



Article Insights for Sea Outfall Turbid Plume Monitoring with High-Spatial-Resolution Satellite Imagery Application in Portugal

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Abstract: Coastal municipalities and industries often discharge poorly treated wastewater into proximate marine and estuarine environments. The urban and/or effluent input can lead to eutrophication and lower water quality, as it holds high concentrations of nutrients and pollutants. One widely applied tool to increase effluent dispersion and direct it away from coastal areas, thus causing fewer impacts on human activities, is sea outfall. In Aveiro, Portugal, the São Jacinto sea outfall construction was completed in 1998; however, limited literature regarding the sea outfall's monitoring using satellite data is available. The methodology in this study involved collecting four years' worth (2016-2019) of satellite data to investigate visible traces of the interaction between the S. Jacinto sewage water mass and the Ria de Aveiro lagoon ecosystem using ocean color and spectral analysis, and producing new qualitative data regarding sea outfall plume dispersion monitoring through high-resolution Sentinel-2 imagery. The results showed a clear spectral signature of the sewage water mass, and a seasonal pattern was observed in which the plume was more evident in winter and autumn. Additionally, the coastal longshore current and the Aveiro lagoon's runoff were able to restrict the marine outfall's dispersion superficially. Ocean color data were revealed to be a factual and cost-effective tool to monitor the plume water. Finally, an exchange between the marine outfall water mass and Ria de Aveiro lagoon could happen in high tide under northern wind conditions. Therefore, it is important to monitor the water quality to ensure the coastal ecosystem's good environmental state.

Keywords: marine outfall; remote sensing; ocean color; eutrophication; spectral signature; sewage plume; effluent detection; Sentinel-2

1. Introduction

In coastal areas, human settlement and its continuous growth have affected estuarine and coastal ecosystems over the years [1,2]. The urban and industrial wastewater discharge into water bodies induces dispersion of contaminants, pathogens, and nutrients in natural aquatic ecosystems. As a result, the water quality degrades in these ecosystems, threatening both marine life and human societies that depend on these water bodies [3–5]. It is thus essential to ensure that society's development is managed sustainably for good environmental state preservation in these areas.

Directive 91/271/CEE of the Council of the European Communities is dedicated exclusively to regulating urban wastewater treatment. In Annex I of Directive 91/271/CEE, the adequate treatment of urban wastewater is delineated, from collection to discharge, and it also lists urban wastewater treatment plants' (WWTPs) water quality requirements



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). that have to be met before the sewage water flows into sensitive ecosystems. In Portugal, for instance, Law-Decree 152/97 transposes Decree 91/271/CEE of the Council. The bathing water quality around the country must be coherent with Directive 2006/7/CE of the European Parliament and the Council.

Before 2000, pollution of water bodies and degradation of water quality were already a general concern in the European Union (EU). However, the water policies were not unified among the member states [6]. Hence, there was room for reinforcing the Community's requirements to preserve the good environmental status of its water bodies. The Water Framework Directive (WFD) was implemented in 2000 to regulate the balance between ecosystems conservation and human activities. The WFD offers guidelines to the member states for the protection of inland surface waters, transitional waters, coastal waters, and groundwater. The main aim of the WFD is to contribute to the reduction and further elimination of the emission of harmful substances into bodies of water to achieve concentrations near background values of the naturally occurring substances in those environments.

In order to decrease the impact of wastewater on the estuarine environment, sea outfalls became the solution for directing the discharge point away from the coast. Furthermore, the ocean seems to be the best alternative for pre-treated effluent input due to the high self-purifying capacity inherent to its composition, the constant water flow, and the dimensions, thus reducing the level of treatment required in the WWTP [7]. In mainland Portugal, for instance, where the coastal hydrodynamic conditions favor the dilution and dispersion of the effluents [8], there are 21 operational sea outfalls; 19 of them discharge urban wastewater and 2 industrial effluents [9].

A reasonable number of studies have employed satellite imagery to monitor the impact of wastewater discharge in the coastal environment [4,10–12]. Overall, those studies proved the Sentinel-2 (S2) ocean color data to be adequate to monitor sea outfall turbid plume dispersion. For instance, Bondur et al. [11] monitored the coastal area of two cities along the coast of the Black Sea affected by wastewater from the sea outfall's pipe cracks. Trinh et al. [12] monitored the biophysical impact of direct sewage discharge in a shallow nearshore environment in California.

Satellite technology developments and improvements have made the investigation of coastal processes possible without the necessity of scheduling aerial/boat surveys for monitoring purposes, as in the past. In this context, S2 twin-satellite imagery emerged as a fundamental and effective tool to monitor the coastal waters, as it offers large areas of coverage (swath width of 290 km on the ground track) within a high temporal (2–5 days) resolution, with spatial resolution up to 10 m. Data access has no inherent cost, presenting as a cheaper and more efficient tool to assist effluent discharge monitoring.

Furthermore, the Sentinel-2 satellite constellation is equipped with a Multispectral Instrument (MSI), which operates within 13 spectral bands (443–2190 nm) [13]. However, the light spectrum addressed in this work belongs to the true color composite: 490 (blue), 560 (green), and 665 (red) nm. This passive sensor measures the signal of water leaving radiance after the sun's radiation interacts with the water constituents [13]. Therefore, water masses can be classified accordingly to their components, which condition their optical properties and color. This classification was first introduced by Morel and Prieur [14]. When chlorophyll (from the phytoplankton) is the constituent that determines the water mass characteristics, this water is classified as Case 1 water, which is typically associated to the open ocean. Case 2 water, on the other hand, encompasses coastal water mass, where the concentration of colored dissolved organic matter (CDOM) or total suspended matter (TSM) influences its optical properties and color [15]. Thus, the spectral signatures of coastal and oceanic water masses are expected to present inherent differences [10,15].

In Portugal, satellite technology has mainly been used to monitor water quality parameters. For instance, Sent et al. [16] examined water quality parameters using Sentinel-2 imagery in the Sado estuary, and Mantas et al. [17] carried out a case study using MODIS and Landsat-7 ETM+ in the analysis of water quality indicators at the Mondego river estuary. A remote sensing approach for monitoring marine outfall dispersion patterns was

carried out by Silva et al. [18] and Silva et al. [19]. In those studies, the São Jacinto sea outfall plume (Aveiro) was monitored through aerial photography from an airborne after outfall construction in 1998. Since the early 2000s, however, the local population and tourism in the north central region and Aveiro have grown, and more effluent water is being discharged into the sea. The aim of building the sea outfall was to relieve anthropogenic pressure on the Ria de Aveiro coastal lagoon, where the totality of wastewater used to be discharged.

Hence, as an inherent process in coastal areas, marine outfall plumes' dispersion deserves special attention, as it can impact the economy and fisheries, alter water quality, and prevent leisure activities during bathing season [1,11]. However, no study has reported on the sea outfall's plume dispersion using high-spatial-resolution satellite remote sensing technology in Portugal. In order to fill this gap in the literature, this work aims to (i) prove the feasibility of monitoring the São Jacinto outfall turbid plume through high-resolution S2 imagery, (ii) map the areas most frequently affected by the turbid plume, (iii) identify a pattern in the sea outfall plume's dispersal behavior through qualitative analysis of the ocean color, and (iv) understand the influence of meteo-oceanographic conditions on the outfall turbid plume's visibility and dispersion.

Therefore, this paper describes the methodology used in this study for monitoring the São Jacinto sea outfall turbid plume with high-resolution ocean color imagery over four years, the results obtained for annual and seasonal analyses, as well as the respective discussion, conclusions, and suggestions for future work.

2. Methods

2.1. Study Site

The Ria de Aveiro lagoon (Figure 1) is an example of a coastal ecosystem whose environmental quality was wrecked due to an increased volume of poorly treated or untreated effluent input, which required an important process of re-qualification. The coastal lagoon's main sources of pollution were domestic and industrial sewage discharge, as well as wastewater from fish and shellfish production [20]. Hence, to mitigate the wastewater discharge into the lagoon, the São Jacinto sea outfall was built in 1998. Nowadays, it drains the effluent from the Cacias, Ílhavo, and São Jacinto WWTPs and from 10 municipalities, which accounts for over 300,000 inhabitants [21,22].

The São Jacinto sea outfall, which lies on a nearshore continental shelf of 1.4 to 22.5 m depth, is located 3 km north of the Barra inlet channel north jetty and in front of the São Jacinto Dunes Natural Reserve. According to Ramos and Neves [23], the mean outflow of discharged wastewater was 0.8 m^3 /s. However, recent data on the São Jacinto sea outfall flow rate and operational characteristics are not publicly available. Moreover, the submarine outfall has an extension of 3.378 km, reaches a depth of 15 m, and has a diameter of 1.6 m [22]. The diffuser contains 20 operational holes, disposed alternatively with an angle of 30° and 150° about the horizontal axis, found in the last 98 m of the outfall [23].

In addition, São Jacinto beach, north of the Barra inlet channel, has held the Blue Flag award for the past 17 years and received the Golden Flag award in 2020 [24–26]. These recognitions are given to beaches that hold good environmental and urban state conditions, promote sustainable use of the space, and present high water quality during bathing season. Hence, monitoring wastewater dispersion becomes imperative.

Regarding the marine outfall's discharge, the initial behavior of the wastewater jet is mainly determined by the diffuser hole's geometry and location on the pipe, the flow rate of the fluid, buoyancy force, and momentum. The buoyancy force will act when the density gradient between the adjacent ocean and sewage inflow dominates the dynamics of the jets, overlapping the discharge momentum due to its distance from the pipe's mouth. As the wastewater jets are less dense than seawater, they reach the surface due to the buoyancy force and advection, and the patch can be labeled as a plume [27].

The receiving-water state is dominated by wind and tidal flow; however, swell waves are also relevant, as they influence the coastal longshore current [28]. The region of interest (ROI) is also characterized by northwesterly alongshore wind-driven currents that

induce an upwelling circulation pattern, typical for summer months, while southwesterly wind causes downwelling flow mainly in autumn and winter [19,29]. Moreover, the coastal water mass stratification primarily depends on the salinity and water temperature range, which changes seasonally and can limit the plume's ascension. For example, where significant density stratification exists, the sewage plume will face an energy barrier to rise to the ocean surface and therefore will take more time to ascend to the surface or remain submerged at the intermediate location, whereas on a non-/weakly-stratified water column, the mixed seawater and effluent plume freely ascends to the surface [23], becoming visible on satellite images.

The Aveiro coastal lagoon's hydrodynamics depend mainly on the semidiurnal tide flow [30,31]. Its main tributaries are *valas* de Mira, and the rivers Vouga, Antuã, Caster, and Boco. Furthermore, the coastal lagoon's outflow is expected to interact with the marine outfall plume, as it is located near the São Jacinto marine outfall [19]. Henceforth, the coastal system presents two sources of nutrient load: the marine outfall discharge and the lagoonal water inflow from Ria de Aveiro. These contributions can induce not only nutrient enrichment but eutrophication processes, which can affect the water quality of the neighboring beaches [21,32].



Figure 1. Study area. The main urban areas, Aveiro and São Jacinto, are identified. Likewise, the Port of Aveiro facility, Barra inlet channel, and the sea outfall are shown.

2.2. Sentinel-2 Constellation Data Acquisition and Processing

Ocean color data from the S2 mission were acquired from 1 January 2016 to 31 December 2019. A preliminary analysis was carried out on the Copernicus Open Access Hub (COAH) [33] before the products' downloading to ensure that only cloud-free images over the ROI, the São Jacinto sea outfall area, were obtained. The steps followed for this first investigation are presented in Figure 2. Data acquisition and processing were carried out for clear atmosphere days; alternatively, in case where there were clouds over the ROI, the image was not retrieved.



Figure 2. Sentinel-2 satellite data retrieval and processing flowchart.

Data acquisition was focused on Level-1 imagery to implement the data processing to Level-2 (L2) and to access additional helpful information for this work. Nevertheless, it was necessary to use the ONDA [34], an open-access platform that also supports users at various levels of expertise in exploiting geospatial data, as it contains all open-access Copernicus data, such as Sentinel-2 data. The reason another platform needed to be used was that some data from COAH came with missing spectral bands when downloaded. For the L1 to L2 imagery processing, the software ACOLITE [35] was used. It is free and open-source software useful for processing data from turbid waters and small inland water bodies in particular. It also performs both atmospheric corrections and can output several parameters derived from water reflectances according to the algorithms employed; finally, RGB composites and PNG maps can also be generated. This step ensured the final ocean color data had an equally spaced grid on geographically referenced images. Additionally, the software offers users several algorithms for water physio-chemical indexes.

To improve the sea outfall turbid plume detection when the sea surface conditions were not favorable to identifying differences in the water masses' colors, we employed four algorithms available on ACOLITE. They were spm_nechad2016 (for SPM detection), t_nechad2016, and t_dogliotti (both for turbidity studies), as well as k_d 490_qaasw (for diffuse attenuation of light) [36]. As for qualitative analysis of the sea outfall plume visibility proposed by this study, the k_d 490_qaasw was found to be the most effective algorithm to detect the marine outfall outflow (the comparison among the four algorithms can be found in Supplementary Materials). The selected algorithm provides information about inherent optical properties (IOP) related to water clarity, derived from the diffuse attenuation coefficient [36].

2.3. Sea Outfall Turbid Plume Detection

Following the cloud's free data processing to L2 on ACOLITE, the imagery was analyzed on the Sentinel Application Platform (SNAP), an open-source platform developed by ESA (European Space Agency) that is ideal for Earth data observation processing and analysis [37], for the marine outfall's turbid plume detection (Figure 3).

If no patch was identified through ocean color data, the spectral analysis was carried out, aiming to find the spectral signature of the wastewater plume around the São Jacinto sea outfall's mouth coordinates. Nevertheless, if there was no clear spectral signature of this water mass, we checked the results generated by the water clarity algorithm on ACOLITE. Finally, if no sign of the wastewater plume was detected, the no-data day was documented, and the image was discarded.

On the other hand, the spectral analysis was carried out if the turbid plume was detected. Some measurements were taken with SNAP tools, such as extent and catchment area; for each case, a polygon was manually drawn around the patch and exported for later analysis. Additionally, the predominant dispersion direction and relevant characteristics were documented. An annual and seasonal analysis was carried out on MATLAB to

determine if any temporal dispersion patterns of the São Jacinto sea outfall's turbid plume could be identified.

Following turbid plume identification and documentation, the polygons were imported into GIS software, such as ArcMap, to create a global catchment area for each year of analysis, following Bondur et al. [11]. In addition, the daily area under the influence of the sea outfall plume has been studied to understand whether there was any seasonal tendency in the dataset. For that reason, an area anomaly analysis was carried out by subtracting the sea outfall daily area of the respective month from the monthly sea outfall average area.



Figure 3. São Jacinto sea outfall turbid plume identification and study flowchart.

Nevertheless, to comprehend the influence of the local meteo-oceanographic conditions on the outfall turbid plume's dispersion, sea surface elevation data were acquired for the Aveiro lagoon mouth from an existing hydrodynamic model [38], and hourly wind speed and direction were acquired from a WRF model (the Weather Research and Forecasting (WRF) Model is a mesoscale numerical weather prediction system used for atmospheric research and operational forecasting applications), with a spatial resolution of 12 km [39]. For this reason, one example of the wastewater plume dispersing inward toward the Ria de Aveiro coastal lagoon, observed through ocean color data, will be addressed.

3. Results

This section is structured around the results of the annual and seasonal analysis for cloud coverage and turbid plume visibility, followed by the São Jacinto outfall plume's catchment area evaluation and mapping. Additionally, true color high-resolution images, sea surface elevation, and wind intensity and direction are presented for the period where the plume dispersed towards the Barra inlet channel.

3.1. Annual and Seasonal Evaluation

As a resource employed for turbid plume identification and characterization, the spectral signature of the three different water bodies on a cloud-free day is presented in Figure 4. The reflectance peak for Aveiro lagoon's runoff (red line) is clearly different from the other two. It lies between the green and yellow bands, which characterize waters dominated by suspended sediments. The other two water bodies (sea outfall outflow and ocean) have distinguishable reflectance peaks, although they present an analogous behavior. For the marine outfall's turbid plume (the black line), it is possible to see the peak on the same wavelength for the Aveiro lagoon, although it presents a much less intense signal. For the coastal ocean water, the reflectance peak happens between the blue and green bands, one of the peaks for chlorophyll absorption.

From 1 January 2016 to 31 December 2019, there were 463 Sentinel-2 products available for the ROI. From the number of scenes observed for the four years of study, there were 230 cloud-free images. Figure 5 shows a compilation of the number of images available per year, classified according to the cloud coverage over the outfall and the plume visibility.

The most favorable year for the plume's detection was 2017, as on only 1 day out of 65, the patch was not visible. For the other years, the wastewater plume was detected in: 50% of the cases in 2016, 78.5% in 2018, and 86.5% in 2019. In addition, 2018 was identified as the year with higher data availability. These results represent a good sign for the turbid

plume's monitoring through Sentinel-2 imagery, considering the morning fog events in Aveiro that might align with the time of the satellite's passage over the region—between 11:20 and 11:40 a.m.



Figure 4. True color image and example of a spectral signature for ocean water (blue pin), Aveiro lagoon run-off (red pin), and São Jacinto sea outfall plume (black pin) on a cloud-free day (21 March 2019).



Figure 5. Annual São Jacinto sea outfall plume visibility.

For the seasonal analysis, the evaluation of Figure 6 indicates that the ratio between cloud coverage and clear sky days is balanced overall. In winter and spring, fewer images were available considering the total image number per season, 111 and 105, respectively. Furthermore, clouds were less present in summer and autumn. Additionally, the number of cloud-free images for winter and summer exceeds the number with cloud coverage. Winter and autumn are the seasons with the best turbid plume view, meaning 56 out of 59 cloud-free images and 58 out of 60, respectively; summer and spring follow. Nevertheless, in summer, the number of days where the plume was not visible is greater than in the other seasons, even under clear sky conditions.



Figure 6. Seasonal São Jacinto sea outfall plume visibility.

3.2. São Jacinto Sea Outfall's Plume Catchment Area

The results of the polygon compilation created in GIS software are shown in Figure 7. Each map contains the polygons for the respective annual daily observation. The number of shapes varied as the marine outfall's visibility changed over time. For the first year of analysis (2016), 28 polygons of the plume's patch were gathered, 64 in 2017, 53 in 2018, and 58 in 2019. In 2017 and 2019, the direction of the plume dispersion was predominantly southward. In 2016 and 2018, however, the plume presented a more variable dispersion direction.

Furthermore, some transparency was applied to the polygons to evaluate the area more often impacted by the turbid plume. In this sense, the darker the area is, the more frequently it has been under the influence of the sewage discharge plume. With this in mind, we observed that the main wastewater runoff dispersion direction was southward during the study period.

3.3. São Jacinto Sea Outfall's Plume Monitoring through High-Spatial Resolution True Color Product

The average catchment area for the study period was approximately 1.80 km² with a standard deviation of 3.41. The greatest areas were found in the second half of 2017, where it reached the largest catchment area, 19.12 km², on 24 December 2017. In order to detect unusual patterns in the dataset, the seasonal tendency was removed, although there was no strong tendency identified (see Supplementary Materials) by calculating the anomaly from each area of each image against the average of the month that image was captured; the result is shown in Figure 8. The "0" in the figure was established as the mean value calculated for the total period. For this, the inter-annual monthly average area was calculated, summed, and divided by 12 (months of the year). Finally, the bars represent the result of removing the monthly average value from each daily sea outfall plume area. October 2017 was found to be the most continuous period of the sea outfall's plume visibility. Thus, to exemplify the ability to monitor the São Jacinto sea outfall turbid plume dispersion with true color imagery, the images from this period are addressed.



Figure 7. Annual plume catchment area for the respective period of analysis.



Figure 8. São Jacinto sea outfall turbid plume area anomaly throughout the four years of study. The anomaly was calculated by subtracting the monthly sea outfall average area from the daily sea outfall area of the respective month.

In total, for the aforementioned month, 11 images were available, and the turbid plume was observed propagating towards the Barra inlet channel, which means that the wastewater components could be entering the Aveiro lagoon. Hence, to understand the wastewater plume's dispersion during this period, the sea surface elevation, wind magnitude, and wind direction were also considered. Figure 9 shows the observed tidal condition and the wind magnitude and direction, the main forces that influence the coastal hydrodynamic.



Figure 9. (**A**) Sea surface elevation and (**B**) wind speed and direction for October 2017. The dashed lines represent the days when ocean color data are available, and the dots represent the precise water level at the time of the satellite passage. The dashed line and letters correspond to the moment of the tidal wave and wind condition when Sentinel-2 (S2) passed over the region, resulting in a total of 11 images (A to K).

Following the hydrographic characterization, the ocean color images are displayed in Figure 10. The aforementioned conditions are visible in E, B, and F, respectively. Furthermore, during low tide (C, D, H, I, and J), the Aveiro lagoon plume acted as a superficial barrier for the wastewater's plume dispersion, which can be seen in particular in C and J. The flood tide (A, B, E, F, G, and K) drove the pollutant plume towards the coastal lagoon, detectable in B and E. Nonetheless, D was the only exception, with the wastewater discharge not being detected by the true color images.

The tidal phases, ebbing and flooding, were able to restrict or induce the pollutant plume dispersion towards the Barra inlet channel, respectively. The Ria de Aveiro coastal lagoon runoff during low tide seemed to have acted as a superficial barrier for the turbid plume's diffusion. Additionally, the wind conditions also influence the plume's dispersion; however, its effect takes time to change the current's direction. In this sense, the continuous wind blowing from north/northwest favored the diffusion of the sea outfall plume towards the southeast quadrant and the shore, whereas the northward wind restricted the dispersion onshore.



Figure 10. Cont.





4. Discussion

When comparing the spectral signature exhibited in Figure 4 with the spectral signature of phytoplankton, colored dissolved organic matter (CDOM), and total suspended matter (TSM) from Sutcliffe et al. [15], it is possible to infer that the Aveiro lagoon plume is dominated by TSM, as its runoff carries particulate matter from the land wash towards the sea. The marine outfall plume, however, carries a high concentration of CDOM, as the water discharged derives from urban and industrial sewage and, subsequently, from the open ocean water as a typical Case 1 water.

The substantial difference in the total number of products obtained for 2016 relative to the following years (Figure 5) was due to only one satellite being in orbit. The Sentinel-2A was launched in June 2015, while Sentinel-2B was launched in March 2017 [13]. Nevertheless, the number of cloud-free scenes for 2017, 2018, and 2019, when both satellites were in orbit, was almost identical. It indicates that there are, on average, 66 cloud-free images per year of the ROI.

For the results obtained from the annual visibility analysis, it is important to consider the dilution induced due to the precipitation and the hydrodynamic condition of the coastal area. Moreover, the period of the day the wastewater is discharged into the sea—information that was not accessible—can also influence the São Jacinto sea outfall plume's visibility.

The dark water mass color seen in Figure 10 can be explained by the anaerobic activities when the old sewage decomposes, acquiring a dark grey and black color, known as stale or septic color. Also, the color may be related to the formation of sulfide produced under anaerobic conditions reacting with the metals present in wastewater [40,41].

Ocean true color and derived reflectance water quality parameters still present limitations. For instance, the events that make turbid plume detection and coastal monitoring through S2 imagery difficult are shown in Figure 11. The sunglint phenomenon (Figure 11A) happens with the formation of a silver-mirror-like cap when the sunlight reflects at the sea surface at the same angle the satellites view it. This limitation often occurs for Sentinel-2 imagery, as the viewing geometry of the satellite makes it vulnerable to sunglint contamination [42].



Figure 11. (A) Sunglint and (B) morning fog events detected through Sentinel-2 satellites.

Additionally, morning fog (Figure 11B) is frequently detected on the west coast of Portugal, especially in the summer, as described by Morais [43]. The fog develops from dawn to morning, lasting until the early afternoon, when the air becomes warmer than the sea and the breeze blows more intensely. Thus, as this study focused on extracting information from the true color products, the visible light spectrum of the spectrum used

for the MSI does not obtain information from the Earth's surface when an area does not receive direct sunlight (when it is cloudy or at night).

Thus, for turbid plume seasonal visibility, some factors are considered to have influenced the results:

- Water column stratification incremented with temperature, which limits the plume's ascension, as observed by Ayad et al. [10] and Ramos and Neves [23]. According to the latest results, coastal water stratification increases from January, when it is dominated by salinity, to June, when it starts to be ruled by the water temperature as it increases throughout the summer. Coastal water experiences a less stratified gradient when the seasons change, as the dominant parameters' range is altered;
- Less storm-water runoff carrying CDOM and sediments due to less precipitation in summer months;
- Sunglint and morning fog events which occur more often towards the end of spring and early summer.

As the primary force influencing the nearshore circulation patterns on the Aveiro coast, the wind prevails from the northwestern quadrant of the study area, as observed by Silva et al. [19] and Ramos et al. [44]. Therefore, mapping the São Jacinto sea outfall turbid plume catchment area corroborates the findings of Silva et al. [19], which states the plume's dominant dispersion direction is southward.

The observations derived from the high-resolution true color images showed that, depending on the meteo-oceanographic conditions and on the lagoon's flow rate, the sea outfall's plume could exchange water with the coastal lagoon. These results corroborate those of Ramos et al. [44], who suggested that the float concentration released by the outfall reached the adjacent critical zones during flood tides.

Silva et al. [19] suggested that the dark color of the plume is due to the intense color of pulp mill industry wastewater, which accounts for more than 90% of the flow discharged. During this investigation, offshore transport of the wastewater plume was not observed at the surface as might be expected following the upwelling shelf circulation in that region. Commonly, the transport was to the south, in the direction of the inlet channel, or with an onshore component. The inshore dispersion of the waste-water plume observed here anticipates a possible release of pollutants into the inlet of the Aveiro coastal lagoon. In contrast, previous work by Silva et al. [19] suggested that the lagoon's eutrophication is unlikely to change due to the operation of the submarine outfall.

Future improvements to this study could be achieved by running a retrospective numerical simulation of the sea outfall plume that allows for a comparison of the results obtained with available wastewater plume image data to predict their dispersion patterns. Exploring this numerical model in operational mode would permit simulation of the coastal environment when satellite data face restrictions that limit their applicability.

Moreover, for validation proposes, in situ sampling should be planned to quantify the biogeochemical water parameters around the sea outfall, the Barra inlet channel, and beaches nearby. Additionally, it is essential to bring to light that the monthly mean area dataset may not be reliable, as satellite data were not available for some months. However, the objective of this study was to show the academic/scientific community that highresolution satellite technology can be applied to support São Jacinto sea outfall plume detection. This methodology is helpful to evaluate whether the water exchange between the marine outfall and those ecosystems can threaten the adjacent environments or alter water quality, affecting the population's health and seafood quality; however, it is not a substitute for field measurements.

5. Conclusions

Observing and detecting effluent plumes in the marine environment using satellite data is a challenging task because of the particularity of the discharges and the variations in the coastal hydrodynamic conditions. However, this study proved that this approach

is feasible for marine outfall plume monitoring, as the Sentinel-2 mission offers enough temporal and spatial resolution, requiring in situ sampling only when necessary.

Moreover, a seasonal pattern for the wastewater turbid plume visibility was found within the studied years. The outfall plume was more evident during winter and autumn and was less visible in spring and summer. These findings may be related to the water column's high stratification, lower volume of storm-water runoffs, and sunglint episodes.

This preliminary study to support coastal monitoring showed promising results, and hopefully it is just the beginning. According to the ocean color imagery, the coastal drift current and the Aveiro lagoon plume can restrict the superficial dispersion of the submarine outfall turbid plume. However, the sewer plume can reach the adjacent beach and exchange water with the coastal lagoon, mainly in flood tide and northwesterly wind conditions.

On the other hand, according to the scant available literature, the sewer plume's concentration was insufficient to harm the water quality of the nearby ecosystems. Thus, it would be an excellent opportunity to implement a new strategy for sea outfall plume dispersion monitoring using ocean color, collecting fewer water samples, and using numerical modeling data to continuously follow the plume's patch. Nevertheless, 20 years out from these studies, the human pressure has increased, and new research was not been carried out.

Overall, the next approach for this study would be to investigate the effect of the outfall's turbid plume on the local primary production and to work on automating an algorithm for the outfall's plume detection through Sentinel-2 imagery.

Supplementary Materials: The following supporting information can be downloaded at: https: //www.mdpi.com/article/10.3390/rs15133368/s1, Figure S1: True color composite from the Sentinel-2 image Level 2 after processing the Level 1 image on ACOLITE; Figure S2: Comparison between the employed algorithm for plume detection. (A) kd490_qaasw (B) tspm_nechad2016; (C) t_nechad2016; and (D) t_dogliotti; Figure S3: Seasonal average sea outfall catchment area.

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Data Availability Statement: The Sentinel-2 satellite images are publicly available on the Copernicus Open Access Hub https://scihub.copernicus.eu/ (accessed on 1 June 2023) and on ONDA https: //www.onda-dias.eu/cms/services/catalogues/?meta_service_category2=Data-Access (accessed on 1 June 2023). Likewise, hourly wind magnitude and direction are available on Meteogalicia http://mandeo.meteogalicia.es/thredds/catalogos/WRF_2D/catalog.html (accessed on 1 June 2023).

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References

- Hafeez, S.; Wong, M.S.; Abbas, S.; Kwok, C.Y.; Nichol, J.; Ho Lee, K.; Tang, D.; Pun, L. Detection and monitoring of marine pollution using remote dsensing technologies. In *Monitoring of Marine Pollution*; Fouzia, H.B., Ed.; IntechOpen: London, UK, 2019; Chapter 2, p. 26. [CrossRef]
- Mozetič, P.; Malačič, V.; Turk, V. A case study of sewage discharge in the shallow coastal area of the Northern Adriatic Sea (Gulf of Trieste). *Mar. Ecol.* 2008, 29, 483–494. [CrossRef]

- Cravo, A.; Barbosa, A.B.; Correia, C.; Matos, A.; Caetano, S.; Lima, M.J.; Jacob, J. Unravelling the effects of treated wastewater discharges on the water quality in a coastal lagoon system (Ria Formosa, South Portugal): Relevance of hydrodynamic conditions. *Mar. Pollut. Bull.* 2022, 174, 113296. [CrossRef] [PubMed]
- Gancheva, I.; Peneva, E.; Slabakova, V. Detecting the surface signature of Riverine and effluent plumes along the Bulgarian black sea coast using satellite data. *Remote Sens.* 2021, 13, 4094. [CrossRef]
- Reifel, K.M.; Corcoran, A.A.; Cash, C.; Shipe, R.; Jones, B.H. Effects of a surfacing effluent plume on a coastal phytoplankton community. *Cont. Shelf Res.* 2013, 60, 38–50. [CrossRef]
- 6. European Commission. Water Framework Directive 2000/60/EC; European Commission: Brussels, Belgium, 2000.
- Chaves, F.D.S.C. Dimensionamento Hidráulico-Estrutural de Emissários Submarinos. Estudo de Caso. Master's Thesis, Universidade do Porto, Porto, Portugal, June 2014.
- Santos, C.; Catarino, J.; Marques, E.; Figueiredo, Z.; Trancoso, A.; Barata, P.; Marecos, H.; Neves, R. Monitorização Ambiental Do Emissário Submarino Da Guia. In Proceedings of the 7° Congresso da Água, 2004 ; p. 15. Available online: https: //www.aprh.pt/congressoagua2004/PDF/51.PDF (accessed on 10 January 2023).
- Direção-Geral de Recursos Naturais Segurança e Serviços Marítimos. Ordenamento do Mar Português (PSOEM). Available online: https://www.psoem.pt/geoportal{_}psoem/ (accessed on 10 January 2023).
- Ayad, M.; Li, J.; Holt, B.; Lee, C. Analysis and classification of stormwater and wastewater runoff from the Tijuana river Using remote sensing imagery. *Remote Sens. Front. Environ. Sci.* 2020, *8*, 599030. [CrossRef]
- Bondur, V.G.; Vorobyev, V.E.; Zamshin, V.V.; Serebryany, A.N.; Latushkin, A.A.; Li, M.E.; Martynov, O.V.; Hurchak, A.P.; Grinchenko, D.V. Monitoring anthropogenic impact on some coastal water areas of the Black Sea using multispectral satellite imagery. *Atmos. Ocean. Phys.* 2018, 54, 1008–1022. [CrossRef]
- 12. Trinh, R.C.; Fichot, C.G.; Gierach, M.M.; Holt, B.; Malakar, N.K.; Hulley, G.; Smith, J. Application of Landsat 8 for Monitoring Impacts of Wastewater Discharge on Coastal Water Quality. *Front. Mar. Sci.* **2017**, *4*, 17. [CrossRef]
- European Space Agency. Colour Vision for Copernicus. The Story of Sentinel-2; Technical Report; European Space Agency: Paris, France, 2015.
- 14. Morel, A.; Prieur, L. Analysis of variations in ocean color. Limnol. Oceanogr. 1977, 22, 709–722. [CrossRef]
- 15. Sutcliffe, A.; Brito, A.C.; Sá, C.; Sousa, F.; Boutov, D.; Brotas, V. Ocean Colour. In *Observação da Terra: Uso de Imagens de Temperatura da Superfície do mar e cor do Oceano para a Monitorização de águas Costeiras e Oceânicas*, Eletronic ed.; DGRM: Lisboa, Portugal, 2016; Chapter 3, pp. 67–104.
- 16. Sent, G.; Biguino, B.; Favareto, L.; Cruz, J.; Sá, C.; Dogliotti, A.I.; Palma, C.; Brotas, V.; Brito, A.C. Deriving water quality parameters using sentinel-2 imagery: A case study in the Sado Estuary, Portugal. *Remote Sens.* **2021**, *13*, 1043. [CrossRef]
- 17. Mantas, V.M.; Pereira, A.J.; Neto, J.; Patrício, J.; Marques, J.C. Monitoring estuarine water quality using satellite imagery. The Mondego river estuary (Portugal) as a case study. *Ocean Coast. Manag.* **2013**, *72*, 13–21. [CrossRef]
- Silva, J.F.; Duck, R.W.; Anderson, J.M.; McManus, J.; Monk, J.G. Airborne observation of frontal systems in the inlet channel of the Ria de Aveiro, Portugal. *Phys. Chem. Earth Part B Hydrol. Ocean. Atmos.* 2001, 26, 713–719. [CrossRef]
- 19. Silva, J.F.; Duck, R.W.; Hopkins, T.S.; Anderson, J.M. Nearshore circulation revealed by wastewater discharge from a submarine outfall, Aveiro Coast, Portugal. *Hydrol. Earth Syst. Sci.* **2002**, *6*, 983–988. [CrossRef]
- 20. CPU Urbanistas e Arquitetos LDA. *Plano Intermunicipal de Ordenamento da Ria de Aveiro;* CPU Urbanistas e Arquitetos LDA: Lisbon, Portugal, 2007.
- Polis Litoral Ria de Aveiro. Intervenção de Requalificação e Valorização da Ria de Aveiro. Plano Estratégico. 2010. Available online: https://www.polisriadeaveiro.pt/docs/303017N1812011317686275.pdf (accessed on 12 December 2022).
- Águas do Centro Litoral. Exutores Submarinos em Manutenção. 2021. Available online: https://www.aguasdocentrolitoral.pt/ exutores-submarinos-em-manutencao/?cn-reloaded=1 (accessed on 12 December 2022).
- Ramos, P.; Neves, M.V. Monitorização de Descargas de Águas Residuais no Mar através de Veículos Submarinos Autónomos (VSAs). Ing. Agua 2009, 16, 201–216. [CrossRef]
- 24. Blue Flag. Blue Flag Sites. Available online: https://www.blueflag.global/all-bf-sites (accessed on 25 September 2021).
- 25. Câmara Municipal de Aveiro. São Jacinto recebe Bandeira Azul e Bandeira de praia com Qualidade de Ouro 2020. 2020. Available online: https://www.cm-aveiro.pt/municipio/comunicacao/noticias/noticia/sao-jacinto-recebe-bandeira-azul-e-bandeira-de-praia-com-qualidade-de-ouro-2020 (accessed on 25 September 2021).
- Diário de Aveiro. Bandeira Azul Hasteada em São Jacinto pelo 17.º ano Consecutivo. Available online: https://www.diarioaveiro. pt/noticia/83628 (accessed on 25 September 2021).
- Malhadas, M.M.d.S. Modelling the Impact of Submarine Outfalls Plume in a Coastal Areas—Foz do Arelho Case Study. Master's Thesis, Instituto Superior Técnico, Lisboa, Portugal, April 2008.
- Silva, P.A.; Ramos, M.; Almeida, M.; Dubert, J. Water Exchange Mechanisms between Ria de Aveiro and the Atlantic Ocean. J. Coast. Res. 2004, 1622–1626.
- Sousa, M.C.; Ribeiro, A.S.; Des, M.; Mendes, R.; Alvarez, I.; Gomez-gesteira, M.; Dias, J.M.; Si, M.; Dias, J.M.; Alvarez, I. Integrated High-resolution Numerical Model for the NW Iberian Peninsula Coast and Main Estuarine Systems. In Proceedings of the International Coastal Symposium (ICS), Busan, Republic of Korea, 13–18 May 2018; Volume 85, pp. 66–70. [CrossRef]
- Dias, J.M.; Lopes, J.F.; Dekeyser, I. Hydrological characterisation of Ria de Aveiro, Portugal, in early summer. Oceanol. Acta 1999, 22, 473–485. [CrossRef]

- 31. Mendes, R.P.d.S. Numerical Modeling of the Ria de Aveiro Plume: A Preliminary Study. Master's Thesis, Universidade de Aveiro, Aveiro, Portugal, 2010.
- Sobrinho, J. Balanço de nutrientes na plataforma continental ao largo da Região de Aveiro. Master's Thesis, Instituto Superior Técnico, Lisboa, Portugal, June 2012.
- 33. Copernincus Open Access Hub. Available online: https://scihub.copernicus.eu/dhus/{#}/home (accessed on 20 July 2021).
- 34. ONDA. Available online: https://www.onda-dias.eu/cms/services/catalogues/?meta{_}service{_}category2=Data-Access (accessed on 25 July 2012).
- 35. RBINS. ACOLITE. Available online: https://odnature.naturalsciences.be/remsem/software-and-data/acolite (accessed on 26 July 2021).
- 36. Vanhellemont, Q. ACOLITE Python User Manual; Version 20210114; RBINS: Brussels, Belgium, 2021; 21p.
- 37. European Space Agency. SNAP (Sentinel Aplication Platform). Available online: https://earth.esa.int/eogateway/tools/snap (accessed on 15 May 2021).
- Rocha, A.; Aguiar, M.; Lima, K.; Mendes, R.; Dias, J.M.; Sousa, M.C.; De Sousa, J.B. Optimal AUV trajectory planning and execution control for maritime pollution incident response. In *Oceans Conference Record (IEEE)*; IEEE: Piscataway, NJ, USA, 2021. [CrossRef]
- Meteogalicia. Servidor THREDDS de MeteoGalicia. Available online: http://mandeo.meteogalicia.es/thredds/catalogos/ WRF{_}2D/catalog.html (accessed on 15 June 2021).
- 40. Dwivedi, V.; Singh, C. Performance Evaluation of Sewage Treatment Plant Relating to Chemical Characteristics and Re-use of Treated Sewage in Landscaping. *Int. J. Res. Appl. Sci. Eng. Technol.* **2019**, *7*, 1833–1835. [CrossRef]
- VEOLIA. Chapter 37—Wastewater Treatment. Website. 2023. Available online: https://www.watertechnologies.com/handbook/ chapter-37-wastewater-treatment (accessed on 15 May 2021).
- 42. Harmel, T.; Chami, M.; Tormos, T.; Reynaud, N.; Danis, P.A. Sunglint correction of the Multi-Spectral Instrument (MSI)-SENTINEL-2 imagery over inland and sea waters from SWIR bands. *Remote Sens. Environ.* **2018**, 204, 308–321. [CrossRef]
- 43. Morais, M.G. Previsão e Análise de Nevoeiros em Portugal Continental com o Modelo de Mesoescala MM5. Master's Thesis, Universidade de Aveiro, Aveiro, Portugal, 2009.
- 44. Ramos, M.; Almeida, M.; Silva, P.; Dubert, J.; do Carrno, J.A. Modelling Study of the Dispersal of Pollutants at São Jacinto Submarine Outfall (Aveiro, Portugal). *WIT Trans. Built Environ.* **2003**, *70*, 133–141. [CrossRef]

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