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Influence of Solar Radiation on Microbiological Degradation of Sewage Submarine Outfalls and the Safety of Bathing Areas

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Abstract: The ocean disposal of wastewater is an efficient alternative in the sewage system of coastal areas since the urban density of such regions is a barrier to the settlement of conventional sewage treatment plants. In addition, the associated costs of this alternative are significantly lower than the convention in the long term. The degradation of microbiological contaminants strongly depends on solar radiation and the factors that regulate its intensity, such as the depth of the effluent plume, seasons, and cloud cover. The submarine disposal of domestic sewage constitutes a low-sanitation-risk alternative regarding the contamination of bathing areas. The results based on computational modeling corroborate this alternative, showing that the coastal zone is not affected by marine sewage discharges.

Keywords: submarine outfalls; bacterial decay; water quality

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1. Introduction

The urbanization of coastal regions without sanitation infrastructure has significantly impacted the water quality of the beaches due to the flow of sewage to the shore [1–3]. However, environmental damage depends on the mass of the pollutant discharged into marine waters. Considering that the mass of pollutants is directly related to population density, in dense population areas the impact on rivers and lacunar systems will be significant due to the volumetric limitation of semi-confined water bodies. Considering the potential dilution of sewage in open waters and concern about minimizing health risks, it is evident that the use of submarine outfalls is a feasible option in densely populated regions without space for sewage treatment due to the low risk of contamination of bathing zones. In addition, even when areas are available, conventional treatment plants require considerable energy demand, increasing the costs for operation and maintenance [4].

Marine outfalls comprise an efficient alternative for sewage disposal due to the dynamics of sewage dispersion and the microbiological degradation that occurs in the marine environment [5–9]. Several factors, such as temperature, salinity, solar radiation, pH, sedimentation, predation, and nutrients, respond to microorganisms' decay in marine waters [10–12]. However, it is important to highlight that sunlight is the most effective [10–19].

The evaluation of microbiological risk in coastal waters is based on the concentration of fecal indicator bacteria (FIB) that classifies recreational waters as suitable or not for balneability. In addition to Enterococcus, Brazilian [20] and European [21] regulations also consider *E. coli* as a fecal indicator for both fresh and marine waters.

According to local regulations, the use of fecal coliforms as an indicator microorganism in the quantification of fecal contamination in marine waters by domestic effluents is justified by the high densities of these microorganisms in domestic sewage [20].

Previous local studies [22,23] evaluated coliform concentration in coastal waters from submarine sewage outfalls but considered constant daylight coliform decay rates. Such an assumption underestimates the microbiological assessment since coliform decay rates vary substantially according to solar radiation levels. Aiming to include a realistic approach, the present work related to the coliform concentration plumes, from the three main submarine sewage outfall systems in Rio de Janeiro to the influence of solar radiation under different weather and seasonal scenarios. The methodology adopted in this study is based on computer modeling that considers variable coliform decay rates as a function of temperature, salinity, and solar radiation. The SisBaHiA v11 (Base System for Environmental Hydrodynamics) [24] model developed in the Coastal and Oceanographic Engineering Area of the Federal University of Rio de Janeiro (UFRJ) was used in the study of the hydrodynamic circulation, transport, and decay of the coliform plume.

The results presented a significant influence of solar radiation in the coliform concentration plumes. In addition, it was shown that submarine outfalls do not compromise the quality of the beaches, agreeing with in situ studies that evaluated the quality of coastal waters and the possible contamination of bathing areas [25,26]. The use of submarine outfalls improved beaches' water quality, minimizing health risks for bathing [27].

2. Materials and Methods

The evaluation of the coliform concentration plumes in coastal waters released by submarine outfalls based on computer modeling comprises, in addition to hydrodynamic modeling, different methodological processes that evaluate the mixing and the microbiological degradation of the effluent. Additional details covering the entire methodological process employed in the modeling are described in [24,28].

2.1. Study Area and Outfall Characteristics

Figure 1 illustrates the positioning of Ipanema (IPSO), Barra da Tijuca (BTSO), and Icaraí (ICSO) sewage outfalls in the state of Rio de Janeiro (Brazil). The first two are located, respectively, in the south and west zones of the municipality of Rio de Janeiro, and the last is in the municipality of Niterói.

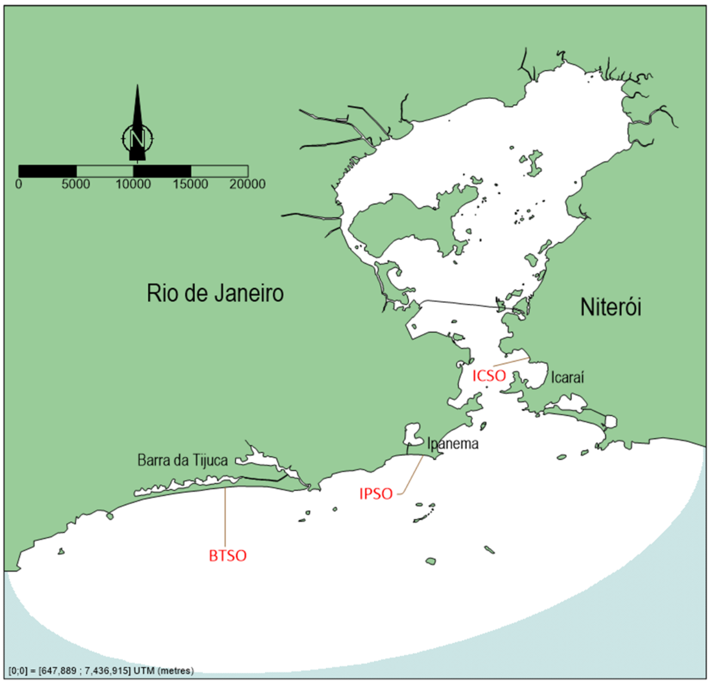

Figure 1. Study area and location of the outfalls.

The IPSO, the oldest outfall system, started operating in 1975. The current flow rate is 6 m^3/s and is designed to flow up to 12 m^3/s at a depth of about 27 m. The pipeline is made of concrete with a diameter of 2.4 m and a total extension of 4326 m, with the last 449 m consisting of the diffuser line. The BTSO has been in operation since 2007, discharging domestic sewage 5500 away from the coast at a depth of about 40 m through a 1.5 m diameter high-density polyethylene (HDPE) pipeline. The current and future design discharge correspond, respectively, to 2 and 5.3 m^3/s. The ICSO has a diameter of 1.0 m and is also made of HDPE. It is 3340 m long and is designed to launch 1.38 m^3/s of domestic sewage at a depth of 22 m.

2.2. Mixing Processes of Sewage in the Marine Environment

The initial mixing process of sewage with marine water comprises two regions with characteristics whose spatial and temporal scales are markedly different. The first occurs in the near field of the effluent jet, called the active mixing zone or initial mixing region. In this region characterized by intense turbulence, the hydrodynamic circulation is extremely influenced by the effluent jet, buoyant forces (lower effluent density), and ocean currents. As it moves away from the diffuser, the ejected plume mixes with the marine water until the mixing becomes neutral in terms of density. In the second region, called the far field or passive mixing zone, the plume is passively transported by ocean currents. In this region, the bacterial decay kinetics must be considered. Due to the mixing differences between the active and passive zones, approaches are adopted for each zone.

Active mixing zone in the near field: In general, in the case of submarine sewage outfalls, effluents are discharged into ocean waters through diffuser pipes. In each nozzle of this diffuser line, an effluent jet is formed with a velocity much higher than the surrounding water. This fact refers to a large difference in the momentum between the effluent jet and the ambient currents that respond to the generation of the near-field flow. This region is characterized by the drag and mixture of the effluent jet with marine water, forming a buoyant plume. Due to the lower sewage density compared to seawater, the mixture rises towards the free surface to the position where the densities of the mixed effluent and the surrounding waters are equal. From this point on, there is a neutral plume passively transported by ocean currents, characterizing the transport in the far field or the passive mixing zone.

As depicted in Figure 2, in the initial mixing region, the main characteristics of the effluent plume are established. In this stage, the methodology of the NRFIELD model [29–31] is used to determine the dilution of the effluent in the initial mixing region and the characteristics of the plume (thickness (h_n) and rise height (R_h)).

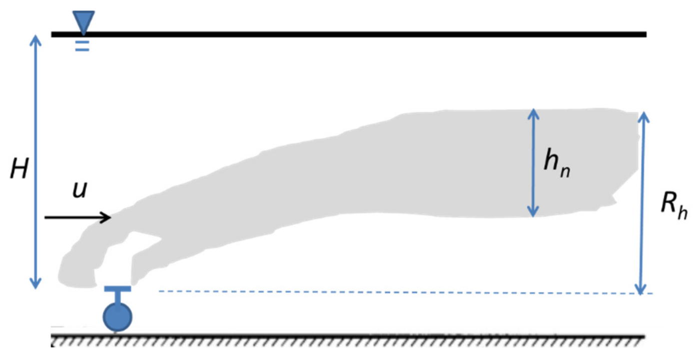

Figure 2. Characteristics of the plume.

These characteristics strongly depend on the angle between the ocean currents and the diffuser line and the ambient density difference between the surface and the effluent discharge point. The higher the difference, the higher the mixing attenuation along the water column. This condition lowers the effluent dilution and the plume's rise height. The rise height is extremely important in coliform bacteria decay since it regulates the intensity of solar radiation over the water column.

Passive Mixing Zone in the Far Field: As it moves away from the point of discharge, the effluent will behave neutrally in relation to the receiving waters. From this point, called the far field, the momentum differences between the effluent jet and the surrounding waters cease, and the sewage plume is passively transported by the ocean currents. The distribution of concentrations of the effluent discharged into the receiving water body depends on the following processes, which are generally highly variable in time and space:

- Advection generated by the ocean currents responsible for the effluent transport.
- Turbulent diffusion of the effluent. This ambient turbulence is generated by internal frictional stresses in the water mass, frictional stresses of the water body with the bottom, and wind friction on the free surface. In general, the transport of sewage plumes is dominated by advection, but turbulent diffusion exerts significant importance.
- Kinetics of bacterial decay of coliforms as indicators of fecal contamination, considering first-order reactions. The bacterial decay in the marine environment varies according to variations in temperature, salinity and solar radiation.

In far-field modeling, from the near-field modeling, the thickness (h_n) and the rise height (R_h) of the plume are used to calculate the incoming solar radiation over the plume, as depicted in Figure 2.

The modeling of the dispersion of the sewage plume in the far field, carried out by SisBaHiA, considers coliform decay kinetics where solar radiation levels can be internally calculated by the model or provided via data file.

2.3. Bacterial Decay

According to Brazilian regulations [20], in addition to enterococcus, coliform bacteria are also considered a fecal indicator in marine waters. The quantification of the decay rates of coliform bacteria is the key to determining the concentrations of these microorganisms in coastal waters. Several field and laboratory studies have been carried out to determine the decay rates of microorganisms that indicate fecal contamination in the marine environment. Aiming to evaluate quantitatively these rates, Feitosa and Rosman [31] and Feitosa et al. [32] verified, through a compilation of the literature studies, the correlation of bacterial decay with variations in solar radiation, temperature, and salinity.

The distribution and quantity of fecal indicators in the marine environment depend on the advection and dispersion promoted by ocean currents and by factors responsible for the decay of bacterial populations.

Bacterial die-off follows first-order kinetics, where its concentration varies over time (t) according to a decay rate (k) as follows:

$$C = C_0 e^{-kt}$$

The decay rates can also be expressed by the T_{90} parameter, which corresponds to the time required for one log (90%) reduction in the initial concentration of coliforms, where for $t = T_{90}$, $C = 0.1\ C_0$.

$$0.1 = e^{-kT_{90}} \quad \rightarrow \quad T_{90} = \frac{2.3}{k}$$

As previously pointed out by Feitosa et al. [32], the survival of fecal bacteria lies on biotic (predation) and abiotic factors such as pH, sedimentation rates, dissolved oxygen, nutrient level, temperature, salinity, and solar radiation. Among these factors, besides salinity, temperature, and solar radiation, predation can also have a significant role in bacterial decay [33], but it is quite difficult to quantify in the modeling process. Thus, in the present work, the reduction in bacteria in the marine environment takes into account the combined effect of salinity, temperature, and solar radiation, where sunlight is the most influential factor in bacterial degradation.

Solar radiation is governed by geographical, seasonal, meteorological, and oceanographic parameters. The first two parameters are represented by the local latitude and by the seasons of the year that influence the angle of incidence of the sun's rays on the Earth's surface. The third parameter represents the condition of cloud cover, and the last is directly linked to the conditions of the water body, represented by turbidity and by the water density profile that limits the rise height of the plume. The solar radiation values were calculated from formulations proposed by Martin and McCutcheon [34].

The Mancini formulation [11] was used to estimate numerically coliform decay rates in the marine environment as a function of temperature (T), salinity (S), and solar radiation over the plume thickness ($\bar{I}$).

$$k = \left[(0.8 + 0.0171\ S)\ 1.07^{(T-20)} + 0.086\ \bar{I}\right]$$

As depicted in Figure 3, the averaged solar radiation over the plume thickness is given by the following expression:

$$\bar{I} = \frac{I_0}{\mathrm{h_n} k_p} e^{-k_e z_p}\left[1 - e^{-k_p h_n}\right]$$

where I_0 is the solar radiation at the free surface; h_n is the plume thickness, and k_e and k_p correspond, respectively, to the light extinction of the ambient water and the sewage plume coefficient that is related to the Secchi depth (S_d) as follows:

$$k_e = \frac{1.8}{S_{de}} \qquad k_p = \frac{1.8}{S_{dp}}$$

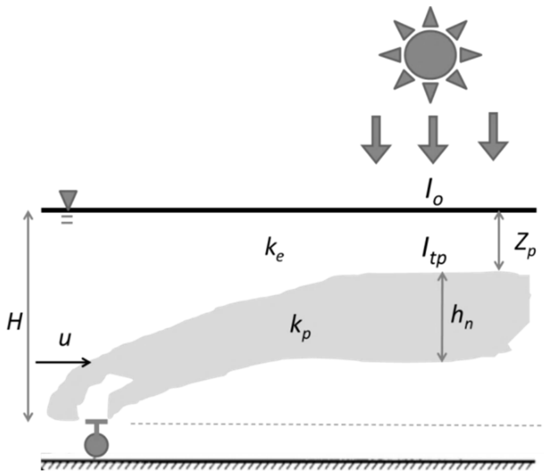

Figure 3. Income solar radiation along the plume over the water column.

2.4. Modeling Procedure

The methodology included in the SisBaHiA model considers the coupling between near-field and far-field models as described by Feitosa et al. [27], which allows considering the simultaneous influence of hydrodynamic, meteorological, seasonal, and oceanographic conditions in the degradation process of coliform plumes. The hydrodynamic module considers the effects of astronomical tides, wind, and drift currents. The near-field modeling establishes, according to oceanographical conditions represented by density profiles over the column, the plume rise height, which, along with turbidity, regulates the solar radiation levels over the sewage plume. The Lagrangian transport model responds to the modeling of the Far-field, considering variable coliform decay rates according to temperature, salinity, and solar radiation to determine the concentration of coliform plumes in the surroundings of the outfalls diffusers.

3. Results

The following results, based on computer modeling, show coliform concentration plumes released from sewage outfalls, considering the influence of solar radiation on microbiological degradation. Different weather and seasonal conditions are evaluated. In the first scenario, during the summer, the levels of fecal coliform concentration are analyzed by comparing a typical situation of clear sky with overcast. The following scenario presents the influence of seasonal variations, comparing the levels of radiation existing in the condition of clear skies between the winter and summer seasons.

3.1. Bacterial Decay Rates

Figure 4 summarizes all bacterial decay rates (T_{90}) observed in the present study, calculated by Mancini's formulation considering fixed values of temperature (25 °C) and salinity (35 parts per thousand—ppt) and variable solar radiation according to seasonal and weather conditions. These decay rates vary cyclically over the day, where the highest microbiological inactivation occurs around noon and the lowest during the nighttime in the absence of solar radiation. The higher the intensity of solar radiation, the lower the value of the T_{90} (higher decay rate).

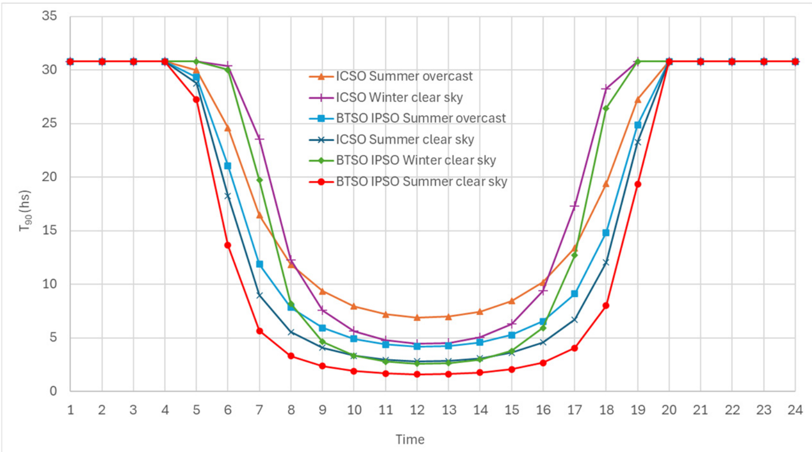

Figure 4. T_{90} values over the day for different weather and seasonal conditions.

However, it is important to highlight that even during the daytime, differences in decay rates can occur due to turbidity, weather, and seasonal variations that regulate the intensity of solar radiation along the plume in the water column. For comparison, Figure 5 highlights the average T_{90} from 9 to 15 h, which represents the highest solar radiation rates over the day, considering the locational, seasonal, and weather differences. Even for identical seasonal and meteorological conditions that provide the same surface solar radiation levels for all locations, there is a higher bacterial decay (lower T_{90}) in the surroundings of Barra da Tijuca (BTSO) and Ipanema (IPSO) outfalls since these waters are less turb than the inland waters from Guanabara Bay around the Icaraí outfall (ICSO).

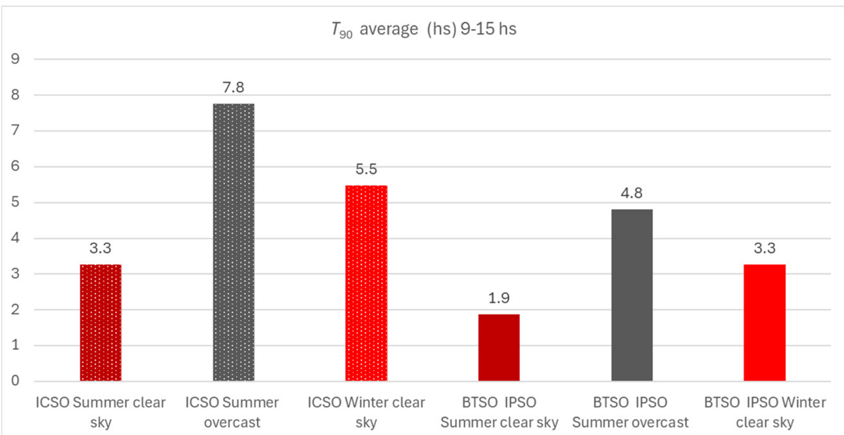

Figure 5. Average T_{90} daytime (9 to15 h) values for all scenarios.

3.2. Coliform Concentration Plumes

On the other hand, comparing the weather and seasonal conditions, T_{90} values follow solar radiation levels, and the best-case scenario (lowest T_{90}) occurs in summer with a clear sky, whereas during winter, with a clear sky and overcast, T_{90} increases substantially.

As a result of the solar radiation levels and the consequent bacterial decay rates, Figures 6–9 present maps of coliform concentration of the sewage plume from BTSO, IPSO, and ICSO under different weather and seasonal conditions. The color scale represents the fecal coliform concentration in MPN/100 mL, where, according to local standards [20], concentrations higher than 1000 indicate unsuitable bathing conditions.

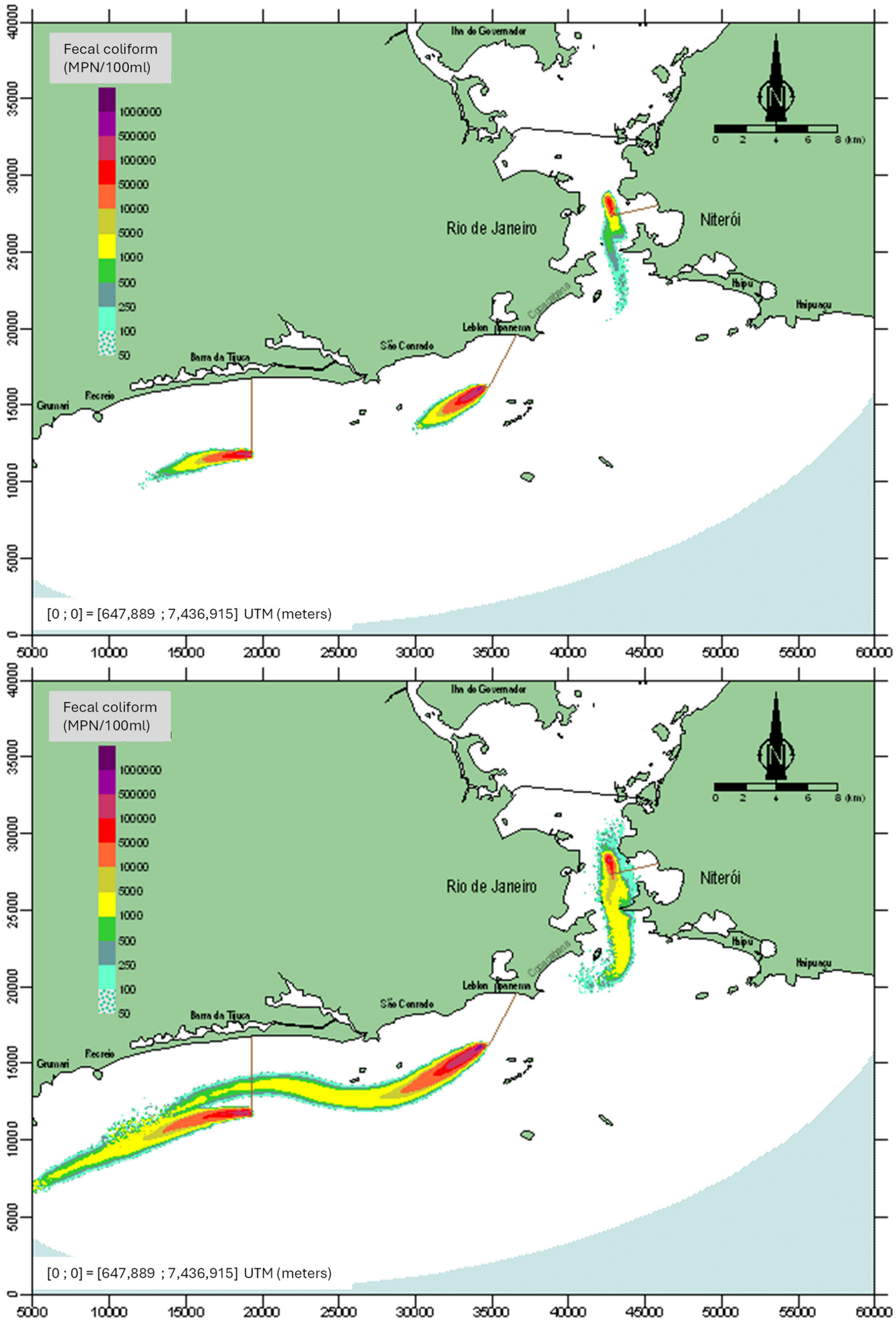

Figure 6. Concentration of coliforms in summer—currents flowing to the west. The upper pattern indicates the clear sky condition, and the lower pattern corresponds to an overcast sky. The intensity of incident solar radiation corresponds to 13:00.

Figures 6 and 7 indicate current patterns flowing to the west, whereas in Figures 8 and 9 the opposite. The plumes of IPSO and BTSO orientate along the coastline according to current patterns driven by wind patterns, whereas the plume of ICSO is located near the mouth of Guanabara Bay, influenced by the astronomical tide, alternating its direction according to flood and web tides.

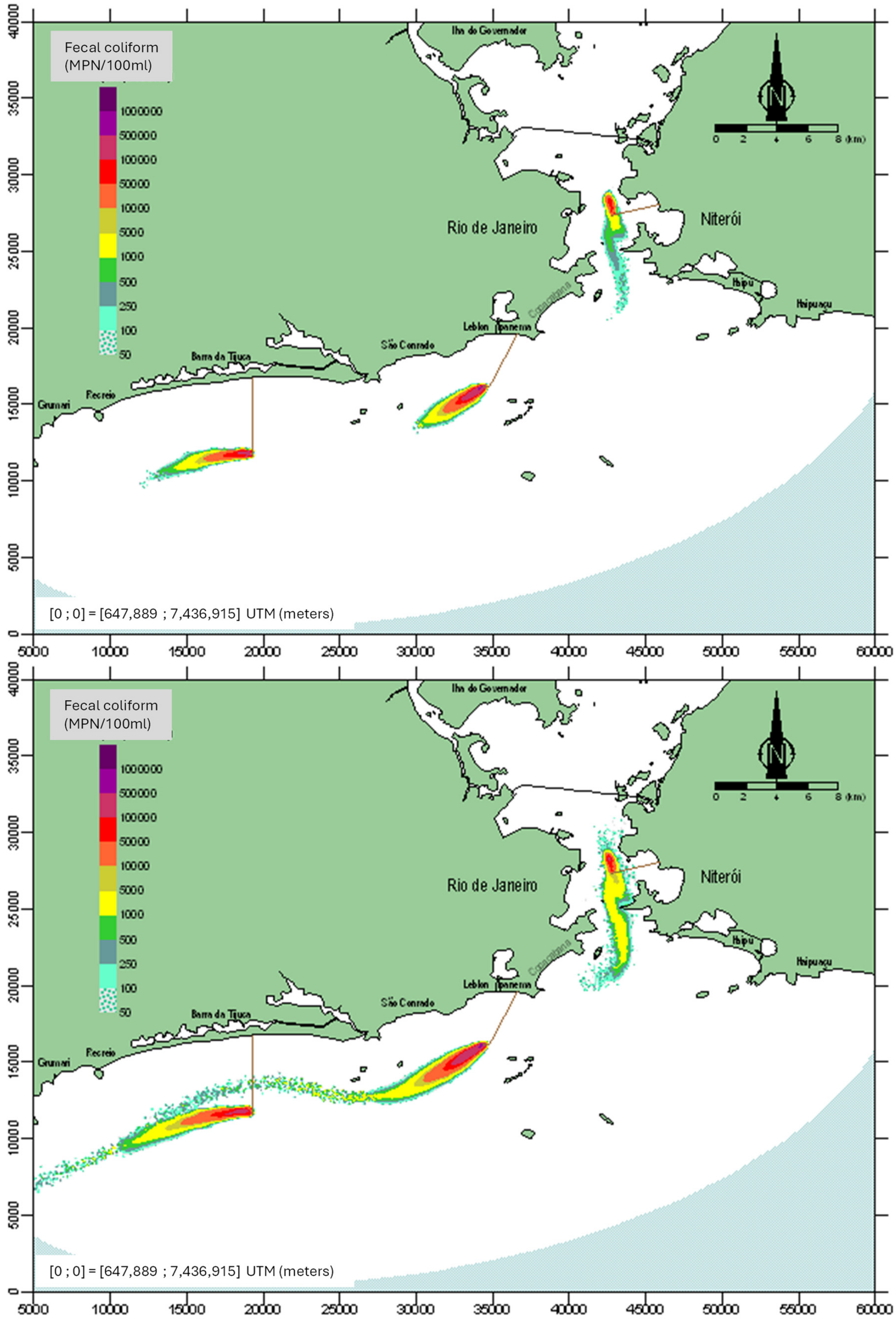

Figure 7. The concentration of coliforms in clear skies—currents flowing to the west. The upper print indicates the summer condition, and the lower print corresponds to winter. The intensity of incident solar radiation corresponds to 13:00 of the day.

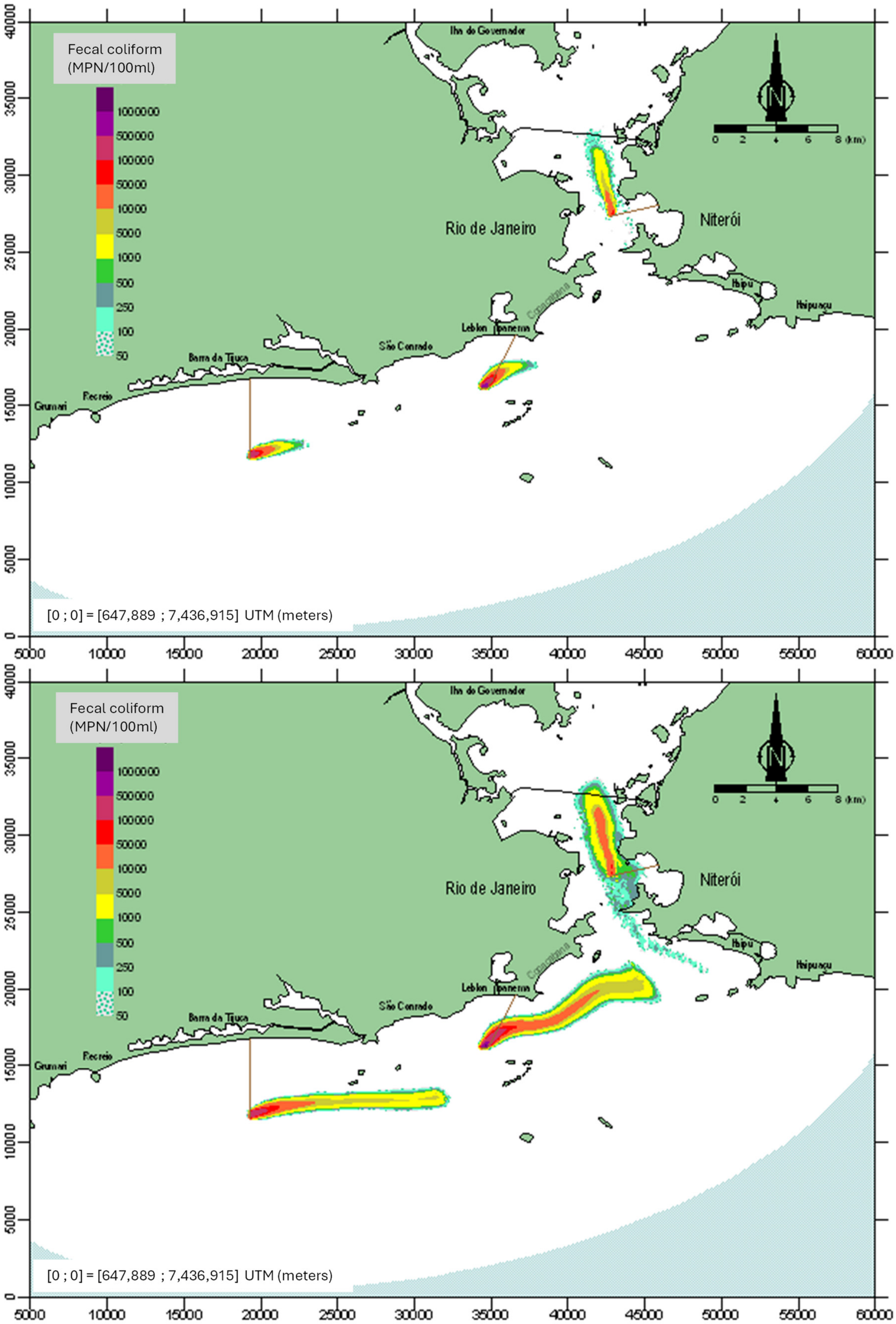

Figure 8. The concentration of coliforms in summer—currents flowing to the east. The upper pattern indicates the clear sky condition, and the lower pattern corresponds to an overcast sky. The intensity of incident solar radiation corresponds to 13:00.

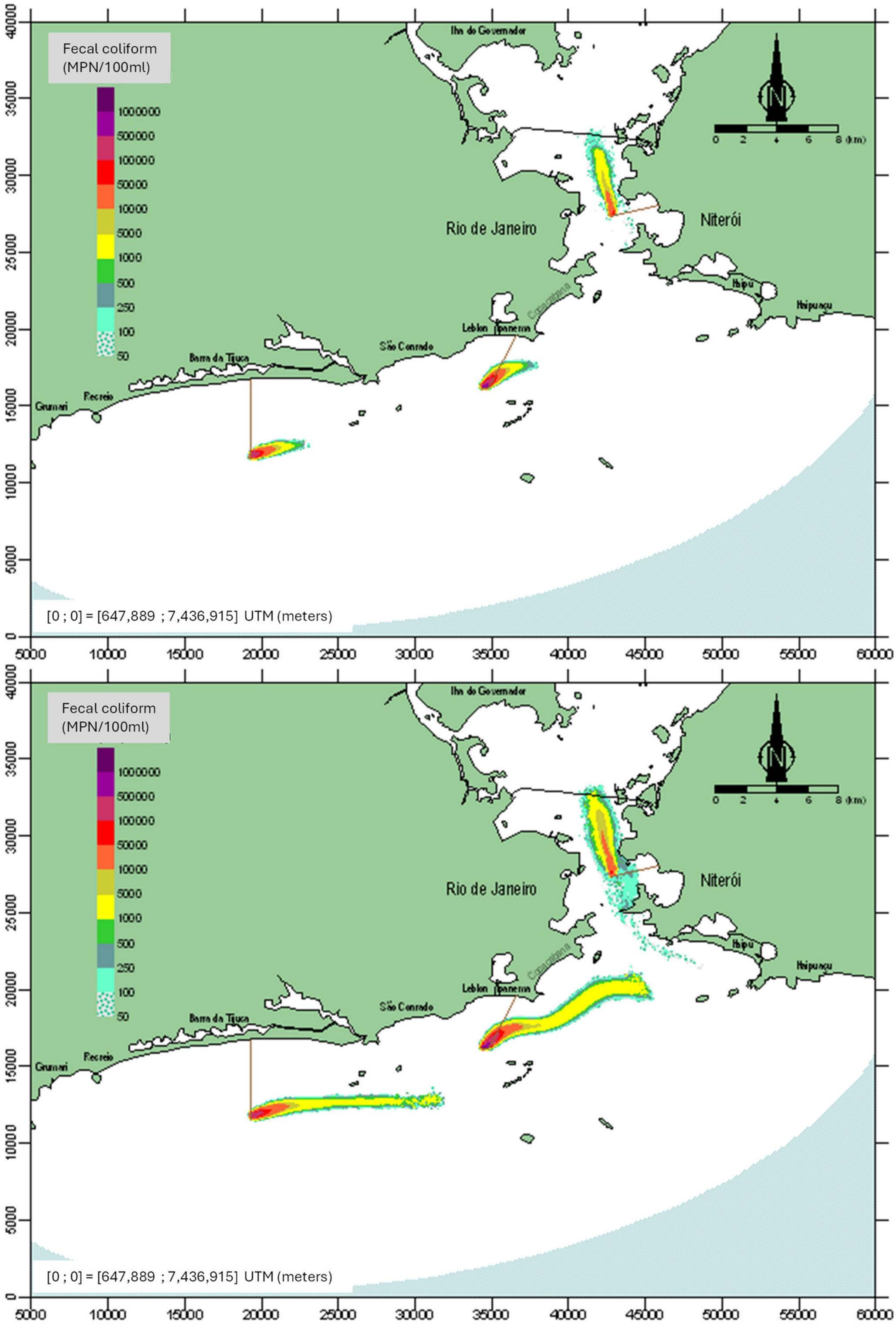

Figure 9. The concentration of coliforms in clear skies—currents flowing to the east. The upper print indicates the summer condition, and the lower print corresponds to winter. The intensity of incident solar radiation corresponds to 13:00 of the day.

Rather than the intensity of the currents, the extension of fecal coliform concentration areas higher than 1000 MPN/10 mL is closely related to the solar radiation levels along the plume. Even under the same current patterns, compared to summer/clear sky, the most extensive coliform plumes result from a lower bacterial decay under winter/clear sky and summer/overcast conditions, respectively. Under the influence of currents flowing to the west, a coliform IPSO plume extent of approximately 4 km away from the source in summer/clear sky increases to 15 and 25 km in winter/clear sky and summer/overcast conditions, respectively. Besides the plume extension, it is observed that there are higher coliform concentration rates in the surroundings of the diffuser under summer/overcast conditions than during the winter with a clear sky. When the currents flow in the opposite direction, the plumes between winter/clear sky and summer/overcast do not distinguish significantly in terms of extension. However, higher concentrations are also evident in summer/overcast sky conditions. In all scenarios, the coliform plumes are oriented parallel to the coast, not reaching the bathing zones.

4. Discussion and Conclusions

The water quality assessment is based on the concentration of fecal coliform, where the estimates of the decay rates of these microorganisms are extremely significant in the evaluation of microbiological impact from sewage outfalls into coastal waters. Several formulations that estimate coliform decay rates in the marine environment were evaluated [11–15,35–37]. Among these formulations, Mancini's formulation [11] is recommended since it considers an extensive database and simultaneous variations in temperature, salinity, and solar radiation.

The results showed that coliform concentration plumes increase as solar radiation levels decrease. Extreme weather and oceanographical events that minimize the effects of solar radiation constitute the worst-case scenarios in terms of coliform concentration plumes. Under such circumstances, it is observed that the higher extensions of coliform plumes lead to microbiological pollution in remote areas, increasing the health risks in the case of contact with bathing zones. All oceanographic and meteorological parameters that directly and indirectly influence solar radiation levels are extremely relevant in the study of the coliform concentration plume. Several studies indicated the influence of solar radiation on coliform decay rates in the marine environment [11–14,34–37]. According to these studies, solar radiation was the most relevant factor in bacterial decay in the marine environment. Temperature and salinity are secondary and relevant factors only in the absence of solar radiation.

It is worth highlighting that the three outfalls considered in the present study attend three different population densities, resulting in different effluent flowrates of sewage among them. The IPSO flow rate is at least three times higher than the BTSO and ICSO. Additionally, unlike IPSO and BTSO, the dynamic in the surroundings of ICSO differs significantly since it is dominated by tidal currents. Even under such disparities, the coliform concentration plumes from BTSO, IPSO, and ICSO did not reach the bathing zones. The same trend was observed in a previous study on the vicinities of IPSO [25]. In this case, the episodes of unsuitable bathing conditions at the beach zone occur due to the drainage of polluted waters from the adjacent watershed to the coast [38]. Regarding Barra da Tijuca, local water quality studies performed in the vicinities of the diffuser of BTSO and along the adjacent beach zone showed that the worst water quality conditions are closer to the canals that connect inland waters to the shoreline [26].

Despite different water quality regulatory frameworks, other studies also reported that sewage outfalls do not compromise beach water quality. After the opening of three submarine sewage outfalls, a significant improvement was evidenced in the water quality of 23 beaches in the coastal region of Sydney, Australia [27]. In addition, according to the Annapolis Protocol published by the World Health Organization in 1999, submarine outfalls are considered an alternative sewage disposal system of low risk to human health [9].

The microbiological assessment presented is restricted to fecal indicator bacteria. The use of these microorganisms aims to evaluate the presence of fecal matter and the likelihood of the presence of enteropathogenic microorganisms in coastal waters. However, it is important to highlight that even though some viruses and antibiotic-resistant bacteria can survive longer than fecal indicators in the marine environment [39,40], the health risks are associated with the concentration levels of these pathogens. The significantly higher concentrations of fecal indicators in domestic sewage can offset its lower resistance to environmental conditions than resistant microorganisms, still suggesting these indicators for microbiological health risk assessment.

Even though there is an occurrence of an environmental impact in the vicinities of the outfall diffuser, well-designed sewage outfall systems do not impact the shoreline, being considered an efficient alternative to preserve the coastal environment and to preserve the bathing conditions of the beach zones.

The use of computational modeling in the evaluation of the impact caused by the discharge of domestic sewage by submarine outfalls is a tool of great value, helping to make decisions regarding the ideal release point and delimiting the areas impacted by the discharge of the effluent.

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References

1. Searcy, R.T.; Boehm, A.B. A Day at the Beach: Enabling Coastal Water Quality Prediction with High-Frequency Sampling and Data-Driven Models. *Environ. Sci. Technol.* **2021**, *55*, 1908–1918. [CrossRef] [PubMed]
2. Heckwolf, M.J.; Peterson, A.; Jänes, H.; Horne, P.; Künne, J.; Liversage, K.; Sajeva, M.; Reusch, T.B.; Kotta, J. From ecosystems to socio-economic benefits: A systematic review of coastal ecosystem services in the Baltic Sea. *Sci. Total Environ.* **2021**, *755*, 142565. [CrossRef] [PubMed]
3. Farkas, K.; Mannion, F.; Sorby, R.; Winterbourn, B.; Allender, S.; Gregory, C.G.; Holding, P.; Thorpe, J.M.; Malham, S.K.; Le Vay, L. Assessment of wastewater derived pollution using viral monitoring in two estuaries. *Mar. Pollut. Bull.* **2024**, *200*, 116081. [CrossRef]
4. Gonçalves, F.B.; De Souza, A.P. Disposição Oceânica de Esgotos Sanitários: História, Teoria e Prática. ABES, Ed.; Brazilian Association of Sanitation Engineer: Rio de Janeiro, Brazil, 1997.
5. Tate, P.M.; Holden, C.J.; Tate, D.J. Influence of plume advection and particle settling on wastewater dispersion and distribution. *Mar. Pollut. Bull.* **2019**, *145*, 678–690. [CrossRef] [PubMed]
6. Besley, C.H.; Birch, G.F. Deepwater ocean outfalls: A sustainable solution for sewage discharge for mega-coastal cities (Sydney, Australia): A synthesis. *Mar. Pollut. Bull.* **2019**, *145*, 707–723. [CrossRef] [PubMed]
7. Akdemir, T.; Dalgic, G. The impact of the marine sewage outfalls on the sediment quality: The Black Sea and the Marmara case. *Saudi J. Biol. Sci.* **2020**, *28*, 238–246. [CrossRef]
8. Birocchi, P.; Dottori, M.; de Godoi Rezende Costa, C.; Leite, J.R.B. Study of three domestic sewage submarine outfall plumes through the use of numerical modeling in the São Sebastião channel, São Paulo state, Brazil. *Reg. Stud. Mar. Sci.* **2021**, *42*, 101647. [CrossRef]
9. WHO. *Health-Based Monitoring of Recreational Waters: The Feasibility of a New Approach (The 'Annapolis Protocol')*; WHO: Geneva, Switzerland, 1999.
10. Fujioka, R.S.; Hashimoto, H.H.; Siwak, E.B.; Young, R.H.F. Effect of sunlight on survival of indicator bacteria in seawater. *Appl. Environ. Microbiol.* **1981**, *41*, 690–696. [CrossRef]
11. Mancini, J.L. Numerical estimates of coliform mortality rates under various conditions. *J. Water Pollut. Control. Fed.* **1978**, *50*, 2477–2484.
12. Chamberlin, C.E. A decay model for enteric bacteria in natural waters. *Water Pollut. Microbiol.* **1978**, *2*, 325–548.
13. Guillaud, J.F.; Derrien, A.; Gourmelon, M.; Pommepuy, M. T90 as a tool for engineers: Interest and limits. *Water Sci. Technol.* **1997**, *35*, 277–281. [CrossRef]
14. Sarikaya, H.Z.; Saatçi, A.M. Bacterial die-away rates in Red Sea waters. *Water Sci. Technol.* **1995**, *32*, 45–52. [CrossRef]

15. Šolić, M.; Krstulović, N. Separate and combined effects of solar radiation, temperature, salinity, and pH on the survival of faecal coliforms in seawater. *Mar. Pollut. Bull.* **1992**, *24*, 411–416. [CrossRef]
16. Suttle, C.A.; Chen, F. Mechanisms and rates of decay of marine viruses in seawater. *Appl. Environ. Microbiol.* **1992**, *58*, 3721–3729. [CrossRef]
17. Kashefipour, S.M.; Lin, B.; Falconer, R.A. Modelling the fate of faecal indicators in a coastal basin. *Water Res.* **2006**, *40*, 1413–1425. [CrossRef]
18. Carneiro, M.T.; Cortes, M.B.V.; Wasserman, J.C. Critical evaluation of the factors affecting Escherichia coli environmental decay for outfall plume models. *Rev. Ambiente Agua* **2018**, *13*, e2106. [CrossRef]
19. Chan, Y.M.; Thoe, W.; Lee, J.H.W. Field and laboratory studies of Escherichia coli decay rate in subtropical coastal water. *J. Hydro-Environ. Res.* **2015**, *9*, 1–14. [CrossRef]
20. CONAMA. *Resolution 274*; Conselho Nacional do Meio Ambiente: Brasilia, Brazil, 2000.
21. Roberts, P.J.W. Dilution and transport predictions for ocean outfalls. *Water Sci. Technol.* **1989**, *21*, 1606. [CrossRef]
22. Carvalho, J.L.B.; Roberts, P.J.W.; Roldao, J. Field observations of Ipanema beach outfall. *J. Hydraul. Eng.* **2002**, *128*, 151–160. [CrossRef]
23. Rosman, P.C.C. *Referência Técnica do SisBaHiA—Sistema Base de Hidrodinâmica Ambiental*; Fundação COPPETEC—COPPE/UFRJ: Rio de Janeiro, RJ, Brazil, 2024.
24. Schaffel, R.; Paranhos, R.; Carvalho, P.; Pereira, M.; Matos, F.; Mendonça-Hagler, L.C.; Mayer, L.; Hagler, A.N. Contagens de coliformes fecais em águas de superfície nas proximidades do emissário submarino de Ipanema, Rio de Janeiro, RJ. In Proceedings of the III Encontro Nacional de Microbiologia Ambiental, São Paulo, Brazil, 3–6 December 1990.
25. Pedrosa de Macena, L.d.G.; Castiglia Feitosa, R.; Couto da Silva, J.; Ferreira, F.C.; Maranhão, A.G.; Brandão, M.L.L.; Caldeira, N.G.S.; Couto, J.S.; Coelho de Azevedo, M.G.; Barbosa de Paula, B.; et al. Environmental assessment of sewage contamination in the surroundings of a marine outfall combining human mastadenovirus and faecal indicator bacteria. *Mar Pollut Bull.* **2023**, *193*, 115110. [CrossRef]
26. Sydney Waters. *Sydney's Deep-Water Ocean Outfalls Long-Term Environmental Performance*; Sydney Water: Sydney, Australia, 2007.
27. Feitosa, R.C.; Rosman, P.C.C.; Bleninger, T.; Wasserman, J.C. Coupling bacterial decay and hydrodynamic models for sewage outfall simulation. *J. Appl. Water Eng. Res.* **2013**, *1*, 137–147. [CrossRef]
28. Roberts, P.J.W.; Snyder, W.H.; Baumgartner, D.J. Ocean Outfalls. I: Submerged Wastefield Formation. *J. Hydraul. Eng.* **1989**, *115*. [CrossRef]
29. Roberts, P.J.W.; Snyder, W.H.; Baumgartner, D.J. Ocean Outfalls. II: Spatial Evolution of Submerged Wastefield. *J. Hydraul. Eng.* **1989**, *115*, 26–48. [CrossRef]
30. Roberts, P.J.W.; Snyder, W.H.; Baumgartner, D.J. Ocean Outfalls. III: Effect of Diffuser Design on Submerged Wastefield. *J. Hydraul. Eng.* **1989**, *115*, 49–70. [CrossRef]
31. Feitosa, R.C.; Rosman, P.C. Emissários Submarinos de Esgotos: Aspectos de Qualidade de Água e Modelagem Computacional. In *Silva RCV, Organizador Métodos Numéricos em Recursos Hídricos VIII Porto Alegre*; ABRH: Porto Alegre, Brazil, 2008; pp. 1–170.
32. Feitosa, R.C.; Rosman, P.C.C.; Carvalho, J.L.B.; Côrtes, M.B.V.; Wasserman, J.C. Comparative study of faecal bacterial decay models for the simulation of plumes of submarine sewage outfalls. *Water Sci. Technol.* **2013**, *68*, 622–631. [CrossRef]
33. McCambridge, J.; McMeekin, T.A. Effect of solar radiation and predacious microorganisms on survival of fecal and other bacteria. *Appl. Environ. Microbiol.* **1981**, *41*, 1083–1087. [CrossRef] [PubMed] [PubMed Central]
34. Martin, J.L.; McCutcheon, S.C.; Schottman, R.W. *Hydrodynamics and Transport for Water Quality Modeling*; CRC Press: Boca Raton, FL, USA, 2018.
35. Bellair, J.T.; Parr-Smith, G.A.; Wallis, I.G. Significance of diurnal variations in faecal coliform die-off rates in the design of ocean outfalls. *J. Water Pollut. Control. Fed.* **1977**, *49*, 2022–2030.
36. Canteras, J.C.; Juanes, J.A.; Pérez, L.; Koev, K.N. Modelling the coliforms inactivation rates in the Cantabrian Sea (Bay of Biscay) from in situ and laboratory determinations of T90. *Water Sci. Technol.* **1995**, *32*, 37–44. [CrossRef]
37. Yang, L.; Chang, W.S.; Lo Huang, M.N. Natural disinfection of wastewater in marine outfall fields. *Water Res.* **1999**, *34*, 743–750. [CrossRef]
38. Vieira, C.B.; Mendes, A.C.d.O.; de Oliveira, J.M.; Gaspar, A.M.C.; Leite, J.P.G.; Miagostovich, M.P. Vírus entéricos na lagoa Rodrigo de freitas. *Oecologia Aust.* **2012**, *16*, 540–565. [CrossRef]
39. Carducci, A.; Battistini, R.; Rovini, E.; Verani, M. Viral removal by wastewater treatment: Monitoring of indicators and pathogens. *Food Environ. Virol.* **2009**, *1*, 85–91. [CrossRef]
40. McKee, A.M.; Cruz, M.A. Microbial and Viral Indicators of Pathogens and Human Health Risks from Recreational Exposure to Waters Impaired by Fecal Contamination. *J. Sustain. Water Built. Environ.* **2021**, *7*, 03121001. [CrossRef]