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Effect of secondary treatment at the South Bay Ocean Outfall (SBOO) on microbial ocean water quality near the US-Mexico border

Katelyn Taylor [a], Kurtis S. Baron [b], Richard M. Gersberg [a,*]

[a] School of Public Health, San Diego State University, San Diego, CA 92182, United States of America
[b] Atkins, SNC-Lavalin Group, San Diego, CA 92130, United States of America

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ABSTRACT

In this study, density plume visualizations and statistical comparisons were made of enterococci bacteria (the main marine recreational microbial water quality indicator) densities, both before and after the upgrade of the discharge from the South Bay Ocean Outfall (SBOO) to secondary treatment level, so that the effect of this upgrade on ocean microbial water quality could be assessed. During the dry weather (bathing) season, reduction in enterococci densities was rather limited with only 2 shore stations and one kelp station showing significant reductions, and none showing increased compliance frequency. During the wet weather season, although the signature of land-based sources of bacterial pollution were evident, a majority of both shore (7 of the 11 stations) and kelp (4 of the 7 stations) stations showed statistically significant ($p \leq 0.05$) reductions enterococci densities pointing to the role of the upgrade to secondary treatment in improving microbial water quality.

1. Introduction

The Tijuana River and nearshore coastal waters of the United States have been contaminated by sewage flows for decades. Over the past 30 years, Tijuana, Mexico has experienced great population and industrial growth, along with intense urbanization which has put a strain on the Mexican sewage infrastructure. These emerging sewage infrastructure inadequacies have created continuing sewage pollution problems on both sides of the California - Mexico border. In an effort to mitigate the volume and improve the quality of sewage that was flowing into the Pacific Ocean via the Tijuana River, United States International Boundary Water Commission (IBWC) agreed to construct a treatment plant and the South Bay Ocean Outfall (SBOO) on the United States side of the border. This plant which became operational in 1999, is operated by the USIBWC and is known as the South Bay International Wastewater Treatment Plant (SBIWTP). It is located in San Diego County about 2 miles west of the San Ysidro Port of Entry at the U.S. –Mexico border. The SBIWTP treats 94.6 million liters (25 million gallons) per day of sewage that originates in Tijuana. Treated effluent is discharged into the Pacific Ocean at a depth of about 30 m via the approximately 5 km long SBOO (City of San Diego, 2013). The outfall continued to discharge primary treated municipal wastewater into the Pacific Ocean up until 2010, despite the fact that under the Clean Water Act (CWA) all sewage that is discharged into waters of the U.S. must be treated to secondary treatment standard prior to being discharged into the ocean. Accordingly, in 2001 the State of California San Diego Regional Water Quality Control Board (SDRWCCB) sued the IBWC over failure to comply with secondary treatment requirements in the Clean Water Act. Eventually, the IBWC agreed to comply with the legal judgement by the U.S. District Court (Case No. 01 CV 0270 BTM) and to the upgrade to secondary treatment at the SBIWTP which came on line in November 2010.

However, despite this upgrade, ocean water quality and beach postings and closures have continued to be a chronic problem, such that beaches in the southern part of the city of Imperial Beach, CA were closed for 295 days in 2020 (City of Imperial Beach, 2021).

Globally and even in the U.S., the cost-effectiveness (cost-benefit) of deepwater ocean outfalls has been questioned for decades (U.S. General Accounting Office, 1981). Indeed, while quantifying the costs are usually rather straightforward, the water quality and public health benefits of ocean outfalls are more difficult to assess. There are very few studies that have well (both long-term and statistically) evaluated the degree of improvement in microbial water quality and reduction in health risk after the commissioning of deepwater ocean outfalls. A long-term study of microbial water quality associated with two deepwater ocean outfalls in the area of Durban, South Africa, found significant improvement in bathing water quality after the commissioning of the outfalls (Rathbone

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* Corresponding author.
E-mail address: rgersber@sdsu.edu (R.M. Gersberg).

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et al., 1998). And the installation of the Sydney, Australia deepwater ocean outfalls resulted in a reduction of gastrointestinal illness at several area beaches of between 63 % and 77 % (Ashbolt et al., 1997). However, due to a variety of oceanographic, meteorological and geographic conditions, after the installation of deepwater outfalls, a corresponding improvement of microbial water quality at nearby beaches has not always been observed (Rathbone et al., 1998; Castiglia Feitosa, 2017).

Despite the continuous monitoring of ocean water quality at the SBOO and nearshore beaches in this impacted U.S. – Mexico border region, there has been no comprehensive analysis to date of the spatial and temporal patterns of water quality improvement both prior to and after secondary treatment was initiated. In this study, statistical comparisons were made of the microbial water quality (densities of enterococci indicator bacteria, as well as the frequency of compliance with recreational water quality standards) at both ocean, kelp bed and shore stations both before and after discharge of secondary treated sewage to the SBOO began, in order to delineate the degree of improvement (if any) after this treatment upgrade. It is hoped that this analysis will serve to inform future management decisions aimed at improving ocean and beach water quality in this U.S. – Mexico border region.

2. Methods

2.1. Sites monitored in the area of the South Bay Ocean Outfall

Water quality data for this study were generated by the City of San Diego Ocean Monitoring Program from Playa Blanco Mexico to Coronado, CA, USA (City of San Diego, 2022). Samples were taken from shore stations, kelp stations and offshore stations in accordance with the NPDES Permit for the South Bay Reclamation Plant and the South Bay Ocean Outfall (Fig. 1). There were eleven shore stations, seven kelp bed stations and nineteen offshore stations that were sampled at depths and frequencies indicated in Table 1. The monitoring area covers a cross-border region that extends 20 km (12 miles) into the US and >10 km (6 miles) into Mexico, with the southernmost shoreline station south of

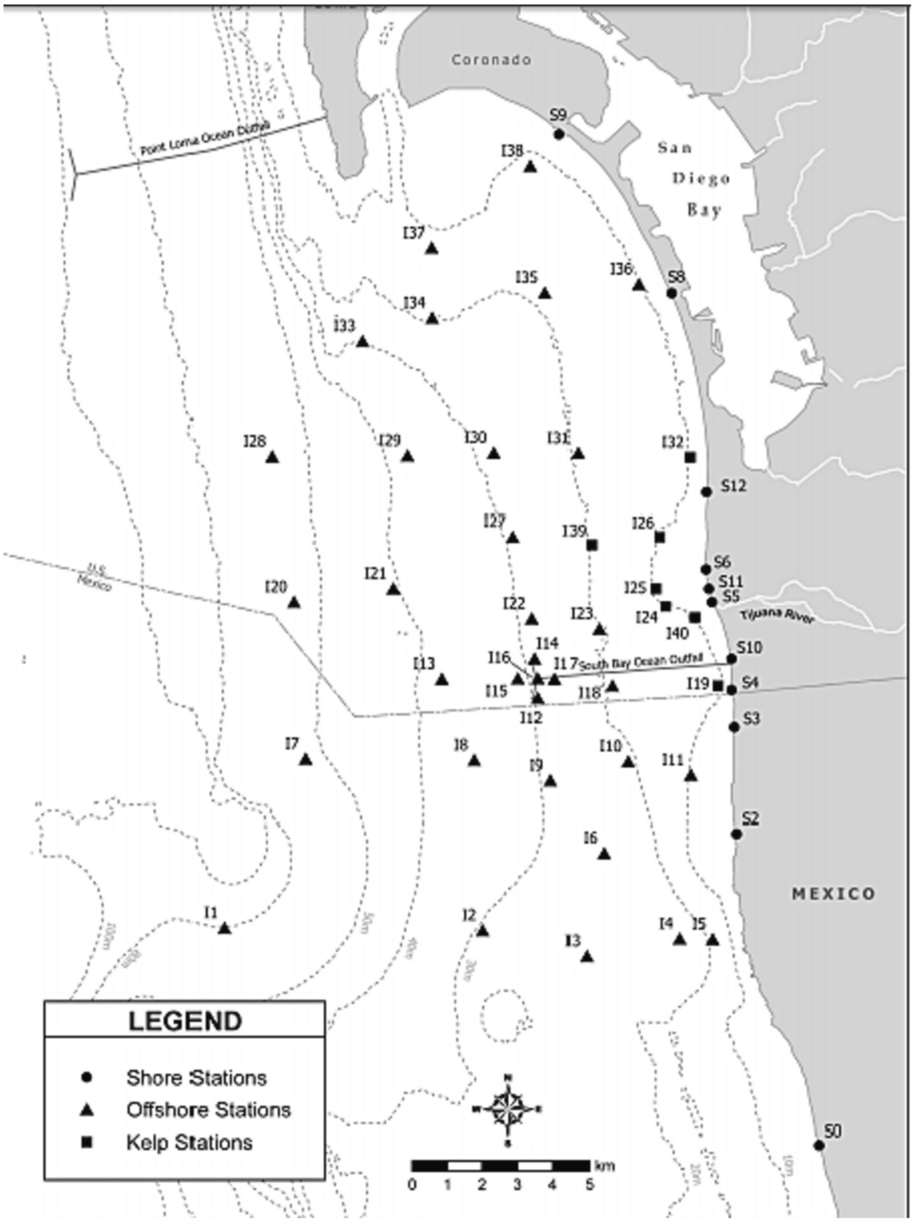

Fig. 1. Monitoring stations of the City of San Diego. (2018). Source: City of San Diego. (2018). Retrieved from (https://www.sandiego.gov/sites/default/files/qarpt18.pdf).

Table 1
City of San Diego ocean monitoring stations.

Station code(s)	Type of station	Depth	Sample frequency
S0[a], S2[a], S3[a]	Shore	Surface	Weekly
S4-S6, S8-S12	Shore	Surface	Weekly
I19, I24-I26, I32, I40	Kelp	10-m Depth Contour	Monthly
I39	Kelp	18-m Depth Contour	Monthly
I4, I5, I10, I18, I23, I31, I35, I34	Off Shore	18-m Depth Contour	Quarterly
I2, I9, I12, I14, I15, I16, I17, I22, I27, I30, I33	Off Shore	27-m Depth Contour	Quarterly

[a] Indicates station located on Mexican territory.

Punta Bandera. The coastline runs roughly in a north-south direction between Punta Bandera in Mexico and Silver Strand, S8, the second most northerly US station. S11 located on beach at end of Monument Road, and S12 at the end of Carnation Street, Imperial Beach. At Silver Strand, the coastline begins to curve substantially and tends approximately east-west on approaching the mouth of San Diego Bay. With the exception of S8, which is located along a state beach, the stations between S9 and S6 are urban in character. The final four US shoreline stations are located within a 5 km (3 mile) stretch of undeveloped land that comprises the National Estuarine Research Reserve and Border Field Park. S5 is located on the north bank of the Tijuana River Estuary. Three of the monitored shore stations (S0, S2, S3) are located south of the International Border in Mexico. Samples from the shore stations were taken on a weekly basis from the surf zone and analyzed for densities of enterococci (was well as other fecal indictors) as well as visual observations such as water color, clarity, surf height, human and animal activity and weather conditions (City of San Diego, 2018). At Imperial Beach, CA, the predominant wind direction in the summer is from the west (about 60–80 % of the time) with a mean direction of about 275° during summer; while in winter, winds from the east increase to a frequency of nearly 40 % of the time, so that the mean wind direction is about 320° (https://www.weatherspark.com; accessed August 18, 2022).

One of the defining characteristics of the Mediterranean climate of southern California is a hot, dry summer. Therefore, with extremely rare exceptions, it does not rain during this May through September “dry” season (which corresponds to the bathing season), so that microbiological pollution in the bathing season is generally not related to the occurrence of rain.

2.2. *Enterococci density monitoring*

All enterococci density analyses were performed by the City of San Diego within eight hours of sample collection and conformed to the standard membrane filtration technique (U.S. EPA, 2009). Densities were determined and validated in accordance with USEPA guidelines. Quality assurance tests were performed routinely on bacterial samples to ensure that analyses and sampling variability did not exceed acceptable limits. The “minimum detection limit” for bacterial colony forming units (CFU) using the above membrane filtration method is based on the volume of water tested. If 100 mL of sample is filtered and no bacteria are detected, the density is then reported as “less than” (<) 1 CFU/100 mL. Therefore, “1 CFU/ 100 mL” is also the minimum detection limit (County of Orange Water Quality Department, 2004).

2.3. *Data analysis*

Data collected by the City of San Diego was stored as CSV files on the online South Bay Ocean Monitoring archive. Data was downloaded and exported to Microsoft Excel worksheets for formatting and consolidation. Two data sets were developed: one for the bathing (dry weather) season when stratification of the water column obviated the need for chlorination (May–September, and one for the period of the wet season (October–April) when stratification breaks down and chlorination was practiced. Chlorination occurred from October through April from the initiation of the SBOO until 2014 when chlorination of effluent was discontinued (T. Stebbins, 2018). Data was then coded by date and categorized as occurring before the secondary treatment upgrade (2001−2010), or after the upgrade to secondary treatment (2012–2018). Secondary sewage treatment is a biological process that removes organic matter (and suspended solids) of sewage through the action of microbes. The upgrade to secondary treatment at the SBIWTP consisted of aeration basins with process air blowers, secondary sedimentation tanks, dissolved air flotation thickeners, and return / waste activated sludge pump stations (https://www.water-technology.net/projects/tijuana/; accessed August 17, 2022). For unspecified reasons, data for 2011 were unavailable in the City of San Diego's archived data files. Using Excel, the number of single sample maximum (SSM) and geometric mean (GM) threshold exceedances of recreational marine water quality criteria (as described below) were calculated and totaled for each data set.

2.4. *Microbial water quality standards for ocean recreation*

In 2019, the State Water Resources Control Board approved updates to the beach water quality standards provided in Part 3 of the Water Quality Control Plan for Inland Surface Waters, Enclosed Bays, and Estuaries (ISWEBE) of California (State Water Resources Control Board, 2019), based upon U.S. EPA Guidelines (U.S. EPA, 2012). In this revised ISWEBE Water Quality Control Plan, the water quality objective for marine waters is that the geometric mean (six week rolling) of enterococci density does not exceed 30 CFU (colony forming units) per 100 mL, and the statistical (95 %) threshold value (STV) of 110 CFU per 100 mL, shall not be exceeded (by >10 % of the samples) in a calendar month. Since enterococci density is now the main indicator recognized by both the State of California and the U.S. EPA to reflect marine recreational water quality, and since it is also recognized as a more conservative indicator of human health risk than the fecal or total coliform bacteria, the latest standards for enterococci bacteria from ISWEBE were used in this study to determine compliance with health-based standards for bathing (Table 2).

2.5. *Statistical analyses*

Microbial water quality data were processed by SAS Statistical Software (SAS Studio). Due to the fact that the densities of enterococci were determined not to be normally distributed, a non-parametric Wilcoxon rank-sum test was chosen to analyze the data on statistically significant effects on enterococci densities associated with the upgrade to secondary treatment. Similarly, the Fisher's exact test was used to analyze the threshold exceedances of the enterococci water quality standard both before and after the upgrade to secondary treatment.

Tijuana River flow data was collected through the Freedom of Information Act from the International Boundary Water Commission. Gage data for the years 2001 to 2018 were organized for years prior to treatment upgrade (2001–2010) and compared to the years after the treatment upgrade (2011–2018). Tijuana River flow rate was determined to be non-normally distributed, so a non-parametric Wilcoxon rank-sum test was used to analyze the difference between the pre- and post-secondary treatment periods.

3. Results

Dwight et al. (2007) who derived bathing rates from two long-term datasets for beaches in San Diego County, found that approximately 80 % of total bathing events occur between May through September. Therefore, the present analysis was divided into the dry weather

Table 2

REC-1 Bacteria Water Quality Objectives from California Inland Surface Waters, Enclosed Bays and Estuaries (ISWEBE) Water Quality Control Plan (State Water Resources Control Board, 2019).

Applicable Waters	Objective Elements	Estimated Illness Rate (NGI): 32 per 1,000 water contact recreators	
		Magnitude	
	Indicator	GM (cfu/100 mL)	STV (cfu/100 mL)
All waters where the salinity is greater than 1 ppth more than 5 percent of the time	Enterococci	30	110
The waterbody GM shall not be greater than the applicable GM magnitude in any six-week interval, calculated weekly. The applicable STV shall not be exceeded by more than 10 percent of the samples collected in a CALENDAR MONTH, calculated in a static manner.			

NGI = National Epidemiological and Environmental Assessment of Recreational Water gastrointestinal illness rate
GM = geometric mean
STV = statistical threshold value
cfu = colony forming units
mL = milliliters
ppth = parts per thousand

(bathing) season (May through September) and the wet weather season (October through April). Significant changes in microbial water quality associated with the treatment plant upgrade were evaluated using the following parameters: changes in the densities (CFU/100 mL) of enterococci which is the primary and sole fecal indicator bacteria recommended for marine waters, the frequency of exceedances of the single sample maximum (SSM) recreational water quality standard, and the frequency of exceedances of the geometric mean (GM) standard (for the shore stations where sampling frequency allowed). Pre-secondary (years 2001–2010) and post-secondary (2012–2018) treatment groups were then grouped by dry weather (bathing) season (May–September), when summer stratification allowed discharge to the outfall without chlorination, and the wet (non-bathing) season (October–April), when water column mixing occurs and the effluent was chlorinated due to the possible surfacing of the wastewater plume. The analysis was separated based upon these periods since the chlorination status would be expected to show a significant effect on indicator densities.

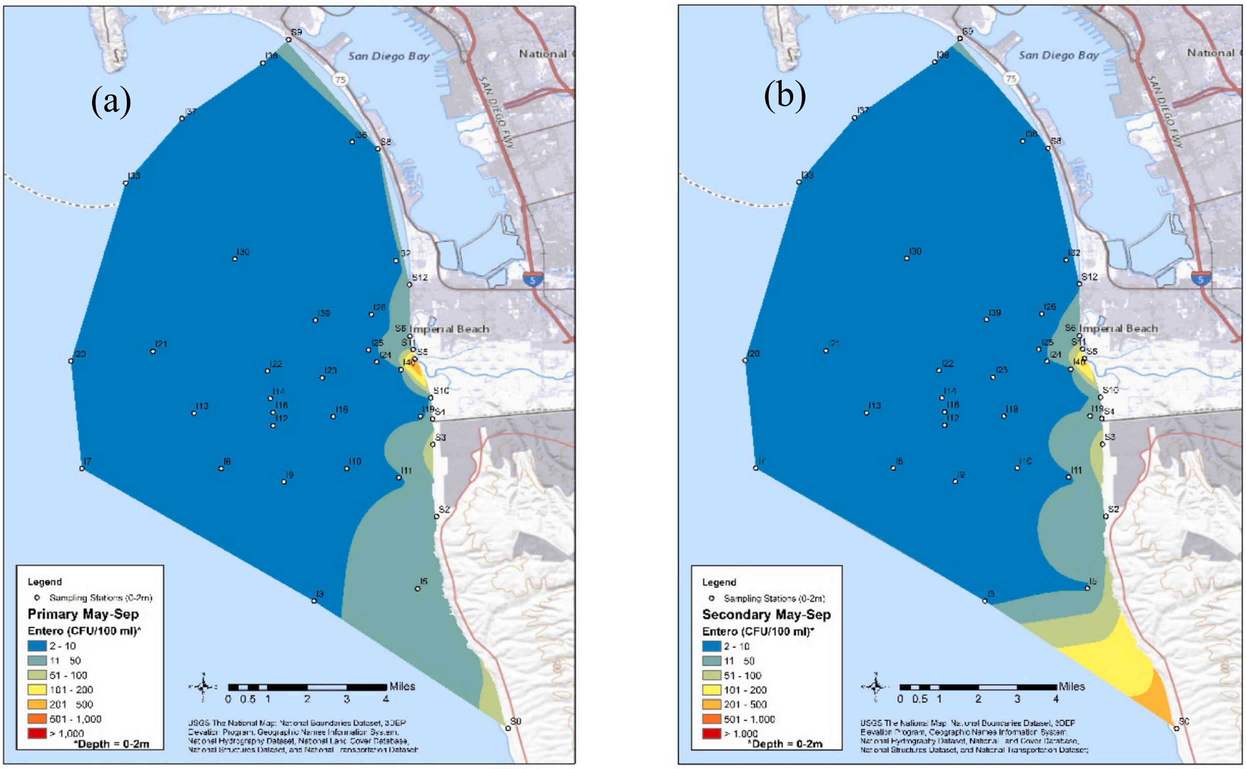

Fig. 2. Isopleth diagram of mean enterococci density in surface waters (0- 2 m) of the SBOO region in the dry weather period before (a) and after (b) the upgrade to secondary treatment.

3.1. *Plume visualization during the dry season*

Fig. 2 shows isopleth diagrams of enterococci indicator densities in surface waters in the region of the SBOO for the dry weather (bathing) season both before (Fig. 2a) and after (Fig. 2b) the upgrade to secondary treatment. Visual inspection of this synoptic data reveal that no signature of the outfall plume (centered at I16) is evident in the surface waters either before or after the upgrade to secondary treatment, most probably due to the fact that stratification does act as a barrier to sewage plume surfacing.

However, two other signatures of enterococci contamination are evident closer to the shore and apparently unassociated with the SBOO. One of these is clearly at the mouth of the Tijuana River (just south site S5) extending north at least up to site S12 in Coronado, CA. Additionally, another signature is evident that appears to originate in Mexico, at or south of site S0 which is about 3.8 km south of the San Antonio de los Buenos treatment plant in Mexico. Although the number of sampling sites in Mexico does not allow resolution of this density gradient, it appears to trend northward (at least to site S10) before its attenuated and is subsumed into the Tijuana River contamination plume. Visual inspection of these density isopleths both before and after the treatment upgrade shows if anything, that this gradient of contamination originating from south of the U.S.-Mexico border seemed to have increased in the period after the upgrade of the SBIWTP to secondary treatment (Fig. 2b).

In deeper waters, the effect of the upgrade to secondary treatment is quite evident during the dry season (Fig. 3). Before the upgrade, Fig. 3a shows a pronounced plume of bacterial contamination centered around station I12 near the SBOO outfall discharge point which still does not appear to impinge upon the coast. However, after the upgrade to secondary treatment, this enterococci density plume completely disappeared in the deeper offshore waters.

3.2. *Statistical analysis of microbial densities during the dry season*

Statistical analysis of the data allows a more robust quantitative analysis of the effect of the secondary treatment upgrade on shore station water quality than by visual inspection of Fig. 2 alone. A Wilcoxon rank sum test was used to statistically compare enterococci indicator densities before with after the upgrade (Table 3). Results showed that there was actually significant degradation of microbial water quality at some of the shore stations during the dry season, with a significant increase in enterococci densities at 2 of the 3 shore stations in Mexico (S0 and S3), but also a significant density increase at shore station S6 in Imperial Beach, CA and S11 in Coronado, CA after the upgrade occurred. On the other hand, two shore stations (S5 and S8) both showed significant enterococci density declines (of 33 % and 64 %) after the upgrade to secondary treatment.

When differences in compliance with recreational enterococci standards were compared for the dry weather season before and after the upgrade, a similar lack of water quality improvement was observed, with not a single shore station in the U.S. showing a significant ($p \leq 0.05$) decrease in the frequency of exceedances of the single sample maximum (SSM) standard of 110 CFU/100 mL for enterococci after the upgrade to secondary treatment (Table 4). It is interesting to note here, that since compliance with enterococci standards at these shore stations was so exceedingly high (> 94 %) (Table 3) during the dry season even before secondary treatment was initiated at the IWTP, that there was

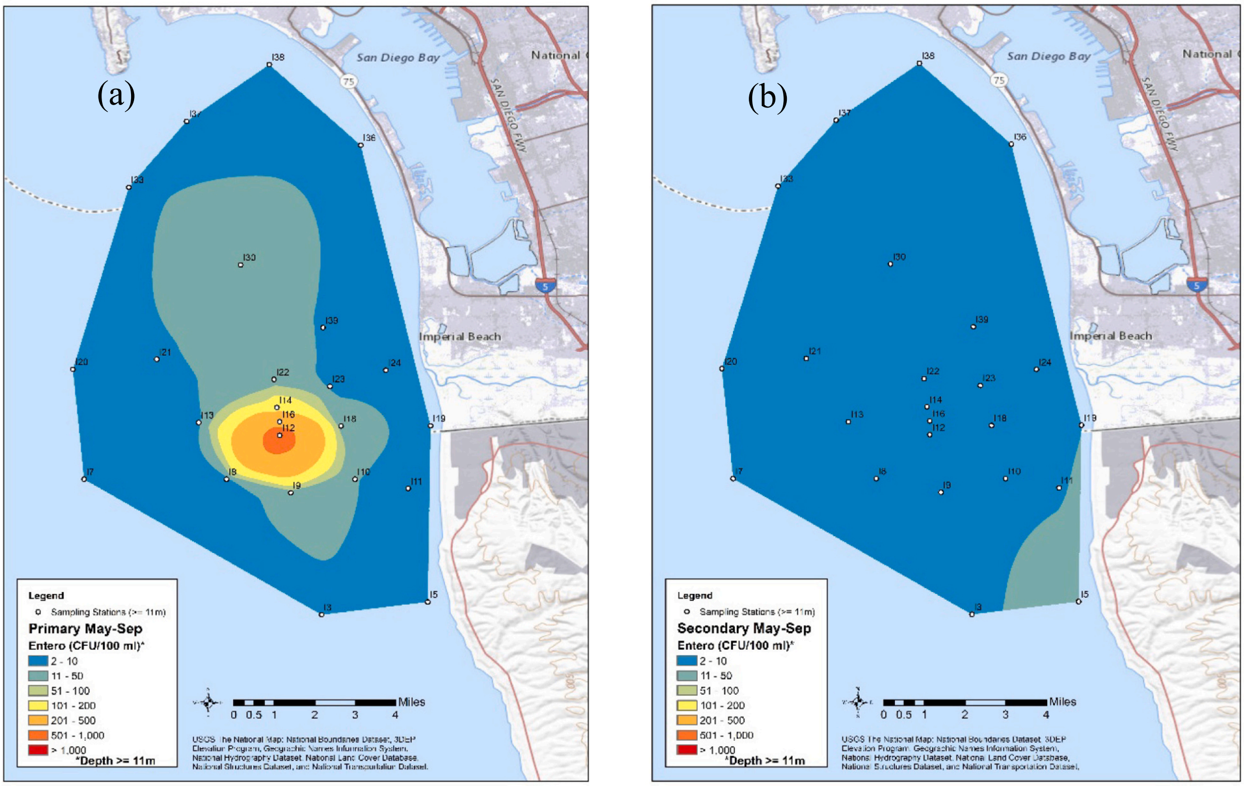

Fig. 3. Isopleth diagram of mean enterococci density in deep waters (mean value of all depths ≥11 m) of the SBOO region in the dry weather period before (a) and after (b) the upgrade to secondary treatment.

Table 3
Comparison of enterococci indicator densities and *P* values from the Wilcoxon Rank Sum Test for Significance, at shore stations during the dry season, before as compared to after the upgrade to secondary treatment at the South Bay International Wastewater Treatment Plant. (*) denotes a significant increase ($p \leq$ 0.05) in the density of enterococci after the upgrade, and (**) a significant decrease.

Shore station	Mean enterococci density (CFU/100 mL) pre-secondary treatment	Mean enterococci density (CFU/100 mL) post-secondary treatment	Percent change post-secondary treatment	*P* value
S0	58	266	+359 %	0.007*
S2	28	40	+43 %	0.089
S3	75	85	+13 %	0.002*
S4	22	16	−27 %	0.338
S5	389	259	−33 %	0.014**
S6	16	20	+25 %	0.003*
S8	11	4	−64 %	0.035**
S9	17	13	−24 %	0.279
S10	11	12	+10 %	0.129
S11	53	86	+62 %	0.000*
S12	19	9	−53 %	0.080

little room for additional improvement in compliance with the enterococci standard at these shore stations. This was especially true when the frequency of exceedance of the geometric mean enterococci standard (running average) of 30 MPN/100 mL was examined. Indeed, for the 10-year period before the upgrade, only a very few shore stations showed more than one exceedance for this whole period, and these were either closest to river mouth (S5, S11) or in Mexico (S6) (Table 4). Needless to say, statistical analysis using the Fishers Exact test did not reveal a single shore station that evidenced significance improvement in compliance for the GM standard after the upgrade to secondary treatment.

Similarly, for the dry season at the kelp stations, statistical testing of enterococci densities before as compared to after the treatment upgrade, showed no kelp station with a significant decline in enterococci density or improvement in compliance with the SSM standard in surface waters during the dry season. Moreover, even at the offshore stations closer to the SBOO, significant reduction in enterococci densities or improvement in SSM compliance for surface waters after secondary treatment began was found at only a single offshore station, I12 very close to the outfall.

On the other hand, statistical analyses indicate a rather marked improvement in the deep waters at both the kelp and offshore stations in the dry weather season, where enterococci levels in deep waters were significantly ($P \leq 0.05$) reduced before as compared to after the upgrade to secondary treatment (Table 5).

3.3. Plume visualization during the wet season

During the wet season, a distinct plume of enterococci contamination was observed in surface waters around the SBOO before the upgrade to secondary treatment, but this spatial gradient declined as it approached the coast and did not appear to impinge upon the coastal beaches in the region (Fig. 4a).

In a similar manner to the dry season pattern, two other contamination gradients are evident, one in surface waters arising from the plume at the Tijuana River mouth that extends from the river mouth northward along the coast to stations in Coronado, CA, and another signature arising south of the U.S.-Mexico border (Fig. 4).

In the deep waters the distinct density plume observed around the SBOO completely disappeared after the upgrade to secondary treatment (Fig. 5).

3.4. Statistical analysis of microbial densities during the wet season

Table 6 shows the results of Wilcoxon rank sum test for enterococci densities at the shore stations during the wet season, before as compared to after the treatment upgrade. The majority of the shore stations (excepting S0, S4, S9 and S10) showed significant decreases in enterococci densities with a mean decline for these 7 stations of 62 % after the upgrade. With regard to compliance with the enterococci bathing standard, during the wet season there was some improvement in microbial water quality, with a significant ($p \leq 0.05$) decrease in the frequency of exceedance the SSM enterococci standard as well, at 5 of the 11 shore stations (S3, S6, S8, S11, and S12). (Table 6).

Evidence of improvement was also evidenced during this period by significant declines in enterococci densities at 4 of the 7 kelp stations (I25, I26, I32 and I 39) in the surface water at several depths (2, 6 and 9 m) after the upgrade to secondary treatment (Table 7). A significant increase in compliance with the SSM enterococci standard in surface waters also occurred at 3 of 4 kelp stations (I25, I26, I32) mentioned above, but any significant reduction in the frequency of exceedance of the SSM standard at the offshore stations was confined to a single station (I12) and only at the 6 m depth.

Similarly, during the wet season, the Wilcoxon rank sum test found many of the offshore stations showed a significant decline in enterococci density associated with the treatment upgrade. However, except at the single station I12, these significant reductions in enterococci densities were only seen in the deeper waters (>12 m).

4. Discussion

In 1999, discharge of primary treated sewage from Tijuana, Mexico began through the South Bay Ocean Outfall (SBOO) into the ocean 3.5

Table 4
Comparison of frequency of exceedances of the single sample maximum (SSM) standard for enterococci indicator densities and *p* values from the Fisher's Exact Test for significance, at shore stations during the dry season, before as compared to after the upgrade to secondary treatment at the South Bay International Wastewater Treatment Plant.

	Pre-secondary treatment			Post-secondary treatment			
Shore station	Total number of samples (N)	Number of exceedances	Percent of exceedances	Total number of samples (N)	Number of exceedances	Percent of exceedances	Fisher's test p value
S0	178	24	13.5	151	26	17.2	0.359
S2	214	11	5.1	151	9	6.0	0.818
S3	214	9	4.2	151	8	5.3	0.624
S4	217	7	3.2	156	5	3.2	1.000
S5	226	14	6.2	164	13	7.9	0.548
S6	220	4	1.8	155	4	2.6	0.722
S8	217	5	2.3	152	1	0.7	0.407
S9	216	7	3.2	155	3	1.9	0.531
S10	218	4	1.8	154	3	2.0	1.000
S11	224	5	2.2	156	5	3.2	0.746
S12	217	6	2.8	153	2	1.3	0.478

Table 5

Comparison of enterococci indicator densities and p values from the Wilcoxon Rank Sum Test for Significance, at kelp and offshore deep water stations (mean value of all depths $\geq$11 m) during the dry weather season, before as compared to after the upgrade to secondary treatment at the South Bay International Wastewater Treatment Plant. (*) denotes a significant increase ($p \leq 0.05$) in the density of enterococci after the upgrade, and (**) a significant decrease.

Station depth (m)	Mean enterococci density (CFU/ 100 mL) pre-secondary treatment	Mean Enterococci Density (CFU/ 100 mL) post-secondary treatment	Percent change post-secondary treatment	Wilcoxon Rank Sum Test P value
Kelp				
I39–12 m	10	3	−70 %	<0.0001**
18 m	6	3	−50 %	0.001**
Offshore				
I5				
11 m	3	30	+900 %	0.032*
I9				
18 m	41	3	−93 %	0.042**
I12				
18 m	1458	4	−99 %	0.001**
27 m	111	3	−97 %	0.000**
I14				
18 m	326	2	−98 %	0.004**
I16				
18 m	528	3	−99 %	0.002**
27 m	92	2	−98 %	0.000**
I18				
12 m	29	2	−93 %	0.012**
I22				
18 m	40	2	−95 %	0.028**
27 m	4	2	−50 %	0.021**
I30				
27 m	8	2	−75 %	0.016**
I33				
18 m	4	2	−50 %	0.049**
27 m	5	2	−60 %	0.012**

miles offshore. In November 2010, the South Bay International Wastewater Treatment Plant (SBIWTP) was upgraded from primary to secondary treatment to conform to the Clean Water Act (CWA). In this study, statistical comparisons were made of the bacterial water quality (as reflected by enterococci densities), both before and after discharge of secondary treated sewage to the SBOO began, so that the effect of this treatment upgrade on nearshore and offshore water quality could be quantitatively assessed.

The results of our statistical analysis shows that the improvements to water quality in the ocean in the region of the SBOO were actually quite modest after the upgrade of the SBIWTP to secondary treatment in 2010. Our analysis showed there was no significant improvement in microbial water quality as reflected by compliance with either the SSM or GM recreational enterococci standards, at any shore station during the bathing season after upgrade to secondary treatment (Table 4). Significant reduction in enterococci densities was observed during the bathing season at just two of the monitored shore stations (Table 3), but since such reductions may not involve reductions below the "bright line" of the enterococci standard itself, then such bacterial density reductions did not result in improved compliance with the recreational standard during the dry weather season when both beach visitation and bathing frequency are highest. A similar lack in improvement in surface water quality was found at the kelp stations, where statistical testing found no kelp station either with a significant decline in enterococci density or improvement in compliance with the SSM standard in surface waters during the dry season.

Our analysis did show that there was some improvement in compliance with SSM standards in surface waters at both shore (S3, 6, 8, 11, 12) (Table 6) and many kelp stations (Table 7) during the wet season, although a strong signature of land-based sources of bacterial pollution was also evident (Fig. 4). A major contributing factor to the water quality of the shore stations in the U.S. is the flow of contaminated water being discharged via the Tijuana River (Weston Solutions, Inc., 2012). In order to correct the data for potential confounding of the indicator bacteria levels at the shore stations by the river, the daily flow of the Tijuana River was analyzed using a Wilcoxon rank sum test. This analysis showed that Tijuana River had significantly ($P \leq 0.05$) higher flow rate for the years following the addition of secondary treatment upgrade in 2010. In spite of this, the significant improvement during the wet season in surface water quality, especially at the kelp stations where 4 of the 7 stations evidenced significant declines in enterococci densities after the upgrade (Table 7) points to the influence of the SBOO on surface water quality of these nearshore waters during the period when plume surfacing may have occur, and does indicate, at least in wet weather, some benefit of the upgrade to secondary wastewater treatment at the SBIWTP.

On the other hand, the limited degree of improvement in surface water microbial quality, particularly at both shore stations and kelp stations during the dry weather bathing season, might seem counterintuitive especially since secondary treatment has been documented to remove >90 % of enterococci bacteria (Barrios-Hernández et al., 2020). Evidence from other global studies also has shown either little or no improvement of beach water quality after commissioning of ocean outfalls in Rio de Janeiro and Niteroi, Brazil (Castiglia Feitosa, 2017), and Durban, South Africa (Rathbone et al., 1998). In these cases, it was shown that shoreline contaminant sources (e.g. river flows) were mostly responsible for adverse impacts to beach water quality even after the commissioning of these ocean outfalls. The only marginal improvement of beach water quality after the upgrade to secondary treatment at the SBOO may be similarly explained by the fact that there are multiple sources of contamination along this portion of the coast near the U.S. - Mexico border.

A study conducted for the U.S. EPA by Largier et al. (2004), showed that shoreline fecal indicator bacteria exceedances in the region of the SBOO are predominately a result of exposure of the shoreline to Tijuana River plume water which was found to account for a large majority of shoreline water quality exceedances. Gersberg et al. (2008) statistically compared the microbial water quality for the same shore stations as for the present study for the years before (1995–1998) and after (1999–2003) the operation of primary-treated sewage through the then newly constructed SBOO, and found that there was no significant reduction at any station in the U.S. in the frequency of exceedances of the enterococci standard after the start of discharge to the SBOO. These authors concluded that the very limited degree of improvement may well be due to the fact that the Tijuana River, with its flows of urban runoff as well as poorly-treated sewage flows from Mexico, play the major role in determining the water quality at adjacent beaches. Indeed, since the SBIWTP only treats up to 95 million liters per day for discharge at the SBOO, during rain events the majority of the flow of Tijuana River flow is bypassed away from the SBIWTP, and therefore wet weather contamination of the nearshore beaches continues to this day mostly unabated even with the SBOO operation.

Visualization of the enterococci density plume in our study showed clear evidence of a bacterial density plume in surface ocean waters in

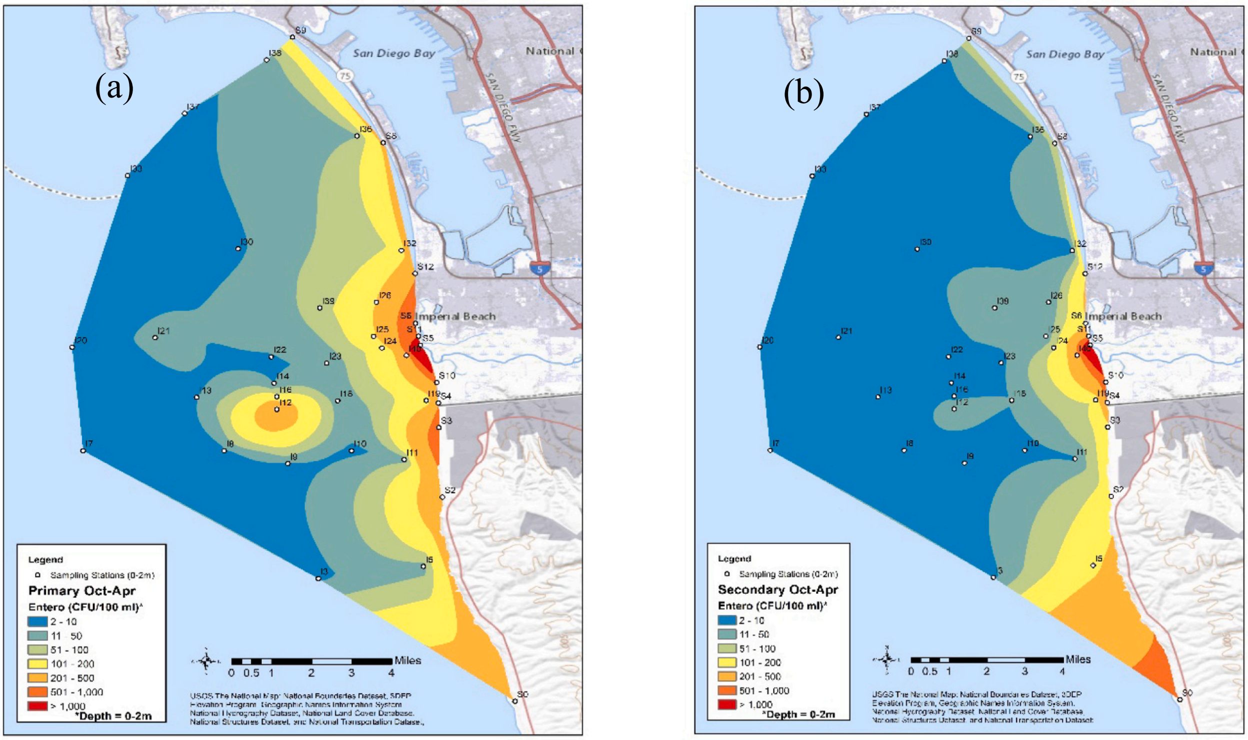

Fig. 4. Isopleth diagram of mean enterococci density in surface waters (0-2 m) of the SBOO region in the wet weather period before (a) and after (b) the upgrade to secondary treatment.

both the dry and wet seasons (Figs. 2 and 4) arising south of the U.S.-Mexico border and moving north across the U.S-Mexico border.

Recently, this gradient of sewage contamination has been linked to the discharge of poorly treated sewage into the surfzone from the San Antonio de Los Buenos sewage treatment facility at Punta Bandera, Mexico which discharges about 8 km south of the U.S. – Mexico Border (Fedderson et al., 2020). Using both dye modeling and plume tracking, these authors estimated these northerly flows of sewage from Mexico to be causing closing of the beach at the Imperial Beach pier (between our sites S6 and S12) almost 25 % of the time. Additionally, evidence of a gradient in human fecal pollution that extended north from the point source discharge at the San Antonio de Los Buenos facility across the United States/Mexico border was observed using human-associated genetic markers and microbial community analysis (Zimmer-Faust et al., 2021) and corroborates the results of the plume visualization in the present study (Figs. 2 and 4).

It is important to note here, that the plume dynamics observed in our visualizations are the result of a complex interaction of both these abiotic and biotic factors, many of which are poorly understood. These factors include the processes such as advection and dispersion (currents, wind, tides), but also inactivation/decay caused by chemical factors (salinity), sunlight, temperature effects, particle interactions, and predation (Boehm and Sassoubre, 2014). Of these processes, the photoinactivation by sunlight of enterococci and other fecal indicator bacteria, has perhaps been the most extensively studied (Boehm and Sassoubre, 2014). Many mesocosm studies have noted the germicidal effect of sunlight on enterococci; however, the time required to achieve a 90 % reduction of their level by photoinactivation (T_{90}) has been reported to vary greatly, depending upon differing site specific factors, season, water quality, and variables in experimental design (Byappanahalli et al., 2012). For example, in marine and estuarine waters, the reported T_{90} values for enterococci ranged widely from 2 h (Fujioka et al., 1981) to 35 h (Kay et al., 2005). Nevertheless, when solar inactivation rates of enterococci and *E. coli* were compared in an in situ study conducted in marine waters at Pilar Point Harbor, CA, both fecal indicators showed nearly identical T_{90} values (about 13 h) (Maraccini et al., 2016). The better performance of enterococci as compared to *E. coli* as indicators of human health risk in marine recreational waters has been attributed to the greater salt tolerance of enterococci as compared to *E. coli* (Byappanahalli et al., 2012).

Overall, our analysis shows that the rather large investment in upgrading the SBIWTP to secondary treatment in 2010, while conforming to the mandate of the Clean Water Act, did not yield significant benefits in reducing the degree of human health risk during the bathing season at either the shore stations or the kelp beds where recreation might occur. Indeed, in the U.S., except for Station S5 (just north of the Tijuana River) during the bathing season even before the upgrade to secondary treatment, the frequency of either GM or SSM exceedances was already exceedingly low (< 5 %) at all the sites, including at the urban beaches of the cities of Imperial Beach and Coronado, CA (S6, S8, S9 and S12). The mean enterococci density at these four urban beach sites was 16 CFU/100 mL which equates to a risk of gastrointestinal disease risk of 17 illnesses per 1000 persons exposed, well below the mean regulatory criterion value of 30 CFU/ 100 mL for bathing waters which itself equates to a risk of 32 illnesses per 1000 water recreators exposed (U.S. EPA, 2012). These already low risk values could be the main reason we did not observe a significant effect of secondary treatment during the bathing season, and implies, at least as far as microbial water quality is concerned, that the upgrade to secondary treatment at the SBIWTP really could not have been expected to yield real benefit in reducing the health risk of recreation in the beaches near the U.S-Mexico border.

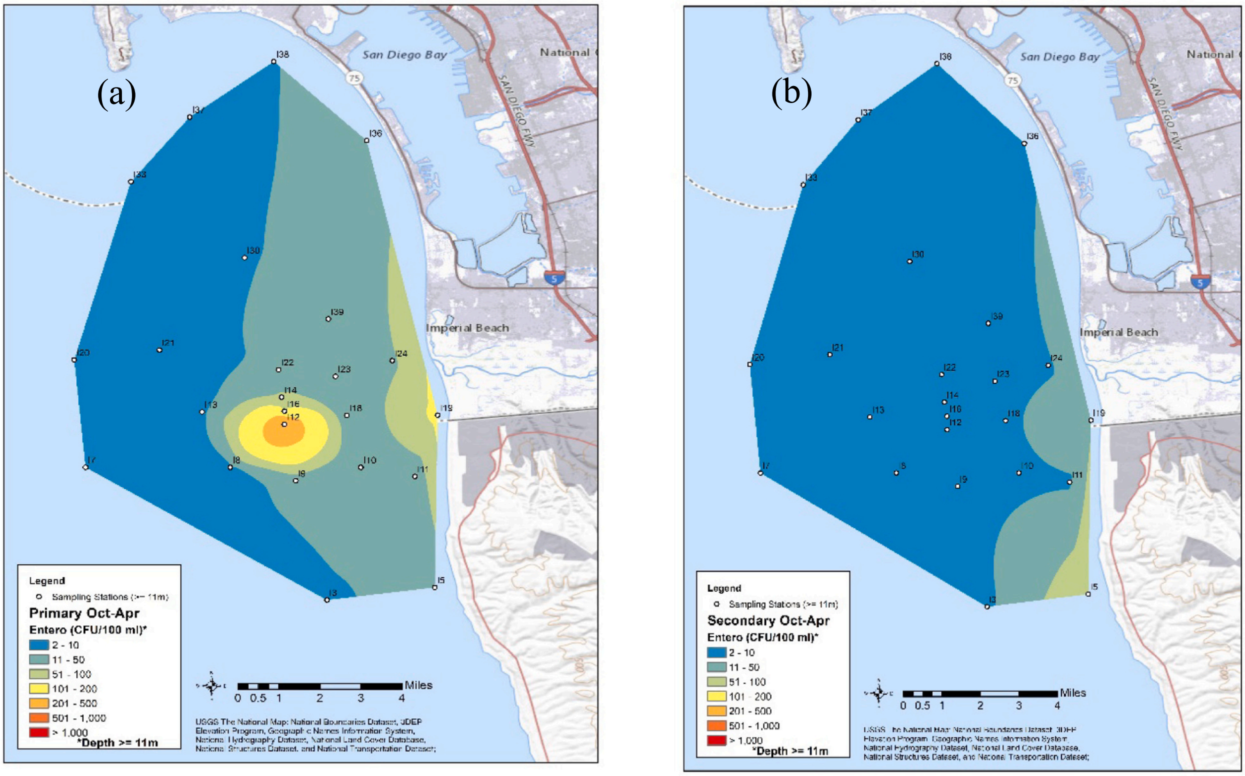

Fig. 5. Isopleth diagram of mean enterococci density in deep waters (mean of all depths ≥11 m) of the SBOO region in the wet weather period before (a) and after (b) the upgrade to secondary treatment.

Table 6

Comparison of enterococci indicator densities and frequency of exceedance of the single sample maximum standard (SSM), and *p* values from the Wilcoxon Rank Sum Test and Fisher's Exact test, respectively for significance at shore stations during the wet season, before as compared to after the upgrade to secondary treatment at the South Bay International Wastewater Treatment Plant. (*) denotes a significant increase ($p \leq 0.05$) in the density of enterococci after the upgrade, and (**) a significant decrease.

Station	Mean enterococci density (CFU/ 100 mL) pre-secondary treatment	Mean enterococci density (CFU/ 100 mL) post-secondary treatment	Wilcoxon test *P* value	Percent of exceedance pre-secondary treatment	Percent of exceedance post-secondary treatment	Fisher's rest P value
S0	353	673	<0.0001*	26	47	<0.0001*
S2	383	144	0.018**	18	12	0.103
S3	793	163	0.007**	26	12	<0.0001**
S4	419	466	0.316	23	18	0.131
S5	2820	2360	0.035**	42	40	0.544
S6	756	181	<0.0001**	20	10	0.002**
S8	239	73	0.020**	9	5	0.044**
S9	155	69	0.336	7	4	0.193
S10	558	738	0.801	24	26	0.581
S11	860	326	0.0002**	23	15	0.011**
S12	461	178	<0.0001**	16	8	0.006**

This all underscores that although a large investment in expanding secondary treatment capacity at the SBIWTP in the future will marginally improve water quality during the bathing season (where compliance is already very high), most of the benefit of expanding treatment capacity will arise from and diversion of raw sewage flows from the Tijuana River, rather from the actual treatment of the SBOO discharge itself. The new United States-Mexico-Canada trade agreement (USMCA) recently reached committed the federal government through the U.S. EPA to provide $300 million dollars for the Border Water Infrastructure Program to address pollution on the U.S.-Mexico border, including the Tijuana River Valley area (U.S. EPA, 2021). This funding likely represents the most significant federal commitment to the problem in decades, and the bulk of the funding will most probably be used to expand and upgrade the secondary treatment capacity of South Bay International Wastewater Treatment Plant, operated by the IBWC (U.S. EPA, 2021). However, our study supports the conclusion that, since other land-based sources of nearshore pollution predominate in this region, the public health benefit of additional secondary treatment of ocean outfall discharge will be marginal. Even with the expanded secondary capacity planned, wet weather flows of the Tijuana River (which are too large to be intercepted and treated) will continue unabated, then chronic contamination of beaches will continue into the future in wet

Table 7

Comparison of enterococci indicator densities and P values from the Wilcoxon Rank Sum Test, at kelp stations during the wet season, before as compared to after the upgrade to secondary treatment at the South Bay International Wastewater Treatment Plant. (*) denotes a significant increase ($p \leq 0.05$) in the density of enterococci after the upgrade, and (**) a significant decrease.

Kelp station depth (m)	Mean enterococci density (CFU/ 100 mL) pre-secondary treatment	Mean enterococci density (CFU/ 100 mL) post-secondary treatment	Percent change post-secondary treatment	Wilcoxon Test P value
I19				
2 m	98	101	+3 %	0.270
6 m	75	52	−31 %	0.473
11 m	115	46	−60 %	0.053
I24				
2 m	116	80	−31	0.605
6 m	104	33	−68 %	0.818
11 m	41	4	−90 %	0.559
I25				
2 m	175	20	−89 %	0.0002**
6 m	73	23	−68 %	0.0009**
9 m	109	42	−61 %	0.0001**
I26				
2 m	199	10	−95 %	<0.0001**
6 m	81	9	−89 %	<0.0001**
9 m	114	10	−84 %	0.001**
I32				
2 m	102	4	−96 %	0.016**
6 m	93	8	−91 %	0.013**
9 m	76	14	−82 %	0.002**
I39				
2 m	72	24	−67 %	0.0001**
12 m	29	2	−93 %	<0.0001**
18 m	22	5	−77 %	<0.0001**
I40				
2 m	281	292	+4 %	0.319
6 m	227	46	−80 %	0.960
9 m	204	49	−76 %	0.410

weather or when the river flow is high. Considering this, it would seem that alternatives which involve further investment in the sewage collection and treatment system in Tijuana, Mexico should be a priority for U.S. EPA's funding consideration. Such collection and treatment closer to the source would seem the best way to assure a permanent solution to the transborder pollution problem.

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CRediT authorship contribution statement

Katelyn Taylor: Methodology, Software, Formal analysis, Writing – review & editing. **Kurtis S. Baron:** Software, Visualization, Writing – review & editing. **Richard M. Gersberg:** Conceptualization, Supervision, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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