for equation (9):

$$K_{C2} = 2{,}3026\frac{[L_i exp(-\lambda z_d)^{0.7}]}{L_c} \quad (9)$$

where L_i is the light intensity expressed in MJ/m^2–hr, L_c is the coliform light coefficient (hr.[MJ/m^2–hr]$^{0.7}$), λ is the light extinction coefficient (1/m), and z_d is the depth below the water surface for 3D (m).

2.3. Model Set up for Buenaventura Bay

The simulation domain was selected to cover an area of 430 km^2 and included both the inner and outer bay. The finite element mesh was created to closely follow the irregular coastline of the bay, using Mesh2D software [21,22]. The resulting mesh consisted of 19.672 elements, with lengths ranging from 15 to 500 meters, and 43.604 nodes. The triangular elements in the mesh were equilateral, which helped reduce the computational efforts. Figure 3 shows the resulting mesh generated by Mesh2D.

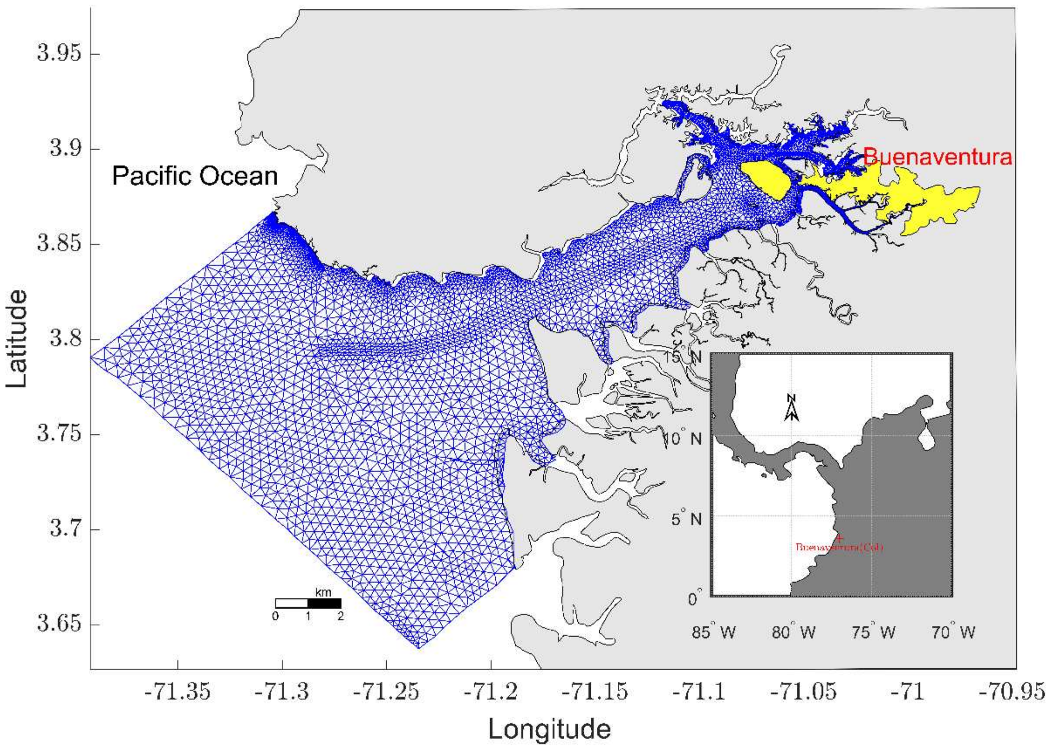

Figure 3. Buenaventura Bay finite element mesh.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

The bathymetry data used in the study were obtained from the CIOH nautical charts of the study area and digitized and interpolated in the finite element mesh nodes. The interpolated bathymetry is shown in Figure 4. The RMA 10 model used sigma coordinates and modified the system of equations to account for changes in the water surface elevation due to tides. The details of the modification can be found in the references Marthanty et al. [11] and Fosati et al. [12]. The finite element mesh was discretized into five layers in the vertical direction.

The open boundaries at the southeast, southwest, and northwest of the outer bay were forced with current, water level, salinity, and temperature data from the HYCOM global model [23]. Wind direction and speed, solar radiation, humidity, and air temperature data were taken from a meteorological station and considered uniform over the simulation domain. The simulation model was run for one year (2021) to determine the effect of wastewater discharges on Buenaventura Bay. Fresh water from the Dagua (66,10 m^3/s), Achicayá (98,90 m^3/s), Humane (30 m^3/s), Gamboa (30 m^3/s), Aguacate (10 m^3/s), San Antonio (20 m^3/s), Hondo (10 m^3/s), and Agua Dulce (80 m^3/s) rivers and estuaries were considered in the model. Mean flows of each river and estuary and mean temperature of 28°C were considered. Average fecal coliform concentrations of 28.960 and 4.724 MPN/100mL, were included in the Dagua and Achicaya rivers, respectively, as reported by Vivas et al. [9].

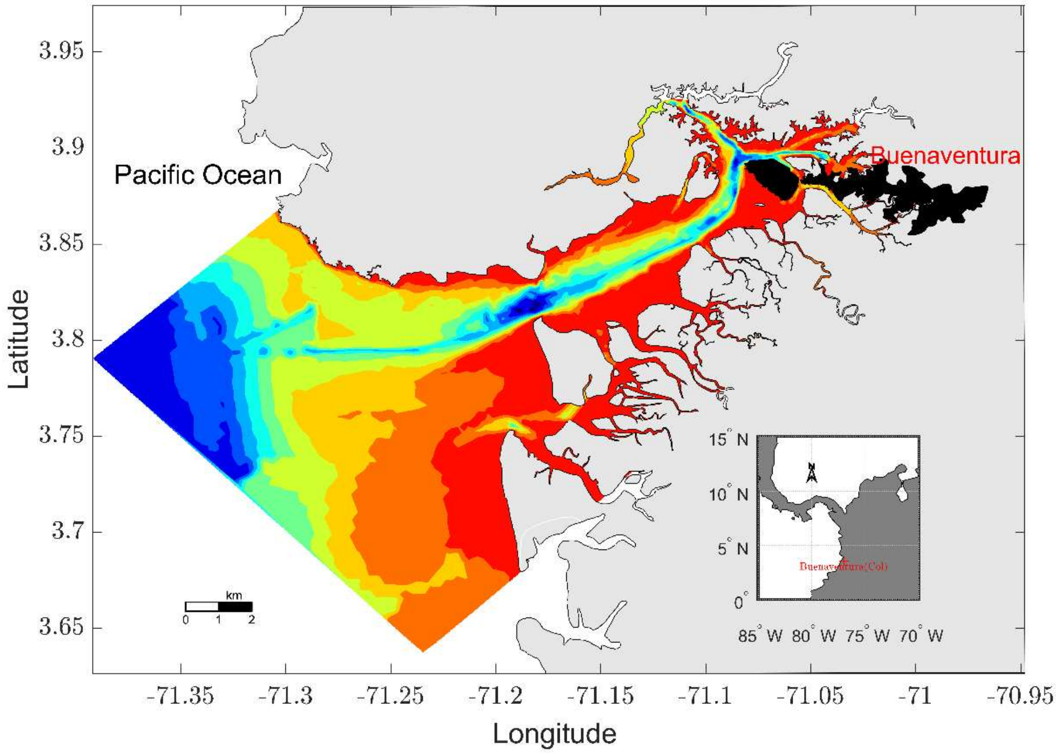

Figure 4. Simulation domain bathymetry, built-up area with black.

2.4. Calibration and Validation of Models

This research used a hydrodynamic and water quality model (RMA 10 and RM11) to evaluate the effect of wastewater discharge in Buenaventura Bay. The models were calibrated by comparing the results of the simulations with measurements of currents, tides, and FC concentrations (MPN/100mL). The calibration period was from February to March, whereas the validation period was from October to November. The purpose of selecting the calibration and validation period was to capture the seasonal variation in rainfall. The region experiences high rainfall of more than 6500mm/year and has two seasons with distinguishable rainy seasons, with the low rainy season occurring from January to June and the high rainy season occurring from July to December [24]. The monitoring station used for currents and tidal measurements is marked in Figure 1 as T1. For current measurements, AANDERAA RCM9 LW (0 to 300 cm/s) equipment was deployed at a depth of 6

 doi:10.20944/preprints202302.0109.v1

meters. The tidal measurements were made with AANDERAA WLR7 equipment (0 – 700 kPa), and both devices were programmed to take data every 15 min.

Weekly measurements of the FC concentration were taken at the measurement station marked as T2 in Figure 1; during the period from February to March to calibrate the RM11 water quality model, the measurement campaigns for validation were carried out from October to November at this same place. The FC measurements were taken at a depth of 1 meter in the seawater column.

To assess the reliability of the models in the calibration and validation processes, the root means square error -RMSE (equation (10)), and SKILL (equation (11)) estimators were used.

$$\mathrm{RMS} = \left\{\frac{1}{\mathrm{N}}\sum_{\mathrm{i=1}}^{\mathrm{N}}[\beta_{\mathrm{m}} - \beta_{\mathrm{d}}]^2\right\}^{1/2} \tag{10}$$

$$Skill = 1 - \frac{\sum[\beta_m - \beta_d]^2}{\sum(|\beta_m - \overline{\beta_d}| - |\beta_d - \overline{\beta_d}|)} \tag{11}$$

Were β_m is the measured parameter, β_d is the model result parameter, N is the number of samples in the time series, and $\overline{\beta_d}$ corresponds to the is the mean value of observation. According to Chen et al. [25], values of SKILL < 0.2 indicate of a poor performance of the model, while values close to 1 represent a perfect adjust.

2.5. Wastewater Discharge Reduction Scenarios

The Buenaventura´s PSMV proposed the construction of a sewerage infrastructure to eliminate untreated wastewater discharges into the Buenaventura Bay. Given the construction costs, it must be developed in stages that include the primary and secondary collectors to transport wastewater and two treatment plants and a submarine outfall for the final disposal of the treated wastewater. The current situation with the 695 existing discharges was the first simulation scenario proposed. The elimination of the discharges will be carried out with works that contemplate collected all the discharges to the sewage system to pass to 6 unique discharges that concentrate the flow of these. The six new concentrated discharges correspond to the second of the scenarios proposed in this study. In a later stage, it will go from six to two discharges concentrated in the sites where the treatment plants will be located. The third scenario considered the two untreated wastewater discharges, while the fourth stage contemplated these same discharges, removing 90% of the wastewater contaminants from them, that is, with the treatment plants in operation. Scenarios one, two, and three propose the reduction and concentration of the wastewater flow and its discharge without treatment. The final disposal of wastewater with a submarine outfall system was not the subject of the analysis of this study. A fifth scenario was proposed considering a future situation without a sanitation solution for the Bay of Buenaventura; it considers that the discharges persist over time, aggravated by the demographic and urban increase in Buenaventura. The location of the discharges in the scenarios two and three–four are presented in Figure 5. The location of the discharges in scenarios one and five correspond to the current location and are shown in Figure 2.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

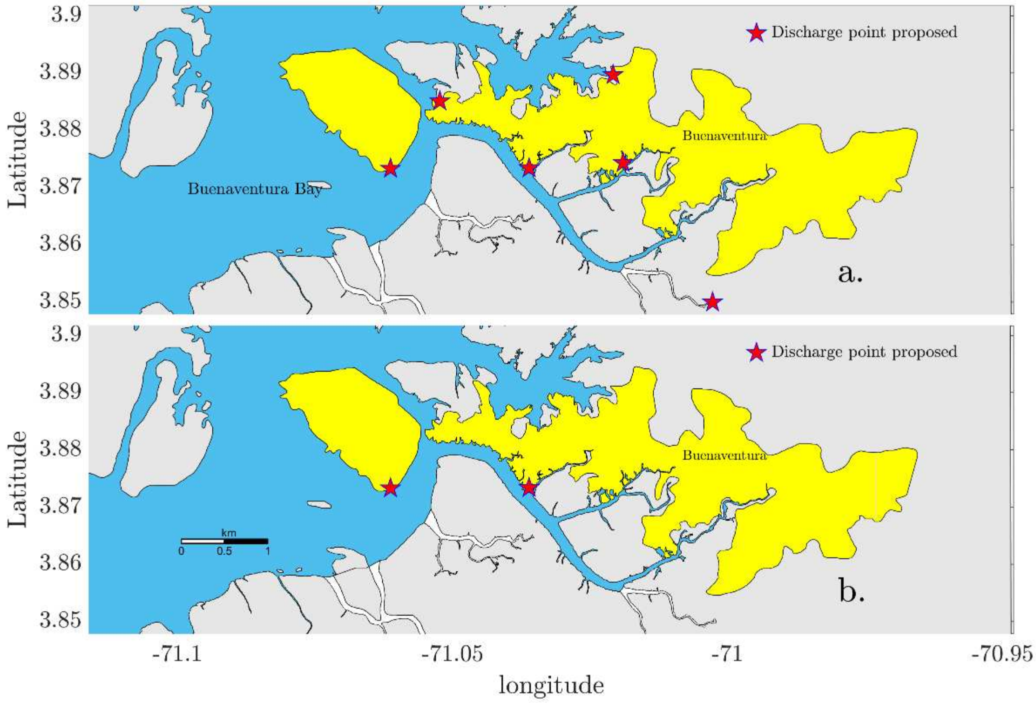

Figure 5. Discharge point in the scenarios proposed, a. scenario two; b. scenarios three and four.

3. Results

3.1. Characterization of Wastewater Discharges

The results of the FC concentration of the characterizations of the wastewater discharges to Buenaventura Bay are shown in Table 1. In the measurement campaigns, an average concentration of 8 × 10^8 MPN/100mL was found.

Table 2. Concentration of FC in wastewater discharge**.**

Parameter	*Unit*	*Maximum*	*Mean*	*Minimum*
Fecal Coliform	MPN/100mL	2 × 10^{10}	8 × 10^8	7 × 10^3

3.2. FC Concentration in the Water Column

16 measurement campaigns were carried out to determine the concentration of FC, 8 corresponded to the calibration phase of the water quality model, from February to March, one every week, and 8 in the validation period, from October to November. Mean values of 2,8 × 10^3 MPN/100mL were found for the calibration stage and 1,8 × 10^3 MPN/100mL for the validation. Table 2 shows the maximum, minimum, and average values of the sampling campaigns for each data set.

Table 2. Concentration of FC in the Wastewater Discharge.

	Unit	*Maximum*	*Mean*	*Minimum*
calibration	MPN/100mL	5× 10^3	3 × 10^3	1.2 × 10^3
validation	MPN/100mL	2.4× 10^3	1.4 × 10^3	4× 10^2

The one-way anova did not show significant differences (p= 0,478) between the two samples sets taken for the calibration and validation of the water quality model; therefore, it can be presumed that despite the difference in the rainy seasons in which the samples were taken, the concentrations tend to be similar given their origin, the discharge of wastewater into Buenaventura Bay.

3.3. Calibration Hydrodynamic Model

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

3.3.1. Sea Level

Values of 0,602 and 0,620 were obtained for the RSME estimator in the calibration periods in February-March and the validation periods in October-November, respectively. The SKILL showed values of 0,747 and 0,742 for the same periods. The comparison between the results of the model and the field measurements for tides at station T1 is presented in Figure 6.

3.3.3. Water Quality Model

The water quality model showed a predictive ability of 0,716 in the calibration stage and 0,799 in validation. A value close to 1 in the "skill" indicates high predictive ability, meaning the model is capable of accurately predicting data. A value close to 0 indicates low predictive ability, meaning the model is unable to predict data accurately. Given the favorable results obtained, it is considered that the model is capable of accurately predicting the water quality data in Buenaventura Bay, regarding FC. The RMSE values were 1 x 10^3 and 1,13 x 10^3 for calibration and validation, respectively. The graphical comparison of the field-measured data at station T2 and the model results is presented in Figure 9.

3.3.2. Currents

Evaluating the performance estimators of the model found an RMSE of 0,007 m/s and a Skill of 0,998 for the magnitude of the currents and an RMSE of 9,87 degrees and SKILL of 0,992 for the direction of the currents, both confirmed the excellent performance of the model to reproduce current data in the Bay of Buenaventura. The graphical comparison of the current roses for the data measured in the field and the model results confirm the results of these estimators (Figure 7).

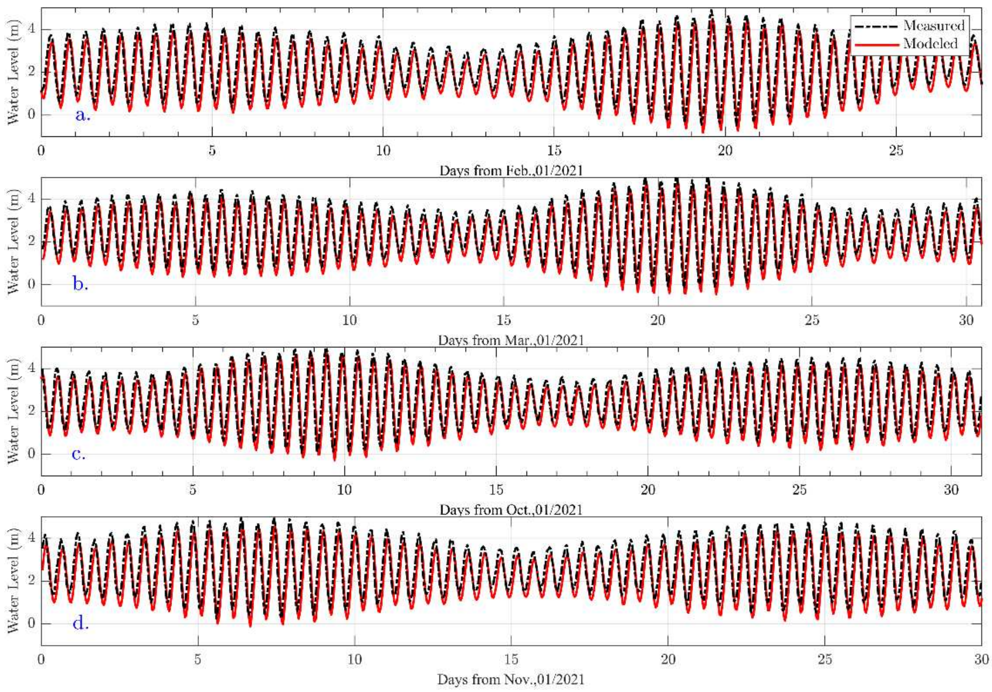

Figure 6. Sea water level comparation for simulations and measurements for, a. calibration in February, b. calibration in March, c. validation in October, and c. validation in November.

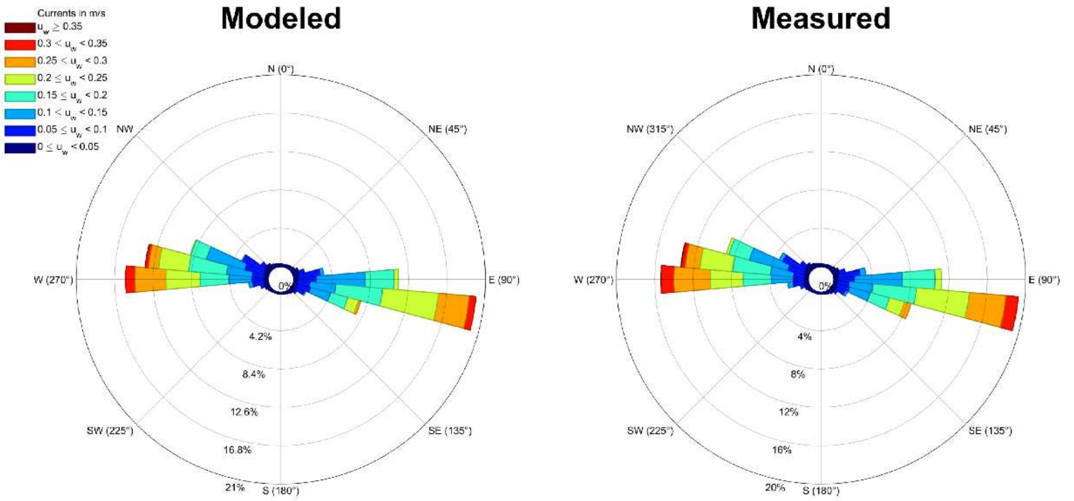

Figure 7. Currents roses comparation comparison for simulations and measurements for the calibration period.

Similar behavior was found in the evaluation of the model during the validation period. For the speed of the current, the RSME was 0,007 m/s and the predictive ability was 0,998, while for the direction of the current, the values were 7,71 degrees and 0,995 for the RSME and SKILL, respectively. The current roses resulting from the validation period (October - November) are shown in Figure 8; this corresponds to the comparison of the measured and simulated current data at station T1.

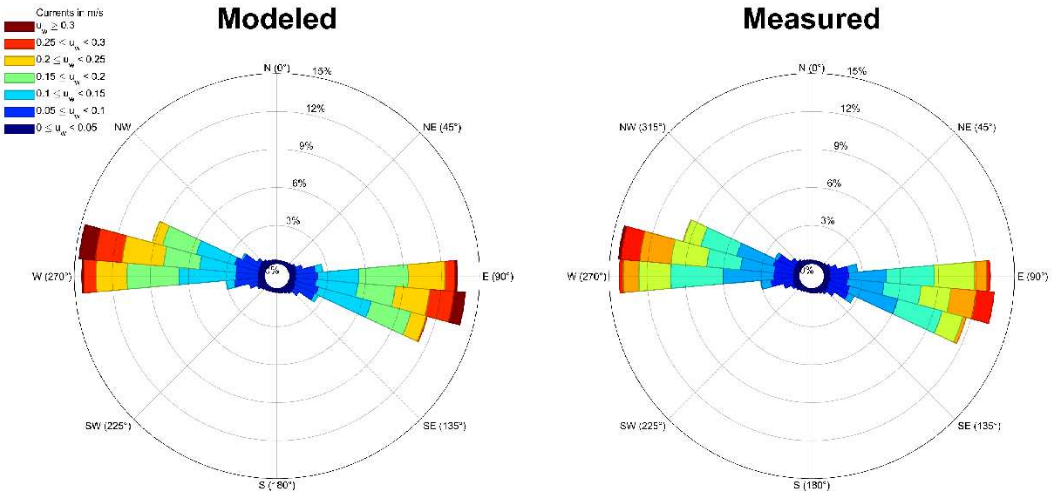

Figure 8. Currents roses comparation comparison for simulations and measurements for the validation period.

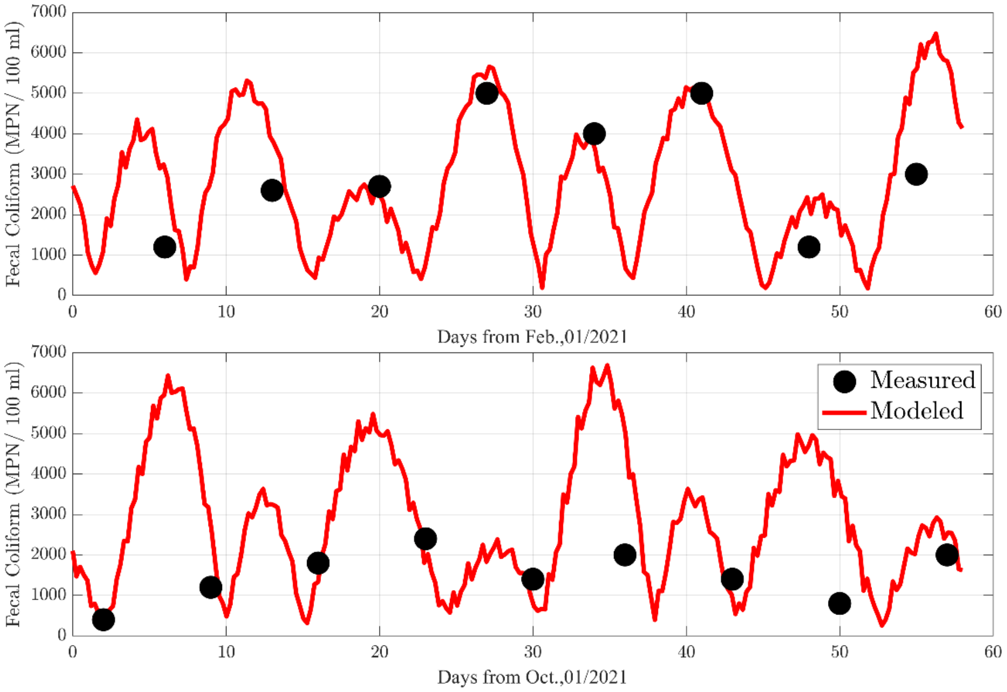

Figure 9. Comparison of fecal coliform concentration in the calibration and validation of the water quality model.

3.3.4. Discharge Reduction Scenario

The concentration of FC in the Bay of Buenaventura for the current scenario, according to the results of the RMA11 model, is presented in Figure 10. The current scenario measures the effects of the 695 untreated wastewater discharges. The highest concentrations of FC was obtained in the San Antonio estuary, where most of the Untreated wastewater discharges were generated in Buenaventura. Maximum concentrations of 1,45 × 10^7 MPN/100mL of FC were found in this scenario.

The Colombia´s Law contemplates a limit concentration of 200 MPN/100mL of FC for primary contact; this value was used as a reference for the analysis of the impact on the reduction of discharge points in the Bay of Buenaventura. The time step of the water quality model was 15 min, and it was run for one year (2021) equivalent to 35.040 results per node. For each node, the frequency of the data that exceeds the reference limit concentration established by the Colombian standard was found, from this analysis the frequency of affected areas with concentrations greater than 200 MPN/100mL was found, the result of this analysis It is presented in Figure 11. This is the base scenario to analyze the differences with the proposed discharge reduction scenarios. The areas with a frequency of 100% of values with a concentration greater than 200 MPN/100mL are presented in red in Figure 11. A modification was made to the water quality model with respect to the adjustment parameters found in the calibration and validation phase, to determine the effects of wastewater discharges on the quality of the water in the Bay of Buenaventura, the concentrations of FC in the tributaries that reach the bay were set at zero. This assumption allows knowing the impact of the discharges generated in the urban areas without other interferences.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

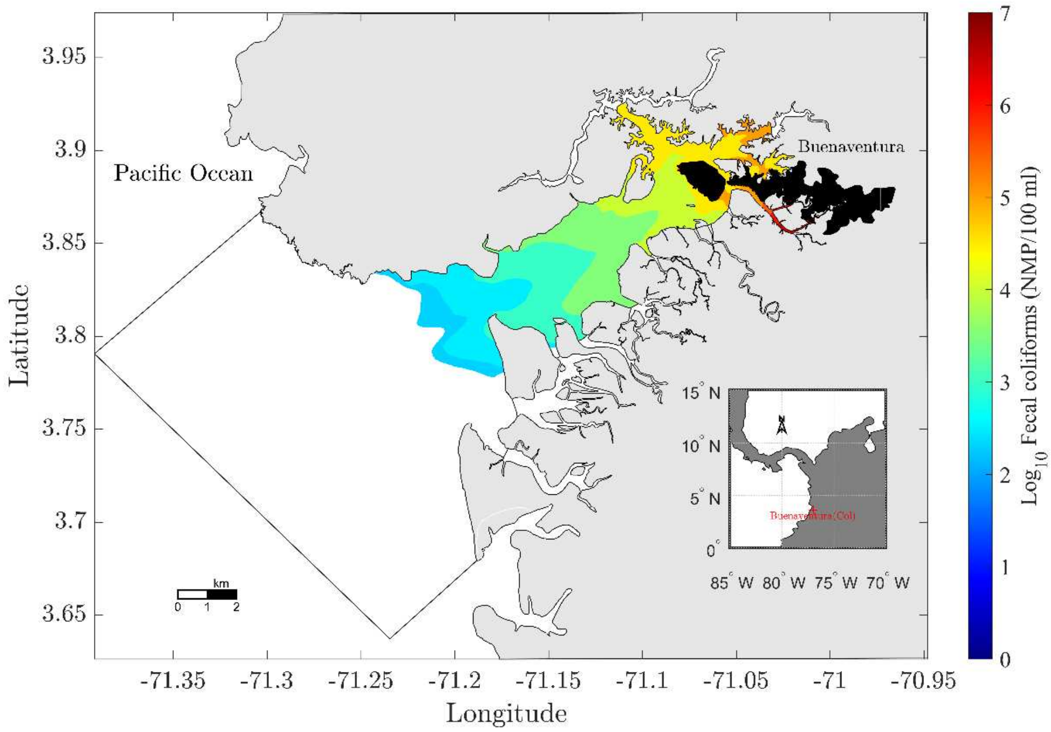

Figure 10. Spatial distribution of the maximum concentration of FC in the Bay of Buenaventura in the current scenario.

It can be noted that the current situation of 695 untreated wastewater discharge into the Bahía de Buenaventura has its greatest effect on the concentration of FC inside the estuary and in the vicinity of the discharges that corresponding to the most internal of it. In this area, there is a frequency of 100% of the occurrence of values that violate the norm. In the middle or central part of the bay, the effects of levels that violate the standard are between 50% and 70%, while outside the bay, the effects are less than 20%. That is, in this section of the Bahía de Buenaventura, only 20% of the time there are concentrations greater than 200 MPN/100mL of FC that are related to the wastewater discharges generated by the urban settlement that occurs in the city of Buenaventura (Figure 11).

The reduction of wastewater discharges was proposed to go from 695 to 6 (Figure 5a), that concentrate the flow of the previous ones; this situation is analyzed in scenario two that increases the concentration of FC in the Buenaventura Bay with respect to the current situation (scenario one) the maximum concentration obtained in this scenario is 1,45 × 10^7 MPN/100mL; this situation is shown in figure 12.

The maximum concentration in the Scenario three is 3,21 × 10^7 MPN/100mL of FC. Concentrating the untreated wastewater discharges at two points (Figure 5b) generates twice the concentration of the 6-discharge scenario and 2,2 times the concentration as the current scenario with 695 discharges. (Figure 13)

When a wastewater treatment system was considered for these two discharge points (Figure 5b), the concentration of FC is drastically reduced, reaching maximum concentrations of 5,32× 10^5 MPN/100mL, which correspond to the lowest concentrations of all scenarios studied. In addition to the low concentrations, a notable reduction in the area affected by FC in Buenaventura Bay can be observed in Figure 14.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 February 2023 doi:10.20944/preprints202302.0109.v1

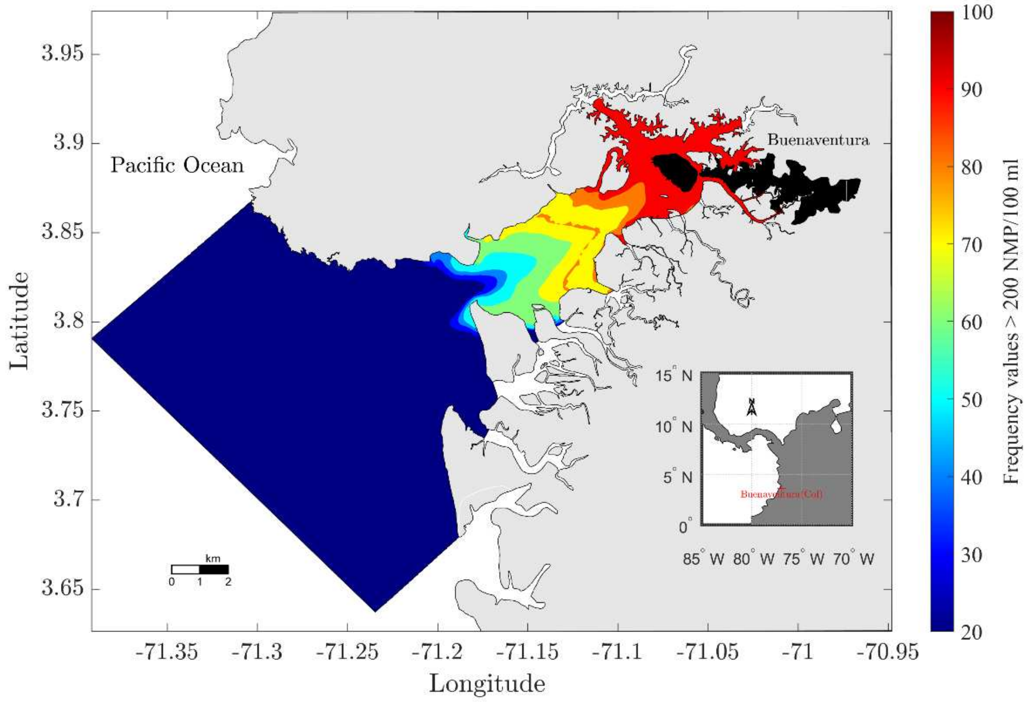

Figure 11. Frequency of areas affected by concentrations higher than 200 MPN/100mL in the water column scenario acts.

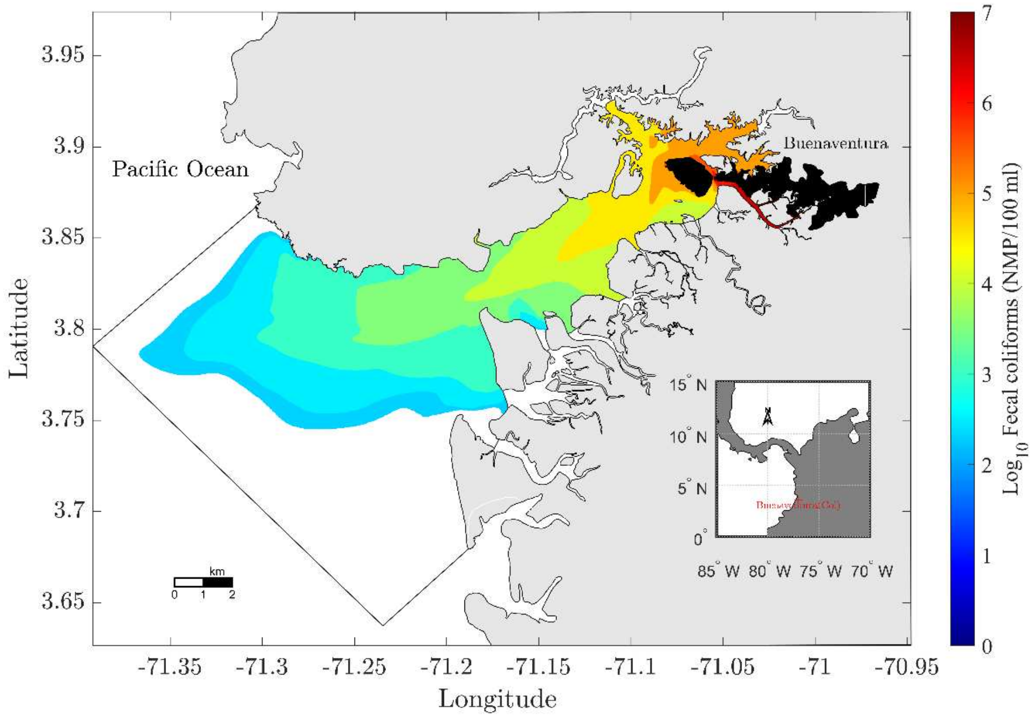

Figure 12. Spatial distribution of the maximum fecal coliform concentration in Buenaventura Bay in scenario two.

The last scenario studied (Figure 15) belongs to the trend situation, which answers the question, What will happen if sanitation solutions are not implemented?. The assumptions made for this scenario contemplate population growth according to the local demographic dynamics (population growth rate of 3%) and consider that the current discharges are conserved over time. In 25 years, Buenaventura is projected to double its population (1,050 × 10^6 inhabitants) and generate 1,45 m^3/s of untreated wastewater if the current situation persists. Under these considerations, it was found that the maximum concentration of FC in the bay of Buenaventura increases by a factor of three to a maximum concentration of 4,32 x 10^7 MPN/100mL. This is undoubtedly the highest concentration of all scenarios studied and justifies the urgent need to adopt a sanitation and discharge reduction plan.

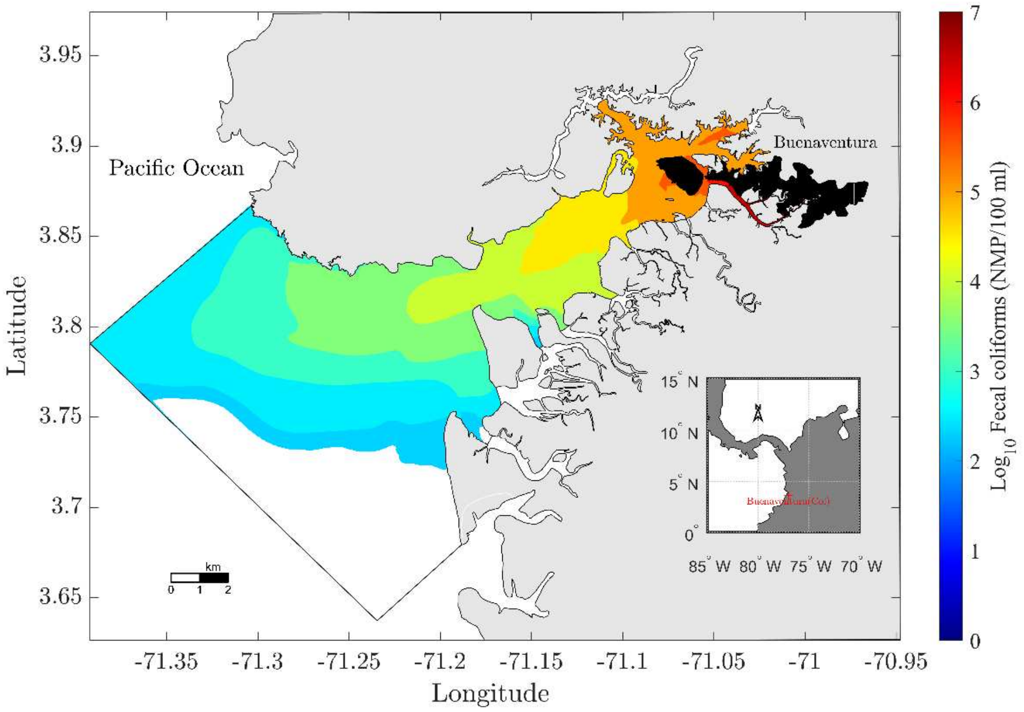

Figure 13. Spatial distribution of the maximum fecal coliform concentration in Buenaventura Bay in scenario three.

4. Discussion

The RMA10 3D hydrodynamic model accurately reproduces the characteristics of the tides and currents in Buenaventura Bay. Two test statistics, RMSE and SKILL, were used, as well as graphical comparison of the time series, all of which confirmed a good approximation between the results of the model and field measurements. Buenaventura Bay has a semi-diurnal tide and a tidal range of up to 5 meters [26], which the hydrodynamic model reproduces both during low rainfall periods (calibration) and high rainfall periods (validation). In both periods, a good approximation was obtained between the model and measurements. It would be desirable for the location of the measurement equipment for calibrating and validating the hydrodynamic model to be inside Buenaventura Bay, but this is a bay high shipping traffic because of the second most important port in Colombia being inside it, making it difficult to locate measurement devices without interfering with the economic activity or being exposed to vandalism. Locating the sample stations for hydrodynamic conditions outside Buenaventura Bay may not accurately reflect the hydrodynamic conditions inside. Good calibration with equipment located outside reduces this uncertainty. For this study, a balance was made by locating the measurement equipment for calibrating and validating the model outside the bay, but far enough from the open borders of the model to increase reliability in the results of the calibration and validation. The distance between the sample point and the open border was greater than 10 kilometers.

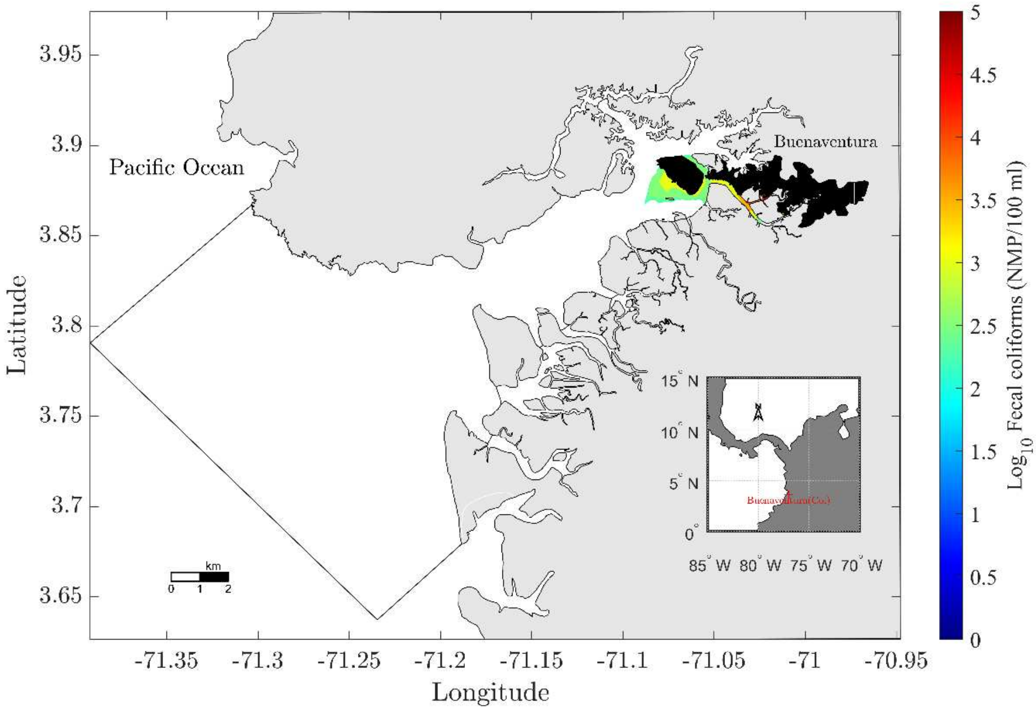

Figure 14. Spatial distribution of the maximum fecal coliform concentration in Buenaventura Bay in scenario four.

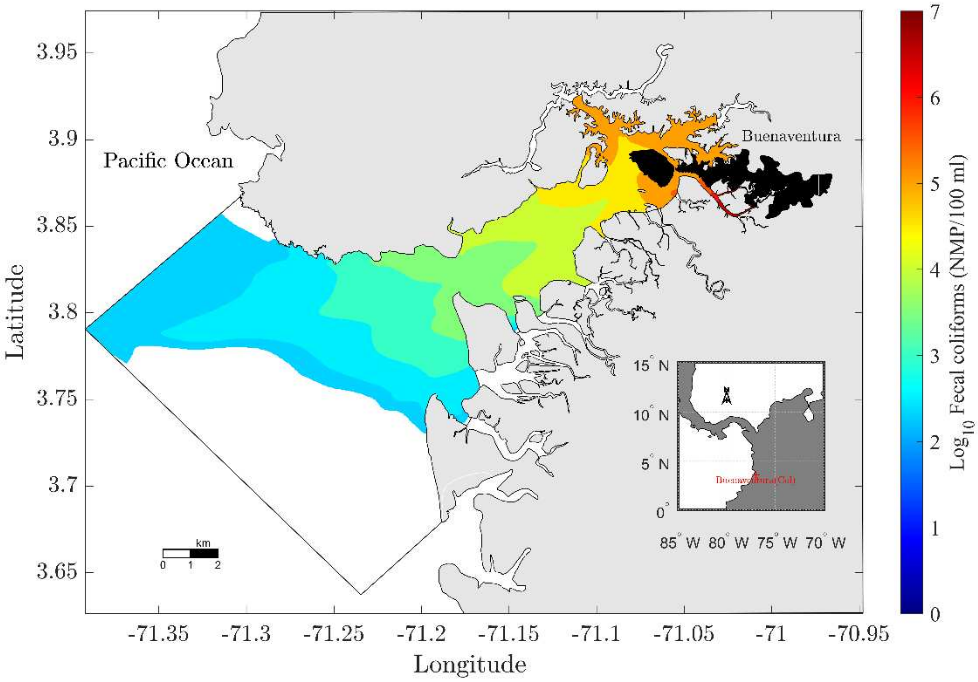

Figure 15. Spatial distribution of the maximum fecal coliform concentration in Buenaventura Bay in scenario five.

A predominant direction of W (frequency of 45%) and E (38%) was found with currents up to 30 cm/s. Buenaventura Bay is recognized as a well-mixed body of water [27]. The 3D model used in this study did not show significant variations in the current conditions in the water sheet, which is consistent with this consideration. Instead of a 3D model, a 2D model would also have been adequate to model the hydrodynamic conditions; however, the 3D model used allows the inclusion of temperature and salinity fields at the open boundaries to be incorporated into the simulations. Temperature and salinity are important variables to determine the survival rate of FC, which is the variable of interest analyzed in the water quality model, for this reason the choice of a 3D model instead of 2D was considered adequate despite not having significant changes in the water column because this estuary is a well-mixed body of water. The temperature and salinity were excluded from the process of calibration and validation of the hydrodynamic model in order not to make its implementation more complex; however, FC, which are finally the variables of interest in this study, considering the best indicator of the presence of wastewater in the bay of Buenaventura was verified.

In this study, no significant differences were found between the fecal coliform samples taken at two different times of the year, during the low rainfall and high rainfall season. Mondragon, et al., reported seasonal differences in the concentration of physicochemical parameters inside the Buenaventura Bay, when evaluating the water quality. No reference to studies was found that would allow us to determine if this condition also extends to the microbiological parameters of water quality in the bay. Establishing whether there are significant temporal differences in the coliform concentration is not the main objective of this stud; however, it is useful in the model implementation process. In the absence of significant differences, the conditions of the parameters of the quality model were not varied in a way for the validation with respect to the constants proposed in the calibration.

Both, the hydrodynamic model (RMA10) and the water quality model (RMA11) were considered calibrated and validated, adequate to simulate the conditions of Buenaventura Bay. Its use allows simulating spring tide and neap tide conditions and currents, as well as the concentration of FC in Buenaventura Bay.

A criterion used in this study to compare the proposed scenarios was the maximum concentration achieved in each one of them. To avoid the interference of other sources of contamination that contribute FC to the Buenaventura Bay, other discharges were eliminated from the analysis, which allowed us to conclude that the changes in the scenarios are due solely to the concentrations contributed by the wastewater discharges according to with the amount of the same raised in each scenario. In addition to this simplification, it should be considered that the scenarios are malted in different years, considering the current situation of scenario one as base years, scenario two is expected to be fully implemented after 10 years, scenario three at 15 years, and scenario 4 with the treatment plants at 25 years. For each scenario displaced in time from the base year, population growth of 3% was considered to include realistic criteria in the analysis carried out.

The increase in maximum concentrations between some scenarios does not seem to be significant; for example, when comparing scenarios one and two, an increase in fecal coliform concentration of only 9% was found. According to the results of the model, reducing 695 diluted discharges to 6 that concentrate the flow of the previous ones does not seem to generate a significant change, if only the comparison between maximum concentrations is used as a criterion. The greatest impact occurs in the extension of the areas affected by concentrations greater than those established by the reference standard for primary contact and its extension, the frequency with which these values that violate the standard are found. The criterion of the extension of the area of exceedance was incorporated into the analysis to compare the effects of the reduction of discharges in the different scenarios proposed in this study.

The frequency of the areas affected by concentrations greater than the FC´s norm for primary contact in the Bay of Buenaventura is presented in Figure 18. The current scenario used for comparison with scenarios from two to five can be appreciated in Figure 13. The reduction of discharges to 6 (scenario two) increases the area affected by values with a frequency of exceedance of 100% and increases up to the mouth that communicates the external and internal parts of the bay the areas with a frequency of exceedance between 50 and 70% (Figure 18a).

The greatest extent of the exceedance frequency zone occurs in scenario three when the current discharges are concentrated at two points that discharge untreated water into Buenaventura Bay (Figure 18b). The 100% exceedance frequency zone extends to the entire internal part of Buenaventura Bay, while the frequency exceedance between 50% goes to the outside of it.

Scenarios two and three confirm that reducing discharges and concentrating the flow of untreated wastewater at 6 and 2 points, respectively, increases the concentration of CF in the Bay and deteriorates water quality, increasing the occurrence of violating levels of CF. These scenarios, despite being part of the sanitation solution contemplated for Buenaventura Bay, generate greater and worse impacts than the current scenario where there are 695. Discharges are reduced in quantity, but are concentrated in the flow of wastewater, going from a situation from dispersed and distributed discharges in the extension of the internal part of the bay, to concentrated discharges in two points. Scenarios two and three must be temporary solutions, and the authorities must implement the necessary measures to shorten the time in which the conditions set forth in these are in force and move quickly to the construction of treatment plants.

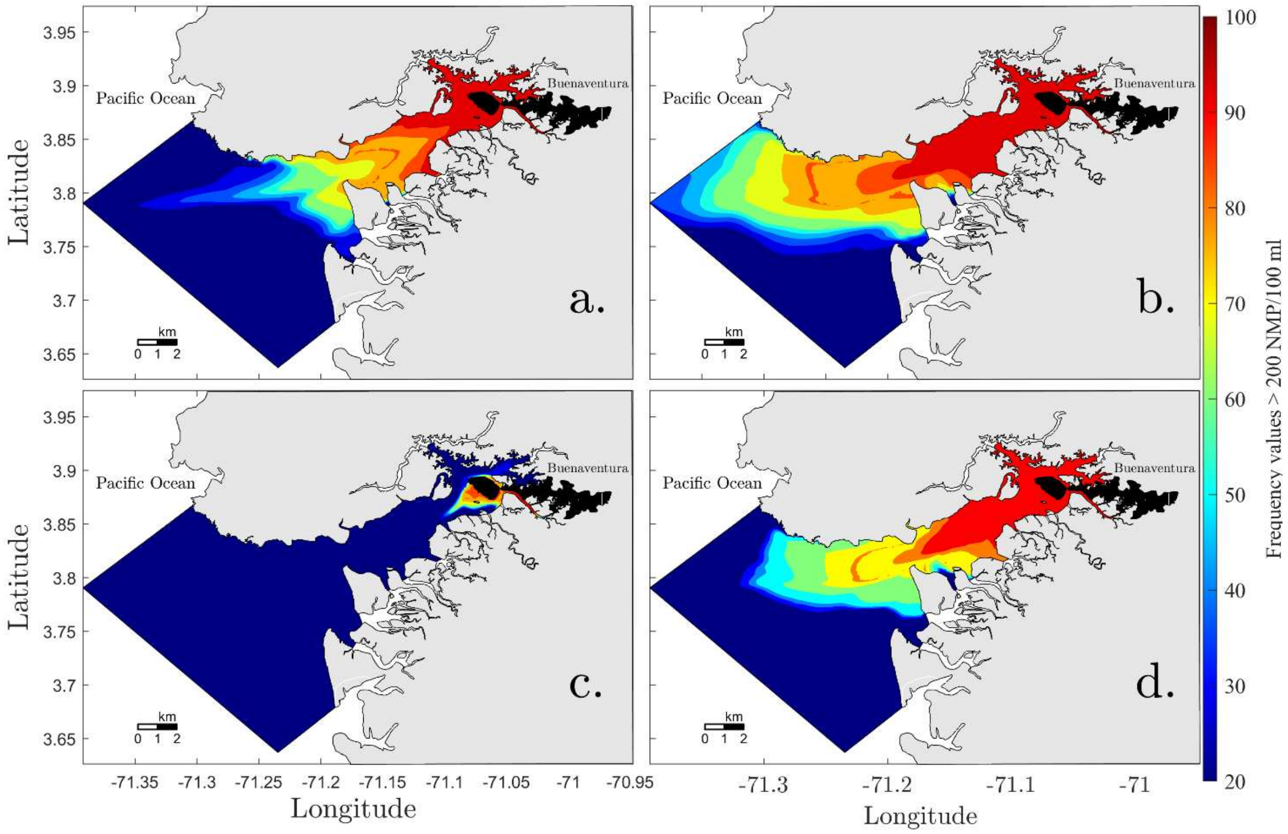

Figure 18. Frequency of areas affected by concentrations higher than 200 MPN/100 ml in different scenarios, a. scenario two, b. scenario three, c. scenario four, and d. scenario five.

The construction of the two projected wastewater treatment plants led to a significant reduction in the concentration of CF in Buenaventura Bay. Scenario 5, shown in Figure 18c, shows a decrease in both the maximum concentrations and the frequency area exceeding the norm. This is in contrast to scenario 5 (Figure 18d), which shows the trend of continued untreated wastewater discharges and existing discharge points affecting the water quality in Buenaventura Bay."

Scenario 5 confirms that if measures are not taken to eliminate discharges in Buenaventura Bay, the concentration of CF will double and the frequency zone exceeding CF values above the norm will extend throughout the internal part of the bay

Building two wastewater treatment plants in Buenaventura Bay is a necessary but not sufficient condition to clean it up. Despite the reduction in contaminant levels that is expected with the treatment systems in operation, there will still be levels of FC concentration exceeding the permitted limit. Figure 19 shows a zoom of the interior of Buenaventura Bay in scenario 4, with the treatment systems in operation. In these scenarios, a reduction in the load of contaminants contributed by effluents is expected; however, there are still levels of frequency exceeding the standard, so an additional system must be considered to solve this situation. The PSMV contemplates a submarine discharge system to take the point and concentrated discharge of the plant effluent and discharge it dispersedly through a diffuser system. This option was not the subject of this stud; however, the built tools, the hydrodynamic model, and the water quality model are enabled to perform this additional analysis.

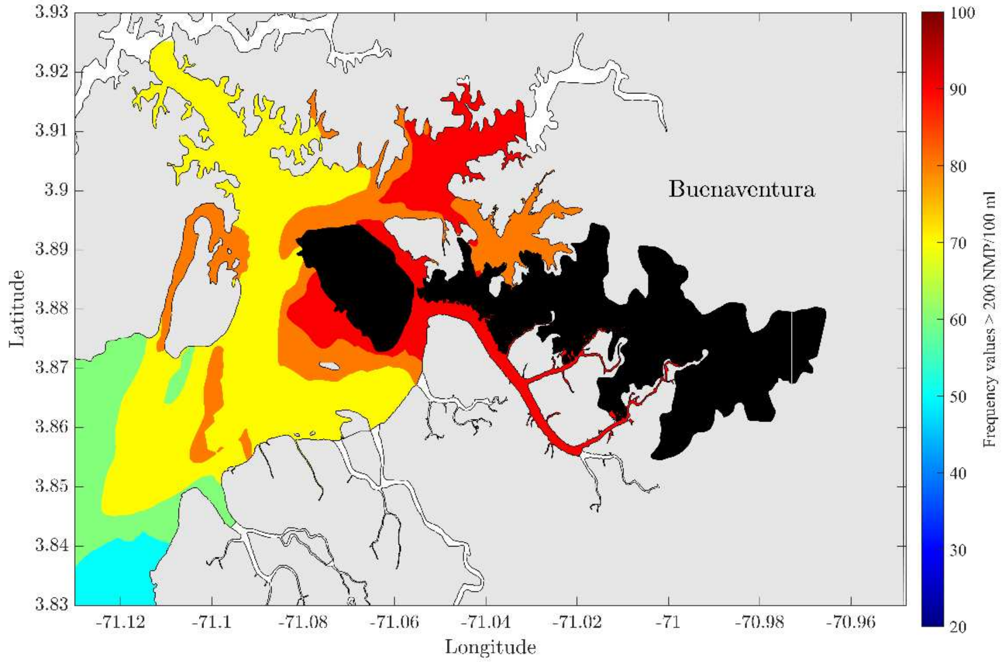

Figure 19. Frequency exceeding in areas affected by concentrations higher than 200 MPN/100 ml in scenario four, inner part of Buenaventura Bay.

The study showed that the Bay of Buenaventura has critical water quality conditions due to untreated wastewater discharge. Only fecal coliform concentration was considered, which suggests that the situation could be even more severe if measures are not taken to sanitize the bay. The chosen sanitation strategy, if implemented in stages, could result in worse conditions compared to the scenario with no measures. Hence, decision-makers must carefully implement the sanitation plan after a comprehensive analysis of the Bay of Buenaventura considering other biological and physicochemical parameters. This study provides a valuable contribution but should be supplemented with additional research.

Author Contributions: Conceptualization, F.G.; methodology, F.G. G.H. and G.C.; software, F.G. G.H. and G.C.; validation, F.G. G.H. and G.C.; formal analysis, F.G. G.H. and G.C.; writing—original draft preparation, F.G. G.H. and G.C.; writing—review and editing, F.G. G.H. and G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding, and the APC was funded by G.F., C.G. and H.G.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Superintendencia de Transporte.. Ministerio de Transporte. Boletín estadístico tráfico portuario en Colombia año 2020. Available online: https://www.supertransporte.gov.co/documentos/2021/Febrero/Puertos_04/BOLETIN-TRAFICO-PORTUARIO-2020.pdf. (accessed on 20 October 2022).
2. DANE. https://www.dane.gov.co/files/investigaciones/planes-desarrollo-territorial/100320-Info-Alcaldia-Buenaventura.pdf. (accessed on 20 October 2022).
3. Gallego. B.E.; Josephraj J. Evaluation of coastal vulnerability for the District of Buenaventura, Colombia: A geospatial approach. Remote Sensing Applications: Society and Environment 2019, 16, 1–16.
4. Otero, J.L. Determinación del régimen medio y extremal del nivel del mar para la bahía de Buenaventura. Boletín Científico CCCP 2004, 11, 30–41.

5. Alonso, D.; Ramírez, L. F.; Segura- Quintero, C.; Castillo-Torres, P.; Díaz, J.M.; Walschburger, T.; Arango, N. Informe Técnico: Planificación ecorregional para la conservación in situ de la biodiversidad marina y costera en el Caribe y Pacifico continental colombiano, 1ra ed.; INVEMAR Serie de documentos generales No. 41., INVEMAR, Santa Marta, Colombia, 2009; 106p.
6. INVEMAR. Informe diagnóstico de la situación ambiental marina de la bahía de Buenaventura-Isla cascajal y las playas de Juanchaco, Ladrilleros y La Bocana. Available online: https://alfresco.invemar.org.co/share/s/sF3nl3iCRWa1THm9Dmc5-g. (accessed on 17 September 2022).
7. Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). Estudio Nacional del Agua 2018. Bogotá: IDEAM. Available online: https://www.andi.com.co/Uploads/ENA_2018-comprimido.pdf. (accessed on 5 October 2021).
8. Espinosa, S.; Delgado, B.; Orobio, L.M.; Mejía-Ladino, L; Gil-Agudelo, D. Estado de la población y valoración de algunas estrategias de conservación del recurso piangüa Anadara tuberculosa (Sowerby) en sectores de Bazány Nerete, costa Pacífica nariñense de Colombia. Boletín de Investigaciones Marinas y Costeras 2010, 39, 161–176.
9. Vivas-Aguas, L.; Vargas-Morales, M.; Guillen, K.; Villarraga, D.; Sánchez, D. Vulnerabilidad de la población costera frente a la contaminación orgánica y microbiológica en la bahía de Buenaventura. Serie de publicaciones generales del Invemar. No. 76. INVEMAR, Santa Marta, Colombia, 2014, 24 p
10. APHA, Standard Methods for the Examination of Water and Wastewater. 20th Edition, American Public Health Association, American Water Works Association and Water Environmental Federation, Washington DC., 1998.
11. Marthanty, R; Soeryantono, H; Carlier, E.; Sutjiningsih, D. Assessment of the capability of 3D stratified flow finite element model in characterizing meander dynamics. Journal of Urban and Environmental Engineering 2014, 8(2), 155–166.
12. Fossati, M.; Piedra-Cueva, I. Numerical modelling of residual flow and salinity in the Rıo de la Plata. Applied Mathematical Modelling 2008, 32, 1066–1086.
13. Garcia, F.F.; Palacio, C. y Garcia, U. Simulation of hydrodynamic conditions at Santa Marta coastal area (Colombia). Dyna 2012, 174, 119–126.
14. Garcia, F.F.; Palacio, C.; Garcia, U. Calibración y validación de un modelo 3D para el área costera de Santa Marta (Colombia). Rev. Fac. Ing. Univ. Antioquia 2012, 62, 177–188.
15. Ezzatti, P.; Fossati, M.; Piedra-Cueva, I. An efficient version of the RMA-11 model. *CLEI Electron. J. 2011, 14*, 1-10.
16. Glamore, W.; Mitrovic, S.; Ruprecht, J.; Dafforn, K.; Scanes, P.; Ferguson, A.; Rayner, D.; Miller, B.; Dieber, M.; Tucker, T.; 2019a. The Hunter River Estuary Water Quality Model. In Proceedings of the Australasian Coasts & Ports 2019 Conference – Hobart, Australia,10-13 September 2019.
17. Ruprecht, J.; King, I.P.; Mitrovic, S.; Dafforn, K.A.; Miller, B.M.; Deiber, M.; Westhorpe, D.P.: Hitchcock. J.N.; Harrison, A.J.; Glamore, W.C. Assessing the validity and sensitivity of microbial processes within a hydrodynamic model. Water Res. 2022, Jun, 1-16.
18. Marthanty, D.; Soeryantono, H.; Carlier, E.; Sutjiningsih, D. Assessment of the capability of 3D stratified flow finite element model in characterizing meander dynamics. Journal of Urban and Environmental Engineering, 2014, 8(2), 155-166.
19. Brown, L. C. and T. O. Barnwell. "The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and Users Manual.", Environmental Research Laboratory USEPA May 1987.
20. Thomann, R.V.; Mueller, J.A. Principles of Surface Water Quality and Control. Harper Collins, New York, 1987; 644 p.
21. Engwirda, D. Locally-optimal Delaunay-refinement and optimisation-based mesh generation, Ph.D. Thesis, School of Mathematics and Statistics, The University of Sydney, Sydney , September 2014.
22. Engwirda, D. Conforming Restricted Delaunay Mesh Generation for Piecewise Smooth Complexes, Procedia Engineering 2016,163, 84-96.
23. Chassignet, E.P.; Hurlburt, H.E.; Smedstad, O.M.; Halliwell, G.R.; Hogan, P.J.; Wallcraft, A.J.; Baraille, R.; Bleck, R. The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system. J. Mar. Syst. 2007, 65), 60–83.
24. Molina, A.; Duque, G.; Cogua, P. Influences of environmental conditions in the fish assemblage structure of a tropical estuary. Mar. Biodivers. 2020, 50, 1–13.
25. Chen, W., Chen, K., Kuang, C., Zhu, D.Z., He, L., Mao, X., Liang, H., Song, H., 2016. Influence of sea level rise on saline water intrusion in the Yangtz River Estuary, China. Appl. Ocean Res. 54, 12–25.
26. Otero, L. Determinación del régimen medio y extremal del nivel del mar para la bahía de buenaventura. Boletín Científico CCCP 2004, 11, 30-41
27. Gamboa-García, D.; Duque, G.; Cogua, P.; Marrugo-Negrete, J. Mercury dynamics in macroinvertebrates in relation to environmental factors in a highly impacted tropical estuary: Buenaventura Bay, Colombian Pacific. Environ Sci Pollut Res 2020, 27,4044–4057

 doi:10.20944/preprints202302.0109.v1