BUILDING A DIGITAL TWIN OF THE ITALIAN COASTS

J. P. Duque[1] *, M. A. Brovelli[1]

[1] Department of Civil and Environmental Engineering (DICA), Politecnico di Milano – juanpablo.duque@mail.polimi.it; maria.brovelli@polimi.it

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ABSTRACT:

The “Destination Earth” initiative of the European Union encompasses the creation of Digital Twin Earths (DTEs), high-precision digital models of the Earth integrating various aspects of the Earth’s system to monitor and simulate natural phenomena and related human activities, being able to explore the past, understand the present, and build predictive models of the future. To achieve this goal, huge amounts of good-quality data are necessary, but also, means to combine and add further utility to them.
To tackle this problem, we created a novel web application that implements the mediator-wrapper architecture as a data integration strategy and uses only open-source software to put together more than 60 geospatial layers from 3 different data sources. This application is a proof of concept of how data integration can be used to implement Digital Twins and is focused solely on the Italian coasts. It integrates data from Copernicus and WorldPop to provide tools for analysing and describing the interaction of marine, land, and demographic variables on coastal areas. It offers both visualization and analysis capabilities, which is a unique feature amongst similar applications, thanks to the implementation of virtual data integration and geospatial data standards.

1. INTRODUCTION

On the framework of the European Commission initiative “Destination Earth” there is a plan to build a Digital Twin of the Earth: a high-precision digital model of the entire planet that makes use of huge amounts of data to simulate and model physical and socioeconomic phenomena, being able to explore the past, understand the present, and predict the future.

In order to build a Digital Twin Earth, a set of technological components are necessary, which includes strong computation capabilities to process and store the vast amount of data available and to be produced, connectivity, cloud computing, artificial intelligence (AI) models that can describe real-world phenomena, high volumes of good-quality data (big data), and interoperable standards to glue everything together.

This work is focused on the description of a novel open-source web application that is designed to tackle de problem of data integration and interoperability. By making use of the mediator-wrapper architecture (also called mediator-based), a well-known data integration strategy for virtual integration, several geospatial layers were integrated into a single web application as a proof of concept of how data integration can be used to create a Digital Twin. The application is currently only focused on the Italian coast and its main goal is to provide means to analyse the interaction between sea, land, and population on coastal areas. The prototype of the application is temporarily available at https://dte-italycoast.herokuapp.com and the source code is available at the GitHub repositories https://github.com/Diuke/italy-coasts-dte-front and https://github.com/Diuke/italy-coasts-dte-back.

There is a huge amount of open data available on the internet, especially for Europe through Copernicus, that can be used to build a Digital Twin. Copernicus provides geospatial data in several categories that can help describe the land and sea segments of the Italian coast, while the WorldPop datasets provide the demographic segment. A further description of these data sources is present in section 3.

Data alone is not useful if there are not means to combine it and add value to it. Therefore, the development of this application helps to fulfil the need to use the already available data to help users visualize and understand the physical and social processes that are currently happening.

In section 2 we present a theoretical framework with a short state of the art and similar applications, followed by the concepts of data integration and geospatial data standards. In section 3 we describe the application developed and the workflow that a user should follow using it. In section 4 we show the data sources that were integrated into the application. Finally, the conclusion is presented, along with ideas for further development.

2. THEORETICAL FRAMEWORK

In this section, we present a short state of the art which depicts the use of data integration for geospatial data in the academic literature and list other applications similar to the one we developed. Then, we show the definitions and descriptions of what is data integration and the geospatial data standards.

2.1 State of the Art

Data integration strategies have been used before for developing geospatial applications. In academic literature there are many examples that implement data integration strategies to put

* Corresponding author

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together geospatial data. Huang and Liang (2014) described how they used the mediator-based architecture to integrate sensor data provided in a standardized way. Regueiro et al. (2015) did a similar work by implementing a mediator-wrapper architecture to virtually integrate sensor data. Virtual integration schemes have been mostly used for sensor's data because of the high amount of raw and unprocessed data, weak standards and multiple data formats that are available.

Another integration strategy that has been used in literature is semantic analysis and ontologies for automatic data integration. Studies from Huang et al (2020), Butenuth et al (2007), Prudhomme et al (2019), and Stoimenov, Djordjević-Kajan (2005) show how semantic technology can aid in data integration schemes. When combined with virtual integration architectures, as the mediator-wrapper, they are helpful for developing modules to integrate new data, in a faster and automatic way. Semantic technology and ontologies are not implemented on the application but are technologies to be considered for further development of the application.

2.2 Similar applications

Other web-based platforms and applications allow visualization and management of geospatial data. A first example is the Copernicus Marine Service's web application called MyOcean Viewer, which allows users to explore and visualize their entire catalogue of data. It also allows users to query the visualized layers and build time series plots and depth profiles. It is available at https://myocean.marine.copernicus.eu.

Another similar platform is the ARIES for SEEA explorer, which integrates multiple world-wide data to generate new information as raster grids using artificial intelligence models that are built using the k.LAB tool. They provide also analysis, insights and explanation of the models used and the underlying data used to produce the results. The application is available at https://klab.officialstatistics.org/modeler/?app=aries.seea.en#/login but requires authentication.

An Italian example is the platform developed by the Ministero dell'Ambiente, which can be used to explore data from the national geoportal. The application only provides visualization of their own layers but no data analysis capabilities. The application is available at:
http://www.pcn.minambiente.it/viewer/

2.3 Data integration

It is a computer science discipline whose goal is to provide uniform access to multiple autonomous, and probably heterogeneous, data sources. For the application developed, the data integration strategy that was implemented was the mediator-wrapper architecture, also called mediator-based, which corresponds to virtual data integration.

In virtual data integration the system integrating multiple data sources does not own nor duplicate information, instead, uses a remote connection to query data. This alternative is cheaper because no additional storage and hosting costs are considered, and easier to implement, but requires deep knowledge of the data sources that are being integrated and is prone to failure if the underlying data source makes a modification or has any downtime.

The mediator-wrapper architecture is an architectural pattern which features a single, centralized mediator that receives generic responses from a client, and a set of modular wrappers that are in charge of communicating and parsing responses from the data sources. This pattern is well-known and is widely used in data integration due to its flexibility and ease of implementation.

2.4 Geospatial data standards

The task of developing and maintaining geospatial data standards is a task of the Open Geospatial Consortium (OGC) and the International Organization for Standardization (ISO). These two organizations create and divulge a wide set of standards, also called specifications, that indicate how geospatial data should be shared over the internet.

Among the multiple specifications that are available, the OGC Web Services (OWS) stand out. The services included under that category are the Web Map Service (WMS) that shares maps as images, Web Map Tile Service (WMTS) which is similar to WMS but delivers the images in tiles, being more optimized for high-resolution and big images, Web Feature Service (WFS) that allows sharing and modification of vector data (geospatial objects) such as points, lines, and polygons, and Web Coverage Service (WCS) that shares maps as coverages, i.e. raster and grid.

Another important set of specifications are the ones regarding file extensions. GeoTIFF, for raster data, and GeoJSON, for vector data, are two very important extensions that are widely used and belong to the set of OGC standards.

3. DEVELOPED APPLICATION

3.1 General Description

The application described in this paper is a web-based geospatial application that allows the visualization and analysis of more than 60 geospatial layers coming from 3 data sources.

The core of the application is the data integration strategy to incorporate several data sources through the mediator-wrapper implementation. The use of this architecture makes the application modular and easily extensible. It is also important to note that the application is fully developed using open-source technologies and all the integrated data is open data.

The application provides two main functionalities: data exploration and data analysis. Data exploration refers to the parametric visualization of the geospatial layers that are integrated into the application. The data analysis functionality refers to a set of data analysis and querying capabilities over the same integrated data.

3.2 General Architecture and used technologies

The platform follows a Client-Server architecture. The client macro-component contains the web application that faces the user and is composed of a frontend web application developed with Angular which makes use of OpenLayers as the mapping library for managing the geospatial data. Angular is a robust web framework and is ideal for creating complex web applications, while OpenLayers is an open-source, robust, and very complete web mapping library used for creating interactive web maps. It is also the oldest mapping library available that it's still being constantly updated.

The server macro-component features a backend web application developed on Django, which is a Python-based web framework that is ideal for creating robust and complex web-based projects that can benefit from the use of Python. Django also provides geospatial capabilities through a set of extensions that are popularly called GeoDjango, which are a great fit for this project. The use of Python is important, as the platform needs to deal with data handling and analysis, which Python excels at.

Also, on the server macro-component, the database management system is located. The database is a PostgreSQL instance with PostGIS for geospatial operations and data types. In the platform, the database is in charge of storing the metadata of the available geospatial layers, such as name, date availability range, dimensions, connection parameters, and so on. PostgreSQL is a powerful, open-source relational database which is widely over the internet for its simplicity and power. Additionally, it provides the extension PostGIS which is very popular on the geospatial field to add geospatial capabilities directly on the database.

Figure 1 shows the architecture of the platform and the technologies used.

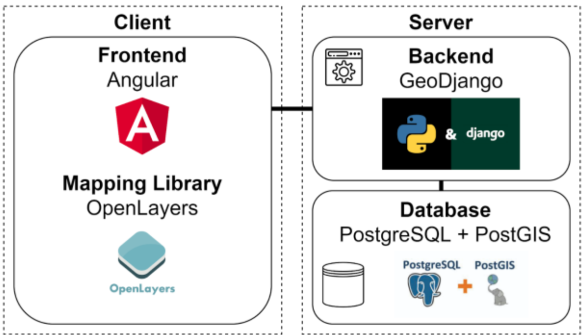

Figure 1. General architecture and technologies

3.3 Mediator-wrapper architecture implementation

To use the data that is already available on the internet without duplicating it and making use of the existing standards, a data integration strategy was implemented on the platform. The mediator-wrapper implementation is the most important component of the system as it is the one that connects and extracts information from data sources in a generic way, dealing with complex querying and responses. Additionally, it provides modularity to the application, which can easily be extended by adding new mediators for new data sources.

The mediator-wrapper architecture consists of two components: a single mediator that deals with communication with the client by a set of generic requests and responses, and multiple wrappers that receive generic requests from the mediator. The wrappers are in charge of communicating with specific data sources and translating its responses to a generic form that the mediator can understand. The conjunction of these two components allows the platform to connect to multiple data sources without changing the way in which the user uses the application. The general architecture is depicted in figure 2.

It is important to mention that data integration is not an easy task. Standards are vague in some aspects, organizations often interpret standards their own way, and even data within the same organization is not interoperable and is not designed to be put together, e.g, Copernicus Land Monitoring Service and Copernicus Marine services.

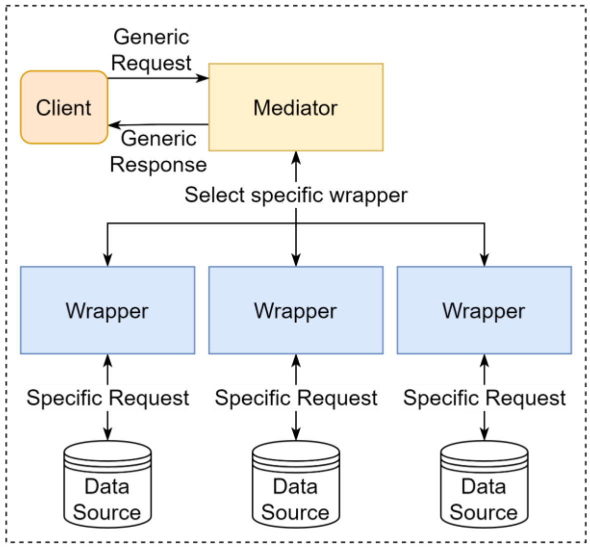

Figure 2. General mediator-wrapper architecture

The actual implementation was done by placing the mediator on the client component and the wrappers on the server component. This way, the mediator directly communicates with the user through the user interface and then communicates with the wrappers through HTTP. Wrappers makes requests to their respective data source, also through HTTP, parse the response, and then send it back to the mediator. In this way, all the heavy processing and data analysis is done on the server side, while the visualization and data display are done on the client side.

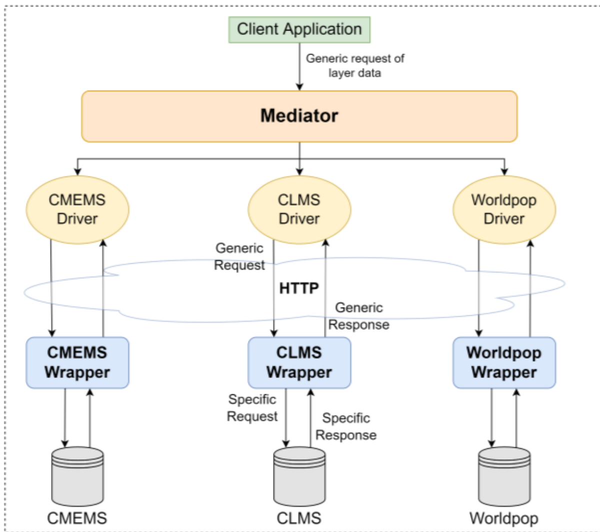

Figure 3. Mediator-wrapper implementation

This implementation allows to quickly scale the application by assigning more computational power to the server side, since the heavy load is managed by it, while leaving the client side lighter and faster. Also, it allows to easily extend the application by adding more wrappers to connect to other data sources.

3.4 Application workflow

The application usage is divided into five steps, which constitute the application workflow, as depicted in figure 4.

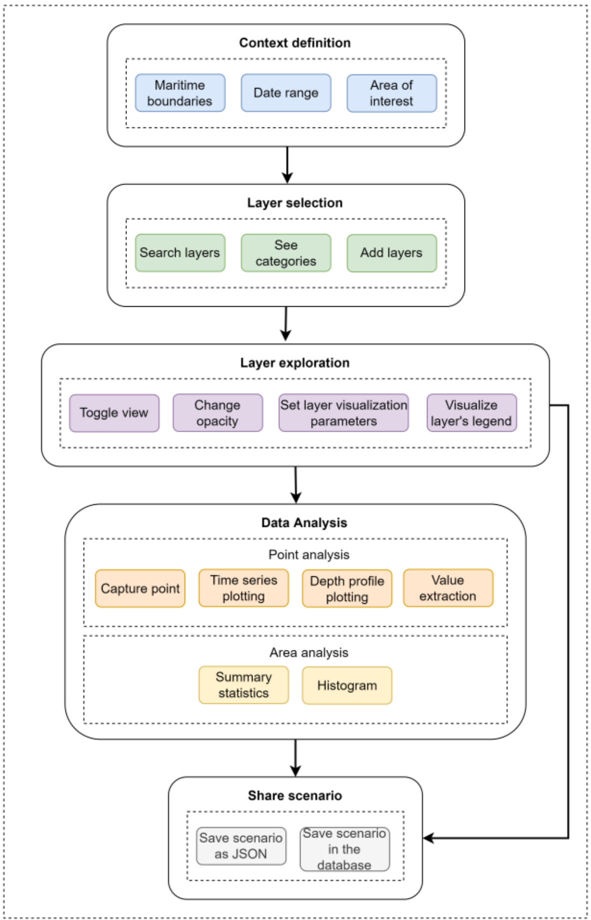

Figure 4. Application workflow

To contextualize the following sections, figure 5 shows the graphic user interface of the application. It consists of five tabs, divided into a left and right menu, which correspond to each one of the five workflow steps. They follow an intuitive order from left to right, and each menu can be closed to declutter the application main screen.

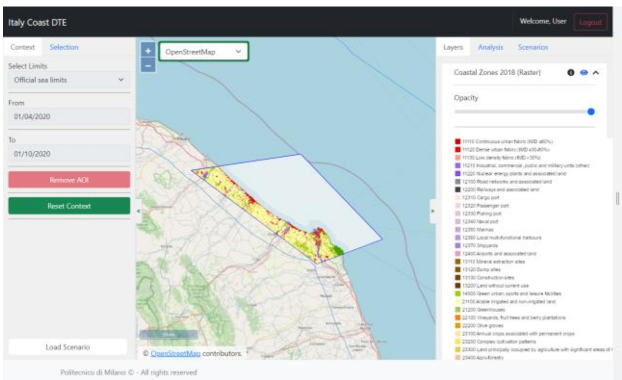

Figure 5. Application user interface

3.4.1 Context Definition

For the application, the context are the spatio-temporal settings in which the layer visualization and analysis is to be performed. The context consists of an area of interest (AOI), a date range, and a maritime limit polygon.

By setting a context, the application is able to scope the analysis that is being made. Ergo, the application does smaller requests, filters a limited number of available layers, and processes less information, depending on the size of the context.

3.4.2 Layer Selection

After setting the context, a set of layers will be made available to the user to select the layers they want to use. The layer availability depends on the context, in particular the date range, since every layer has a date range in which it has data. The layers that are selected in the layer selection step are available for data exploration in the next step of the workflow.

The layers are retrieved from the database, which stores the metadata of the layers, including their connection parameters. Layers are provided by three data sources that deliver land, sea, and demographic data and are further divided into eight categories: sea physics, landcover, sea biogeochemistry, sea winds, imperviousness, forestry, water and wetness, and demographics.

3.4.3 Layer Exploration

With the layers selected in the previous step of the workflow, now it is possible to explore the data. Exploration is done by parametric visualization of the selected layers, which allows the user to set the layer's visualization parameters, such as time or elevation, as well as the visibility and opacity. Some of the integrated layers have dimensions, e.g., time and elevation, that specifies that a certain layer provides data at different timestamps and different depths, respectively. This feature is important because it allows time series and depth profile analysis at the next workflow step.

It is also possible to query the layers underlying data to obtain the value of the layers that are selected on a single point. This is useful to further explore the data and the values of the layer in specific places without doing more intensive data analysis. Additionally, it is possible to see the layers legend in the layer exploration tab.

3.4.4 Data Analysis

A set of data analysis capabilities are available in the application. This feature is a novelty, as there are not yet any platforms that offer both visualization and analysis for multiple data sources at once. Data analysis is possible due to the standards that the data sources are using and the querying capabilities that each data source provides.

The possible analyses available are divided into two categories: point and area analysis.

- Point Analysis: Consist of a set of analyses that can be performed at a single location, specified by latitude and longitude. Depending on the layer dimensions, it is possible to do a time series analysis (when the layer supports the time dimension), depth profile analysis (when the layer supports the elevation dimension), and value extraction at a single coordinate.

- Area Analysis: Consists of analyses that are performed over the entire area of interest selected in the context definition. To execute an area analysis, first a sampling of the layers on the area of interest is performed and then multiple summary statistics are calculated (minimum, maximum, median, average, and standard deviation), as well as histograms to check the value distribution over the area. As WMS do not provide any area analysis capabilities, doing sampling on WMS layers is the only way to produce area analysis results.

All the available analysis are presented as either plot, table or image and are fully downloadable. Also, the data from which plots are built is downloadable, so users can further analyse is apart from the application or use the application to easily extract data from the data sources.

3.4.5 Share Scenario

A final step includes the possibility to save the work by generating a scenario. It is a JSON file with all the necessary information to restore the application state as it was at the moment in which the scenario was generated. When a scenario is loaded, the context, the layers selected, its visualization parameters, and the parameters of the analysis to be performed are loaded into the application.

The scenarios are useful for storing different kinds of studies, but also for sharing analyses and studies with colleagues.

4. DATA INTEGRATED

At the moment of writing this paper, 3 data sources were integrated into the platform, with a total of 68 geospatial layers available to be used.

The main goal with the data that is currently integrated is to provide the information to understand and study the interface between the water and land segments of the Italian coast, considering also the demographic component.

The data sources integrated into the platform are Copernicus Marine Environment Monitoring Service (CMEMS), Copernicus Land Monitoring Service (CLMS), and WorldPop. Additional data in the application includes two base maps and the Italian maritime boundaries layer. All the geospatial layers are open and are provided using OGC standards, principally as Web Map Service (WMS).

In this section each data source will be described, and the layers integrated mentioned, as well as the description of the additional data.

4.1 Copernicus Marine Environment Monitoring Service

This Copernicus service provides maritime data for the entire world with a special focus on European seas. Its catalogue contains more than 190 datasets, called products. The integrated data corresponds only to Mediterranean Sea products, since all the Italian Coasts are engulfed by the Mediterranean, and having a more localized dataset improves accuracy, resolution, processing time, and querying, due to the smaller size with respect to the entire world. A total of 45 geospatial layers are integrated to the application from this data source.

The following datasets are integrated:

- **Mediterranean Sea Physics Analysis and Forecast:**

This dataset provides data on physical variables over the mediterranean sea, such as currents velocity, ocean mixed layer thickness, water temperature, surface height, and salinity. 16 geospatial layers from this dataset are integrated into the application.

Data from this dataset is provided with monthly and daily-mean frequencies and with a spatial resolution of 0.042°.

- **Mediterranean Sea Biogeochemistry Analysis and Forecast:**

This dataset provides biological and chemical data over the Mediterranean Sea. It features 14 variables, which are the concentrations of ammonium, nitrate, phosphate, and silicate, the mass concentration of Chlorophyll, the dissolved inorganic carbon and molecular oxygen, the Phytoplankton and Zooplankton biomass, the net primary production, alkalinity, sea water pH, carbon dioxide flux, and carbon dioxide partial pressure. 28 geospatial layers from this dataset are integrated into the application.

Data from this dataset is provided with monthly and daily mean frequencies and with a spatial resolution of 0.042°.

- **Global Ocean Wind L4 Reprocessed Monthly Mean Observations:**

This dataset provides wind variables over the global oceans in montly mean frequency. A single geospatial layer is integrated into the application from this dataset: the Root Mean Squared (RMS) wind speed. The spatial resolution of this dataset is 0.25°.

4.2 Copernicus Land Monitoring Service

This Copernicus service provides information of the entire European continent on land cover, land use, and its changes over time. It supports decision making for urban planning, forest and water management, agriculture, food security, nature conservation and restoration, amongst others.

A total of 19 geospatial layers are integrated into the application from this data source, coming from the following datasets:

- **CORINE Land Cover (CLC):**

The CORINE dataset provides land cover information of the entire european continent in 44 thematic categories. It is useful to identify what is the use of land close to the marine environments.
It is provided through WMS and has a spatial resolution of approximately 100 meters.
Although the CLC dataset has been released for the reference years of 1985, 2000, 2006, 2012, and 2018, only the 2012 and 2018 datasets are integrated into the application for being the most recent and updated.

- **Imperviousness:**

The Imperviousness datasets provide information on the percentage and change of soil sealing. Impervious areas, also called sealed areas, are the ones where the original natural or semi-natural land cover or water surface has been changed by artificial and impervious cover. Imperviosness data is useful for identifying built-up areas and human modification of the natural environment.
7 geospatial layers from this dataset are integrated: the Imperviousness Density layers of 2006, 2009, 2012, 2015, and 2018, and the Impervious Built-up of 2018.
This layers have a spatial resolution of 20 meters for layers released before 2018 and of 10 meters for 2018 and up.

- **Forests:**

This set of datasets provide vegetation information of the european continent. 3 layers from this group are integrated into the application: Tree Cover Density layers from 2012, 2015, and 2018.
They indicate the level of tree cover density in a range from 0% to 100%. The layers of 2012 and 2015 are provided with a spatial resolution of 20 meters, and the one of 2018 is provided with a spatial resolution of 10 meters.

- **Water and Wetness:**

This dataset provides information of the occurrence of water and wet surfaces over the european continent. The layers of 2015 and 2018 are the ones integrated into the application. Similar to the other datasets, layers before 2018 are offered with a spatial resolution of 20 meters, while the layer of 2018 is offered with a spatial resolution of 10 meters.

- **Coastal Zones (CZ):**

This dataset offers detailed land cover and land use information along the maritime coastline of the european continent. This coastline consists of a 10km inland buffer as the land segment, and a seaward buffer of 12 nautic miles, corresponding to the territorial waters boundary.
This dataset classifies the land cover into 71 thematic classes and has a spatial resolution of 10 meters.
The datasets integrated into the platform correspond to the 2012 and 2018 reference years.
It fulfils the same task of identifying land cover features on the land segment of coasts, but it is more specific due to the higher amount of thematic classes, and is focused on coastal areas.

4.3 WorldPop

WorldPop offers open, spatial demographic data and research. It is used as the demographic data for the application.

6 geospatial layers are integrated from WorldPop, corresponding to the gridded population counts for the years of 2015, 2016, 2017, 2018, 2019, and 2020. These datasets contain information of the amount of people currently living in a pixel of the layer and are validated with official population estimates from each country.

The WorldPop gridded population counts datasets are offered through WMS and WCS and have a spatial resolution of 3 arcseconds, equivalent to approximately 70 meters.
WorldPop data is useful to identify human settlements and population density nearby coastal areas as a demographic factor that may influence certain physical variables.

4.4 Additional data

Additional data integrated into the platform includes two base maps to orient and contextualize the user, and a layer containing the Italian maritime limits, which serves as context and as a limit in which data is retrieved.

One of the base maps is OpenStreetMap, a free, open-source, editable map of the whole world, which is used as a feature base map displaying useful information to the user such as roads, buildings, and points of interest.

The other base map is a Sentinel-2 cloudless satellite imagery map, that provides a satellite view of the entire world with a spatial resolution of 10 meters. This map is produced and distributed by EOX through a WMS service with a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.

The Italian maritime limits were obtained from the Marine Regions geodatabase that contains up-to-date data on the current political maritime boundaries according to international treaties. The limits set as the coastal area in which data is retrieved from the data sources correspond to a 10km inland buffer and to the maritime boundary up to the Exclusive Economic Zone (EEZ). The land portion of the limits corresponds to the Coastal Zones dataset inland buffer.

Figure 6. Italian maritime boundaries layer.

5. CONCLUSION

The developed application presented in this paper constitutes an approach towards the Digital Twin Earth by addressing the problem of data interoperability through the implementation of an integration strategy using the mediator-wrapper architecture.

This innovative platform allows users to integrate and use multiple data sources, that are not easily put together, visualize them, explore them, and perform analysis over them. It integrates 68 geospatial layers coming from three distinct data sources: Copernicus Marine Service, Copernicus Land Monitoring Service, and WorldPop, to model and represent the marine, land, and demographic segment of the Italian coast, respectively.

The application is a proof of concept of what could be achievable with a Digital Twin Earth and shows how data integration is an important task in its development. The current application is a prototype and further development is planned.

Future work includes the implementation of new features such as more analysis capabilities, integration of more data sources, automatic data integration by using ontologies and semantic analysis, artificial intelligence models for forecasting, addition of external data on-the-fly, and the implementation of reference indicators for certain variables. Additionally, replication of the application for other coasts and other types of environments.

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