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A Proposal for Geospatial Mapping of Tidal Energy Potential Using Satellite Data

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A Proposal for Geospatial Mapping of Tidal Energy Potential Using Satellite Data

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***Abstract*—The region of Rio Mearim, located in the state of Maranhão, Brazil, has ideal geographical and climatic conditions for renewable energy projects, with an extensive coastline, consistent winds and large tidal ranges. In this context, the methodology of this study aimed to reduce the costs of tidal data collection and predict hotspots for oceanic and riverine generation. It demonstrated that hydrodynamic modeling and image processing are viable and cost-effective alternatives. These techniques significantly reduce data acquisition time and provide comprehensive information for characterizing the area of interest, thereby facilitating its analysis.**

***Index Terms*—Tidal energy; Image process; Sentinel-1; Satellite; Database.**

I. INTRODUCTION

Information gathering via satellite is a crucial technique for global monitoring across several fields of human knowledge. Over the past decades, it has become an essential tool for detailed analyses, continuous monitoring, and both environmental and technological development [1], [2]. Its use is widespread in numerous applications, from nature conservation and water resource management to energy parks prospecting and collecting tidal data. In this sense, when the mathematical and algorithmic foundations of image processing are well understood, the technique can be used for recognition of oceanic and coastal dynamics, enabling the identification and characterization of areas of interest.

A second method used for studying and obtaining tidal data is hydrodynamic mathematical modeling. These simulations are employed to estimate values within a specific geographical area, using knowledge over short periods of time to forecast longer ones. Hydrodynamic mathematical modeling, combined with the creation of a conceptual model and short-term measurements in the study region, supports the discovery of previously unknown characteristics in areas of great energy importance. Furthermore, this technique can be used in assessing environmental impacts, supporting coastal management, planning marine infrastructure and developing mitigation strategies for natural disasters [2].

In situ data acquisition is highly costly, especially when measurement campaigns are conducted in marine environments. Moreover, operations in rivers and seas incur significant expenses due to the need for renting boats at high daily rates, acquiring specific equipment for aquatic environments, designing routes based on tidal charts, strictly implementing safety measures and ensuring a qualified crew.

Thus, the methodology adopted in this paper seeks to reduce associated costs with tidal data collection, demonstrating hydrodynamic modelling and image processing as viable and economic alternatives. These models can significantly reduce data acquisition time when measurement campaigns are indispensable, while still obtaining comprehensive information for identifying the study area profile, enabling easier analysis.

II. DIGITAL IMAGE PROCESSING

Digital image processing in remote sensing implies mathematical operations aimed at transforming data into images with higher spectral and spatial quality, each one tailored to a different application and requiring various approaches. Consequently, specialized algorithms have specific configurations, offering users a wide range of techniques [1], [3].

Therefore, to build a database with satellite images, a careful choice of attributes is needed, considering the construction, effects and sensibility of the chosen source, along with the specifics of the study proposed. As a result, user discernment and expertise in remote sensing techniques are crucial for the system's success, since good performance of a model in a determined area does not guarantee effectiveness in others [1], [3], [4].

In addition, when using images to seek information, corrections are frequently required, some made before image distribution while others depend on the user's decision. These corrections are a pre-processing step, an arrangement of functions that aims to improve overall image resolution. The sequence of corrections depends on the interpreter's objectives, and

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may include adjusting radiometric, atmospheric or geometric metrics [1], [3].

Regarding the extraction of data obtained through remote sensing, it is essential to establish analyses methods with logic rules based on specific properties, such as color, tone, texture, structure, shadows and homology for each target class [3], [4].

In this study, the application of image processing techniques obtained from satellites allows for detailed analyses of different important variables to the feasibility of energy generation projects in marine environments. These techniques enable the generation of accurate maps of meteorological and ocean conditions - such as patterns of maritime current speeds - essential to identifying areas suitable for the implementation of offshore energy generators [5], [6].

III. DISCUSSION AND RESULTS

The Mearim River region plus the Caranguejo Island, nearby, have geographical and climatic characteristics favorable for the development of renewable energy projects, as can be seen in Fig. 1. The combination of an extensive coastline, consistent winds, tidal range between 5 and 7 meters and a diverse ecosystem compel those areas as promising locations for the implementation of advanced energy generation technologies. Another great characteristic is the presence of two tidal cycles per day [7].

To harness the energy potential of these regions, it is necessary to develop a robust infrastructure, considering the complicated access by land. In this regard, the well-established maritime transport in the region can significantly help the deployment of these types of energy. Another interesting factor is the proximity to urban centers and ports, which facilitates the transport and maintenance of equipment, reducing operational costs and increasing the project economic viability.

A. Real Data Acquisition

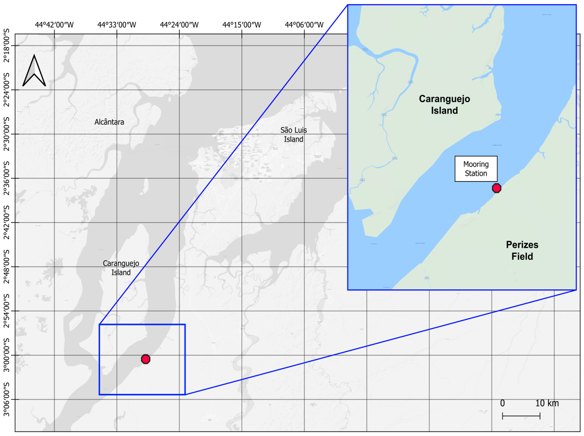


Fig. 1. The location of monitoring station.

In Fig. 1, is shown a map that displays the region selected for this work, located on the Mearim River, between the Caranguejo Island and the Perizes Field, at the coordinates 3°00'32.0"S 44°28'50.9"W. To acquire data, two campaigns were conducted. The first one took place from May 16 to 17, 2022, totaling 25 hours corresponding to a tidal cycle during the spring tide period. The second campaign occurred during the neap tide period, totaling 25 hours on February 27 and 28, 2023.

Three pieces of equipment were used during these periods: the LiDAR (Light Detection and Ranging), the ADCP (Acoustic Doppler Current Profiler) and the CTD (Conductivity, Temperature, Depth). In this work, data from the ADCP and the CTD were used, which provided current velocity, direction, temperature, and salinity data. In Fig. 2, data on current velocity and direction are presented.

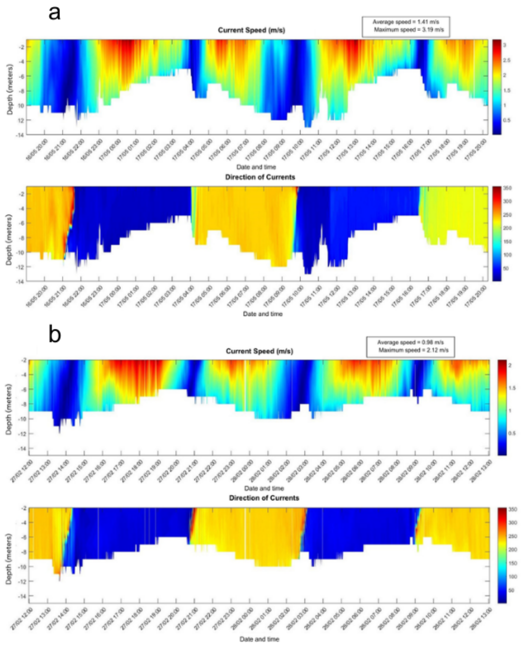


Fig. 2. Absolute speed and direction of currents during the tidal cycle.

Fig. 2 is divided into two sections, a and b. In Fig. 2a, the first campaign during a spring tide cycle is illustrated, where the highest measured velocities were reached, with a maximum velocity of 3.19 m/s and an overall average of 1.41 m/s at the end of 25 hours. In Fig. 2b, the second campaign during the neap tide is illustrated, where the maximum measured velocity was 2.12 m/s with an overall average of 0.98 m/s.

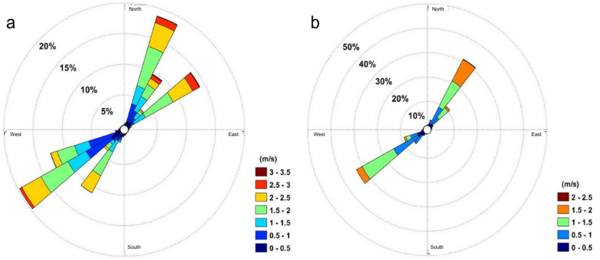


Fig. 3. Histogram of current directions and intensity.

In Fig. 3, the frequency distribution of the intensity and direction of currents throughout the water column over the 25-hour mooring period is presented. Additionally, is possible to identify that the predominant currents were the flood currents, directed towards the southwest (SW), and the ebb currents, directed towards the northeast (NE). It is also possible to observe the difference in intensity between the two campaigns, with Fig. 3a showing more intense movement, and how it differs from the neap tide cycle shown in Fig. 3b.

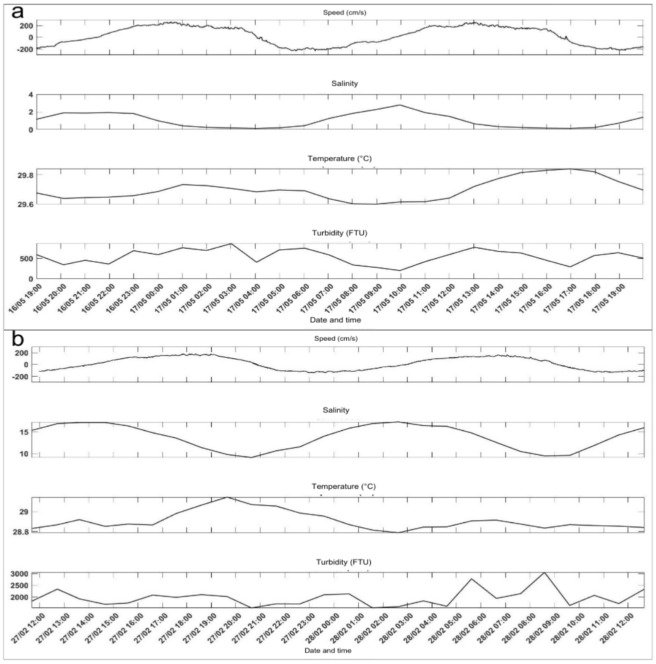


Fig. 4. Vertical average of water velocity, salinity, temperature and turbidity throughout the tidal cycle.

In Fig. 4a and Fig. 4b, a comparison is made between the average current intensities and the physical parameters of the water. It was found that there is a time lag between the peak velocity of the flood currents and the increase in salinity. Additionally, it was identified that the increase in average turbidity in the water column is associated with the ebb currents.

B. Mathematical Modeling Using Delft

After the field data collection, the numerical simulation stage begins. All stages of the hydrodynamic simulation were conducted using the computational tool Delft3D-FLOW [8]. The data used for this stage comes from global models, measured data, nautical charts, and values from the literature. The development of the mathematical model allows for the hydrodynamic simulation of the region of interest for time intervals that exceed the period of the field-collected data.

As mentioned earlier, the initial stage of the modeling consisted of mapping the data of the region, described above. These data were used as input for calibrating a numerical model. The second stage of the hydrodynamic modeling involves delimiting the region of interest, which includes the area around Caranguejo Island, as well as a larger area to mitigate the problem of low accuracy of ocean circulation information outside the model.

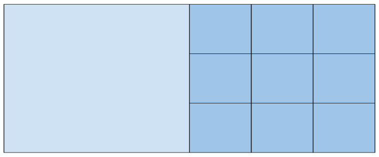


Fig. 5. Grid proportion in the numerical domain.

Two grids were created: a larger, less defined one (see Figure 6a), which receives boundary conditions from the global TPXO model, and a smaller, more refined grid (see Figure 6b), covering mainly the region of interest and its surroundings. The bathymetric grids, as suggested in the literature [9], [10], have a ratio of 3 to 1 (see Figure 5). The resolution of the larger grid is 300 meters and the resolution of the smaller grid is 100 meters, as recommended in the literature.

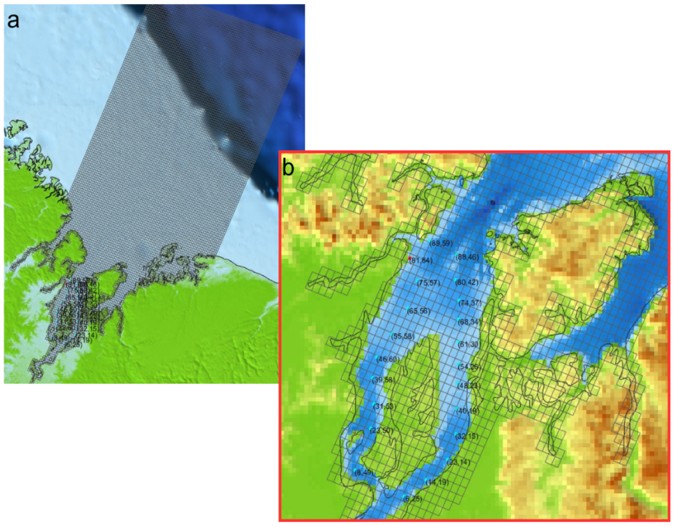


Fig. 6. Grid proportion in the numerical domain.

The data extracted from global models guide the hydrodynamic model, but the external boundary conditions obtained from TPXO lose accuracy within distances less than 30 kilometers from the coast [11]. To address this issue, the simulated model domain extends up to 150 kilometers from the coast of Maranhão State, as illustrated in Figure 6.

The bathymetric characterization of an estuarine region involves detailed mapping of the estuary bed, including depth and bed topography, to predict how water behaves under different conditions such as seasonal variations or extreme events. To adjust the bathymetry in the region of interest, three types of data were merged: global model data, nautical chart data and on-site measurements. For constructing the bathymetry, point and partial measurements were combined using geoprocessing techniques (see Figure 7).

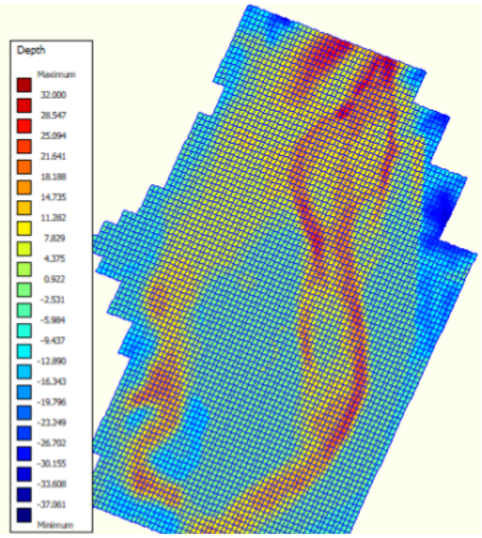


Fig. 7. Bathymetry of the area of interest.

The numerical simulations were initially conducted in 2D and covered the period of measurements solely for data comparison purposes. Subsequently, the plan is selection an one-year interval, as this period includes all seasons, twelve lunar cycles and the time frame when the mooring measurements were conducted.

Right after the 2D simulation run using the larger grid, the 3D simulation begins in the region of interest, this time using the refined grid, covering a smaller area within the determined domain. In this simulation, several parameters were added: 10 layers for the 3D simulation, insertion of observation points, incorporation of boundary conditions from grid nesting, data from harmonic components of the region and estuarine bathymetry data.

During the simulation setup process, it was necessary to reconfigure the model and run it several times. This process involved adjusting the time step, changing the simulation date, inserting points of interest, adding extra information and making repairs until the desired configuration was achieved.

The area in the São Marcos Bay, where the data collection was conducted, showed current velocity and tidal amplitude results that were very similar to the measured data. The consistency between the collected data and the simulations supports the accuracy of the adopted methodology, enabling a detailed analysis of the current and tidal dynamics in the region of interest, a posteriori.

C. Image Processing

Given the real data and modeling already acquired and processed, the possibility of using satellite images to detect hotspots throughout the monitoring area was investigated. The Copernicus program - Europe's eyes on Earth, which operates the Sentinel program (Sentinel 1 to 6), was selected for this study, supplemented by satellites from private partnerships. Sentinel 1 images were used for this study, as illustrated in Fig. 8.

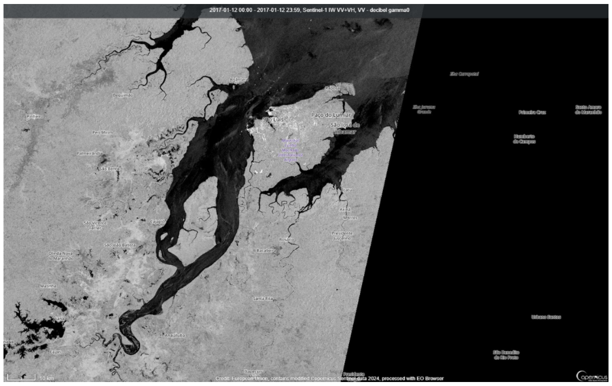


Fig. 8. Satellite image.

The satellite image database was compiled from 8 years of data, from 2017 to 2024, with at least 4 images per month of the studied region, totaling a sample of 340 images. Sentinel 1 was chosen due to its capability to provide radar data in VV polarization - gamma0 decibels, which creates a grayscale image using radar backscatter (gamma0) data from VV polarization. This is particularly sensitive to surface roughness [12]. Visualizing in decibels allows subtle variations in data to be highlighted, such as water wakes.

In this regard, since the acquired image is already in grayscale, MATLAB software was used for image processing. Fig. 9 shows the initial processing of the region of interest [13]:

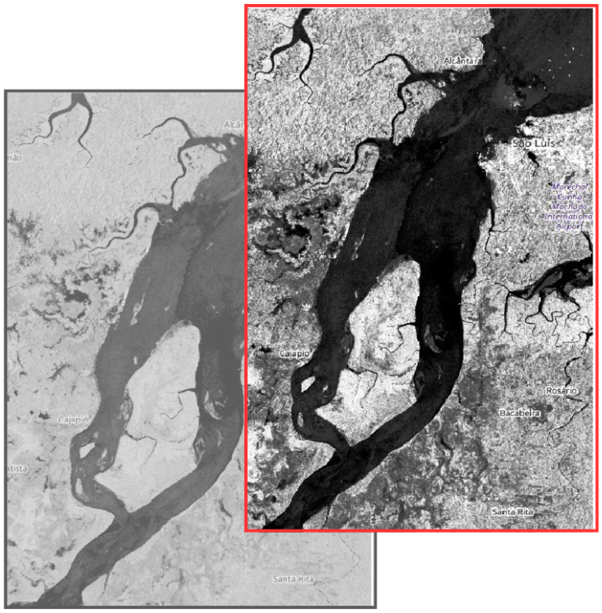


Fig. 9. Linear contrast enhancement in the studied region.

After delimiting the study area, a linear contrast enhancement was applied using MATLAB to further highlight the region in the Mearim River. This allowed for easier identification of sandbanks, areas with greater depth and the direction of sediment transport.

It is possible to identify in Fig. 9 that there is a large amount of sediment being transported along the river, as well as regions with large sandbanks, which can easily be identified at low tide through visual observation, making the deeper channels even more apparent. To enhance this analysis in Fig. 10, filtering, identification, and characterization of the Mearim River region were performed.

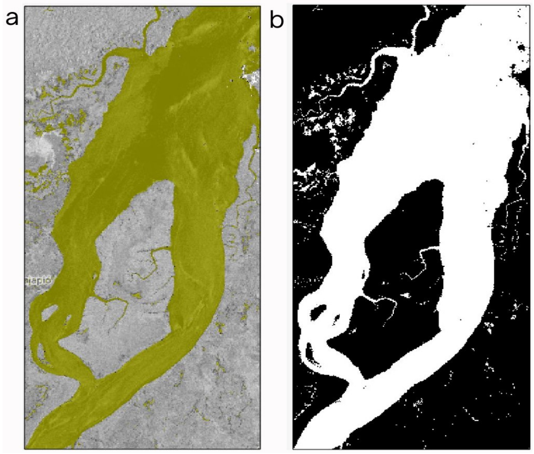
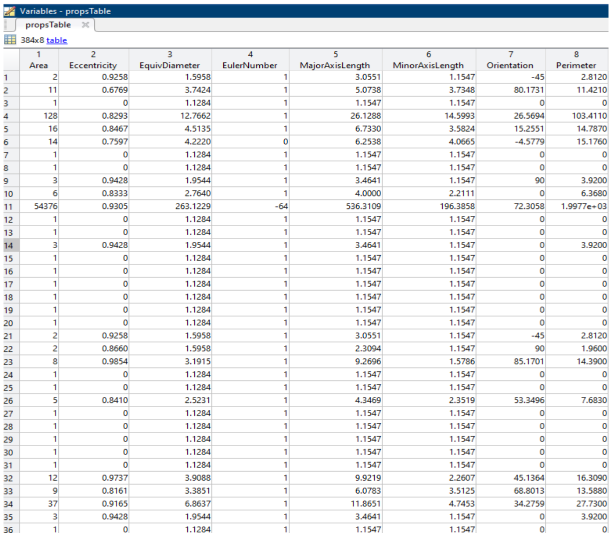


Fig. 10. Enhancement and binarization of the image.

Futhermore, in Figure 10a, the river area was highlighted, considering the presence of several potential points to be studied. Continuing in this direction, Figure 10b shows the binarization of the image, allowing the algorithm to analyze the region that is in white. As shown in Figure 11.



	1 Area	2 Eccentricity	3 EquivDiameter	4 EulerNumber	5 MajorAxisLength	6 MinorAxisLength	7 Orientation	8 Perimeter
1	2	0.9258	1.5958	1	3.0551	1.1547	-45	2.8120
2	11	0.6769	3.7424	1	5.0738	3.7348	80.1731	11.4210
3	1	0	1.1284	1	1.1547	1.1547	0	0
4	128	0.8293	12.7662	1	26.1288	14.5993	26.5694	103.4110
5	16	0.8467	4.5135	1	6.7330	3.5824	15.2551	14.7870
6	14	0.7597	4.2220	0	6.2538	4.0665	-4.5779	15.1760
7	1	0	1.1284	1	1.1547	1.1547	0	0
8	1	0	1.1284	1	1.1547	1.1547	0	0
9	3	0.9428	1.9544	1	3.4641	1.1547	90	3.9200
10	6	0.8333	2.7640	1	4.0000	2.2111	0	6.3680
11	54376	0.9305	263.1229	-64	536.3109	196.3858	72.3058	1.9977e+03
12	1	0	1.1284	1	1.1547	1.1547	0	0
13	1	0	1.1284	1	1.1547	1.1547	0	0
14	3	0.9428	1.9544	1	3.4641	1.1547	0	3.9200
15	1	0	1.1284	1	1.1547	1.1547	0	0
16	1	0	1.1284	1	1.1547	1.1547	0	0
17	1	0	1.1284	1	1.1547	1.1547	0	0
18	1	0	1.1284	1	1.1547	1.1547	0	0
19	1	0	1.1284	1	1.1547	1.1547	0	0
20	1	0	1.1284	1	1.1547	1.1547	0	0
21	2	0.9258	1.5958	1	3.0551	1.1547	-45	2.8120
22	2	0.8660	1.5958	1	2.3094	1.1547	90	1.9600
23	8	0.9854	3.1915	1	9.2696	1.5786	85.1701	14.3900
24	1	0	1.1284	1	1.1547	1.1547	0	0
25	1	0	1.1284	1	1.1547	1.1547	0	0
26	5	0.8410	2.5231	1	4.3469	2.3519	53.3496	7.6830
27	1	0	1.1284	1	1.1547	1.1547	0	0
28	1	0	1.1284	1	1.1547	1.1547	0	0
29	1	0	1.1284	1	1.1547	1.1547	0	0
30	1	0	1.1284	1	1.1547	1.1547	0	0
31	1	0	1.1284	1	1.1547	1.1547	0	0
32	12	0.9737	3.9088	1	9.9219	2.2607	45.1364	16.3090
33	9	0.8161	3.3851	1	6.0783	3.5125	68.8013	13.5880
34	37	0.9165	6.8637	1	11.8651	4.7453	34.2759	27.7300
35	3	0.9428	1.9544	1	3.4641	1.1547	0	3.9200
36	1	0	1.1284	1	1.1547	1.1547	0	0

Fig. 11. Analyzed properties of the image.

From the data in Figure 11, it is possible to delineate the areas that are most relevant for the study, as there is sufficient information to identify with greater accuracy the regions with greater depth.

IV. CONCLUSIONS

The region of Rio Mearim, located in the state of Maranhão, Brazil, has ideal geographical and climatic conditions for renewable energy projects. With an extensive coastline, consistent winds, large tidal ranges and a diverse ecosystem, these regions hold significant potential. Additionally, the presence of two daily tidal cycles further enhances their suitability for such projects.

Based on satellite images acquired by Sentinel-1, using mathematical modeling and validating our investigation with real data obtained from two measurement campaigns, it was possible to identify areas with great potential for tidal current energy generation.

Another finding of this study is the possible monitoring of the movement of sandbanks over the years, whether through their disappearance, displacement, or increase. This makes early identification feasible, assisting commercial navigation in nearby areas.

Thus, the methodology used in this study aimed to reduce the costs associated with direct tidal data collection, as well as predict hotspots for oceanic and riverine generation, demonstrating that hydrodynamic modeling and image processing are economical and feasible options. These approaches can significantly reduce the time required for data acquisition when measurement campaigns are unavoidable, while also providing comprehensive information for characterizing the area of interest, thereby facilitating its analysis and study.

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