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A geoportal of data and tools for supporting Maritime Spatial Planning in the Adriatic-Ionian Region

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ABSTRACT

The multiple anthropogenic threats to marine ecosystems and the increasing spatial conflicts in the Adriatic-Ionian Region (AIR) require transnational, integrated and efficient planning of coastal and marine spaces at macro-regional level. This research presents the Geoportal of the Adriatic-Ionian Region (GAIR), a common platform for information, data and decision support tools for ocean planning in the Adriatic-Ionian sea space. The GAIR is an open source platform; it supports co-production of MSP-relevant knowledge based on 12 databases, portals and tools developed within a set of European projects supporting the implementation of the European Strategy for the AIR (EUSAIR). The study presents the GAIR's software architecture, its technological stack and the seven integrated geospatial tools. A case study of the tool presents its user workflow and main outputs. The paper concludes with an evaluation of the GAIR with respect to MSP, Sustainable Blue Economy and the implementation of the EUSAIR Action Plan.

1. Introduction

The present competition for coastal and maritime space triggered by human activities, as well as climate change effects and natural and manmade hazards, impact coastal and marine ecosystems (Pınarbaşı et al., 2020). Maritime Spatial Planning (MSP) is a strategy that can tackle these challenges and ensure protection and maintenance of ecosystem structure and functioning by applying an Ecosystem-Based Approach (Domínguez-Tejo et al., 2016). Thus, Ecosystem-Based Maritime Spatial Planning (EB-MSP) is a public process that aims at implementing transparent strategic plans providing legal certainty and regulations for the access to marine resources and spaces addressing both socio-economic and ecological objectives, as well as ensuring the involvement of a wide range of stakeholders in participatory interaction processes (Ehler and Douvere, 2009). Hence, EB-MSP implementation should apply a holistic approach and a commonly accepted framework with an ecologically sound visioning, easy to communicate to environmental and marine managers, and to an ample range of stakeholders (Pınarbaşı et al., 2020; Schumacher et al., 2020). In this context, Decision Support Tools (DSTs) were developed and implemented to inform evidence-based decision-making processes for maritime management, and to support the development of long-term strategies for the achievement of the Sustainable Blue Economy (SBE) (COM(2021) 240 final) and of the European Green Deal goals (Depellegrin et al., 2021;

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Pınarbaşı et al., 2020). Consequently, the results produced by applying DSTs strongly support the EU MSP Directive (2014/89/EU) implementation, identifying the areas most suitable to allocate different human activities, taking into consideration habitats, existing sea uses and conflicts and co-use of new potential activities. In the last years, many DSTs were developed in diversified contexts and applied for different planning objectives (Andersen et al., 2020; Gusatu et al., 2021; Kotta et al., 2020; Menegon et al., 2018b; Pınarbaşı et al., 2017). These tools often require input data and Geographic Information System (GIS) and programming skills for their use, together with interdisciplinary competences. This heterogeneity and wide choice of DSTs can generate some difficulties for decision makers in selecting the most suitable tool that can better address the specific planning objectives (Menegon et al., 2018b). Moreover, ideally, these tools should be accessible to users through a Graphical User Interface (GUI) in order to be practically used to address the development of spatial plans, their management and the monitoring and evaluation of their effective implementation (Ehler, 2017; Menegon et al., 2018b).

In full compliance with the MSP principles and policies, and with the Integrated Coastal Zone Management (ICZM) processes, in 2014 the European Commission developed the European Union Strategy for the Adriatic and Ionian Region (EUSAIR) and the related Action Plan (European Commission, 2014) aimed at supporting the blue growth in the area. The AIR basin, due to its bio-physical characteristics and semi-enclosed nature, and due to being shared between different countries, is more vulnerable to space and multi-uses competition (Depellegrin et al., 2019). This basin is shared by seven countries: four EU Member States (Croatia, Greece, Italy, and Slovenia) and three non-Member States (Albania, Montenegro and Bosnia-Herzegovina). These characteristics pointed out the compelling need in the AIR for a transnational integrated and efficient planning and management of marine spaces and uses at macroregional level, enabling the avoidance of potential conflicts and favouring synergies to secure a sustainable growth, whilst allowing the preservation of coastal and marine ecosystems for future generations. MSP can foster transboundary cooperation, defining common objectives, instruments and establishing a close coordination and integration between different administrative and manager levels (Gómez-Ballesteros et al., 2021; Jay et al., 2016).

In the AIR several initiatives to support cross-border MSP in EU Member States exist beyond the EUSAIR Strategy, such as the European Maritime, Fishery and Aquaculture Fund (EMFAF) or the Interreg Adriatic-Ionian (ADRION) Programme. Within the PORTODIMARE Project (geoPORtal of TOols & Data for sustaInable Management of coAstal and maRine Environment; Interreg ADRION; https://www.portodimare.eu/), the Geoportal of the Adriatic-Ionian Region (GAIR) was developed. The GAIR is a single virtual space that integrates and further develops existing geospatial databases, interoperable portals and interactive tools, thus supporting coordinated, transnationally coherent and transparent decision-making processes for cross-border MSP. The GAIR also capitalises and integrates outcomes from prior European and regional initiatives such as the SUPREME project (Supporting maritime spatial Planning in the Eastern Mediterranean; SUPREME Partnership, 2018) that supported the development of the MSP Knowledge Catalogue (MSPKC; Menegon et al., 2018d), a web application to facilitate the collaborative inventory and data preparation of MSP-relevant information (e.g. reports, datasets, scientific publications, policy briefs and reference information to national MSP processes), and the ADRIPLAN (ADRiatic Ionian maritime spatial PLANning, DG MARE, 2013–2015) and RITMARE (The Italian Research for the Sea, MIUR 2013-2016-2018) projects that supported the initial development of the Tools4MSP Geoplatform (Menegon et al., 2018c), a web application providing MSP-oriented tools such as Cumulative Effects Assessment (CEA), Marine Use Conflict Analysis and a Marine Ecosystem Services Threat (MES-Threat) Analysis.

The aim of this research is to present the GAIR, which overcomes the traditional MSP-oriented geoportals functionalities (i.e., data visualisation and sharing) with data analysis modules and a novel instrument to facilitate data preparation and the engagement with data providers. In detail, the core features of the GAIR are the seven geospatial tools, namely: 1) Cumulative Effects Assessment (CEA), 2) Maritime Use Conflicts (MUC), 3) Particle Tracking module (PARTRAC), 4) Aquaculture Zoning Assessment (AZA), 5) Coastal Oil Spill Vulnerability Assessment (OILSPILL), 6) Small Scale Fishery Footprint (SSF) and 7) Medium Scale Fishery Footprint combined with CEA module(MSF/CEA), and an additional module named MSP Knowledge Catalogue (MSPKC) to support data inventory and preparation. This manuscript is structured as follows: firstly, we present the GAIR's software architecture and its technological stack, then we provide an overview of the datasets and modules, and present a workflow on how to use the GAIR for a case study on CEA in the Emilia-Romagna Region (Northern-Adriatic Sea). We discuss the importance of the GAIR for the MSP process in the AIR and conclude with an analysis of its future development needs and challenges.

2. Methods

2.1. Overall architecture of the GAIR

The GAIR is a common platform for co-production of knowledge in coastal and marine areas, mainly focused on supporting MSP and based on an integrated combination of web tools, helping collaborative management processes and geospatial analysis.

The need to integrate and further develop existing repositories, portals and tools aiming at efficiently organising and making accessible through a single virtual space most of the available knowledge and resources, thus supporting coordinated, regionally/transnationally coherent and transparent decision-making processes, has emerged within previous EU projects and initiatives (European Commission, 2016).

Within the PORTODIMARE project (PORTODIMARE Partnership, 2020), the previous experiences have received a further impulse and a full operational GAIR has been developed and implemented to support a transnational cooperation network for the implementation of the Protocol for the Integrated Coastal Zone Management (ICZM) and the Directive 2014/89/EU (Maritime Spatial Planning Directive - MSPD) in the AIR as a concrete instrument for the implementation of the EUSAIR Action Plan.

The overall architecture of the GAIR is presented in Fig. 1. The scheme underlines the interaction with external applications and potential end-users as well it depicts, as a whole, a knowledge co-production system of software, users and web services for supporting the MSP processes.

Five hierarchical levels of user profiles have been implemented in order to balance the trade-off between the need of knowledge co-production and users engagement, and the need to guarantee an appropriate level in the resources and information quality: General public (unregistered users), Registered users (e.g. Citizen, Stakeholders, Scientists, Policy makers and planners), Advanced users (e.g. PPs and invited policy makers and planners, specific scientific networks), Managers/Editors, Administrators. Many GAIR contents and resources (e.g. public layers, maps, documents and case studies) are publicly available to unregistered users. In order to upload and create new resources or perform module analyses, users have to be registered and authenticated into the platform. The registration is open to everyone, however it is subjected to approval by the administrators to prevent registration of spam users. In Annex 1 of the supplementary material, we provide a detailed description of the GAIR user profiles.

The main functionalities of the GAIR include: data sharing among users (e.g. geospatial datasets, documents), maps (collections of layers) creation and sharing, performance of analyses through seven different decision support modules, and results sharing through the platform. The GAIR has been designed following a service-oriented architecture that

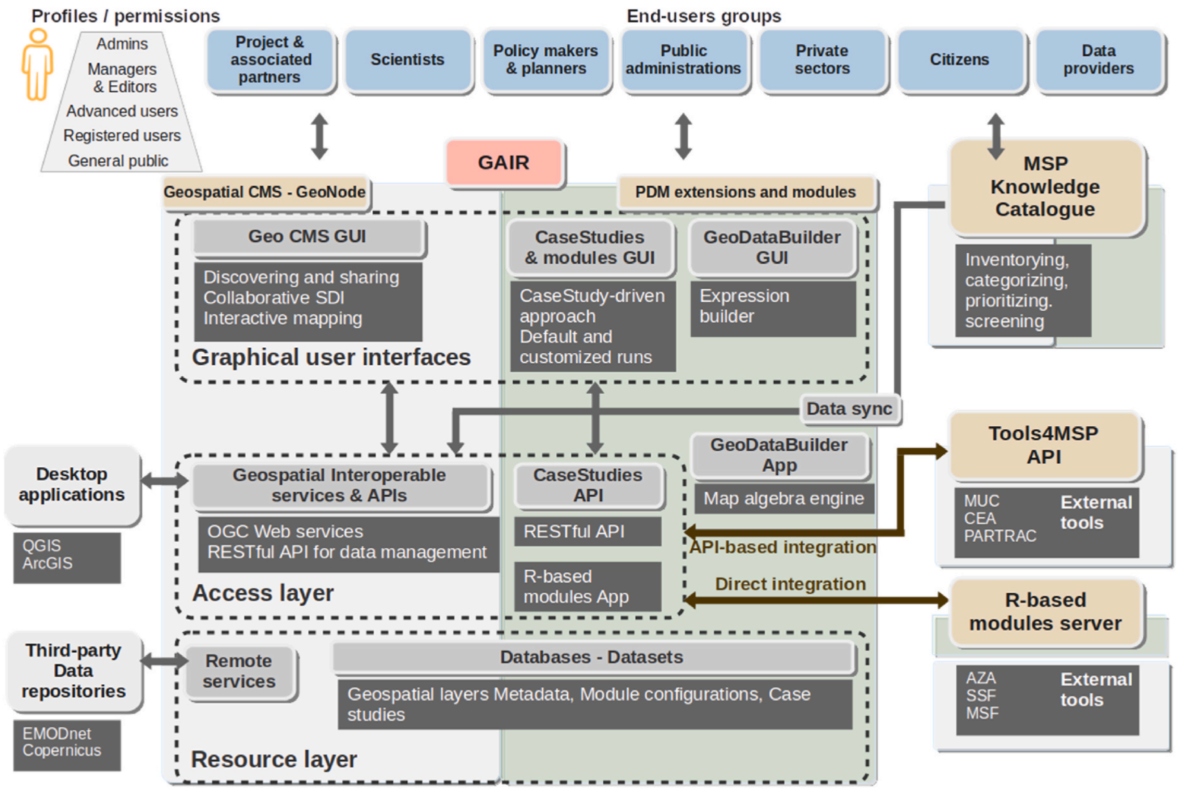

Fig. 1. Overall architecture of the GAIR and interactions diagram. Components identified by sea green colour boxes were developed and released within SUPREME and PORTODIMARE projects.

includes three main abstract layers (Fig. 1):

1) *the Graphical User Interfaces (GUIs)*, which are accessible through HTML5-based web browsers (including mobile browsers) allowing end-users to intuitively and interactively visualise and operate (e.g. search, explore, manage) with local and remote resources (e.g., geospatial layers, maps);
2) *the access layer*, which exposes interoperable services and RESTFull API and acts as a middleware between the "GUIs layer" and the "resource layer" below. Wrapping access to local resources, it also constitutes a single and common point for accessing and managing resources by machine-to-machine communications (third-party data repositories) or by desktop applications (e.g., QGIS);
3) *the resource layer*, which deals with storing, maintaining and low-level controlling the access to different heterogeneous resources such as geospatial datasets, metadata, documents, module configurations, case study setups.

2.1.1. *Graphical User Interfaces*

The three main GUI components are the Geo CMS GUI, the Case Study and Modules GUI and the GeoDataBuilder GUI (see Fig. 1).

The Geo CMS GUI provides content management system (CMS) functionalities to manage, upload, create and modify geospatial resources (e.g. layers, layer styles, maps). Particularly, it includes: a Search GUI, which combines free-text search, faceted navigation and a preview of the filtered results, to search over the different GAIR content types (geospatial layers, maps, generic files and documents and archived model outputs) (see Fig. 2); a GUI to upload and publish new geospatial datasets and documents, including graphical controls to customise the layer styles and to manage permissions in a granular manner (e.g. visualising, downloading, changing); and a Map Viewer and Composer to create and share interactive (e.g. navigating, querying) multi-layered web map applications.

The Case Studies and Modules GUI implements the workflow for the Case Study-driven approach (Menegon et al., 2018b, 2018c) where the users can perform a module analysis, including: CEA - Cumulative Effects Assessment, MUC - Maritime Use Conflicts analysis, PARTRAC - Particle Tracking module, AZA - Aquaculture Zoning Assessment, OIL-SPILL - Coastal Oil Spill Vulnerability Assessment, SSF - Small Scale Fishery Footprint module and MSF/CEA - module for Medium Scale Fishery Footprint and CEA. We refer to section 3.3 on model workflow for a detailed description of a case study module run using the CEA module.

The GeoDataBuilder GUI allows users to define new geospatial layer expressions through map algebra operators and functions for combining one or more layers already stored into the GAIR. Layer expressions may be used to automatically pre-process new layers and use the result to customise the Case Studies and the module analysis. An example of the GeoDataBuilder GUI for creating a new layer expression is presented in Fig. 3. GeoDataBuilder supports base map algebra operations (e.g., addition, subtraction, division, multiplication), rescaling (e.g., to rescale a layer into the 0–1 interval), log-transformation and aggregations (e.g., max, min, average). In addition, the GeoDataBuilder enables the user to pipeline the outputs of a module result with another module/case study and therefore allowing a module-to-module integration. As an example of integration we refer to the case study in section 4.2.7.

2.1.2. *Access layer: web services & API*

The access layer is composed of the "Geospatial Interoperable Services and APIs", and the "CaseStudies API" (see Fig. 1). The "Geospatial Interoperable Services and APIs" mainly implement the Open Geospatial Consortium (OGC - Open Geospatial Consortium Inc, 2021) web services for enabling the discoverability, accessibility and usability of geographic information shared through the GAIR (see supplementary material Annex 2), and additional APIs for securely uploading, registering and publishing new geospatial layers or other generic resources (e.g., documents). Such APIs are also part of the synchronisation mechanism

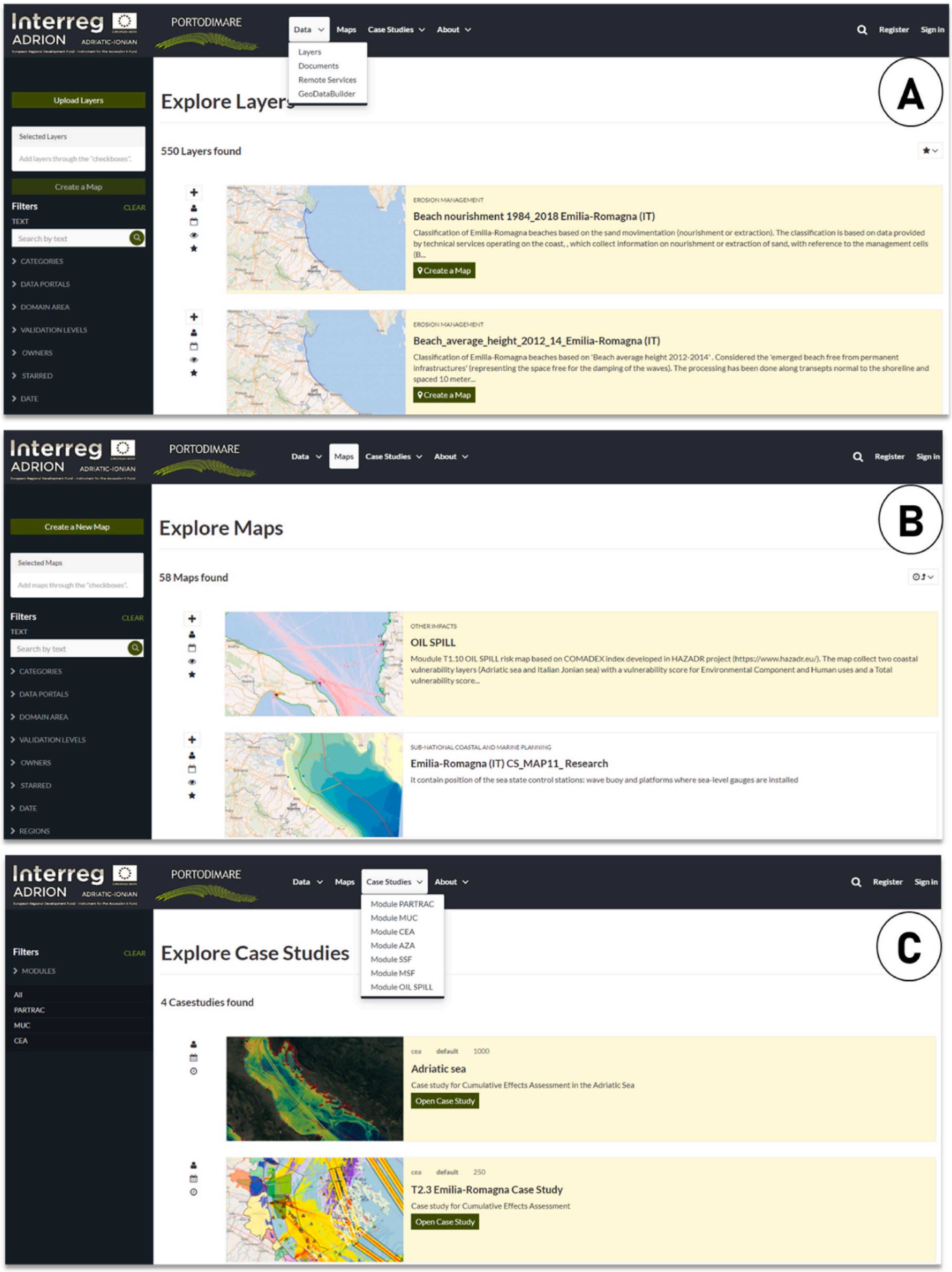

Fig. 2. GUI of the GAIR with three core functionalities: A) Data layers; B) Maps and C) Case studies. The GUI is based on GeoNode core software.

(*Data sync*) between the MSPKC and the GAIR, which allows to ingest the data of the catalogue by the GAIR (see Fig. 1).

2.1.3. Resource layer

The Resource Layer consists of a combination of different storage solutions (e.g., database management systems) to support the heterogeneous data models and formats shared by the data managers and the end-users, and all the information needed to achieve a full operational infrastructure (e.g., geospatial datasets, documents, metadata, catalogue information, user accounts and profiles, case study configurations and model run parameters). Direct access to the resources is usually interdicted since the access is exclusively provided by the

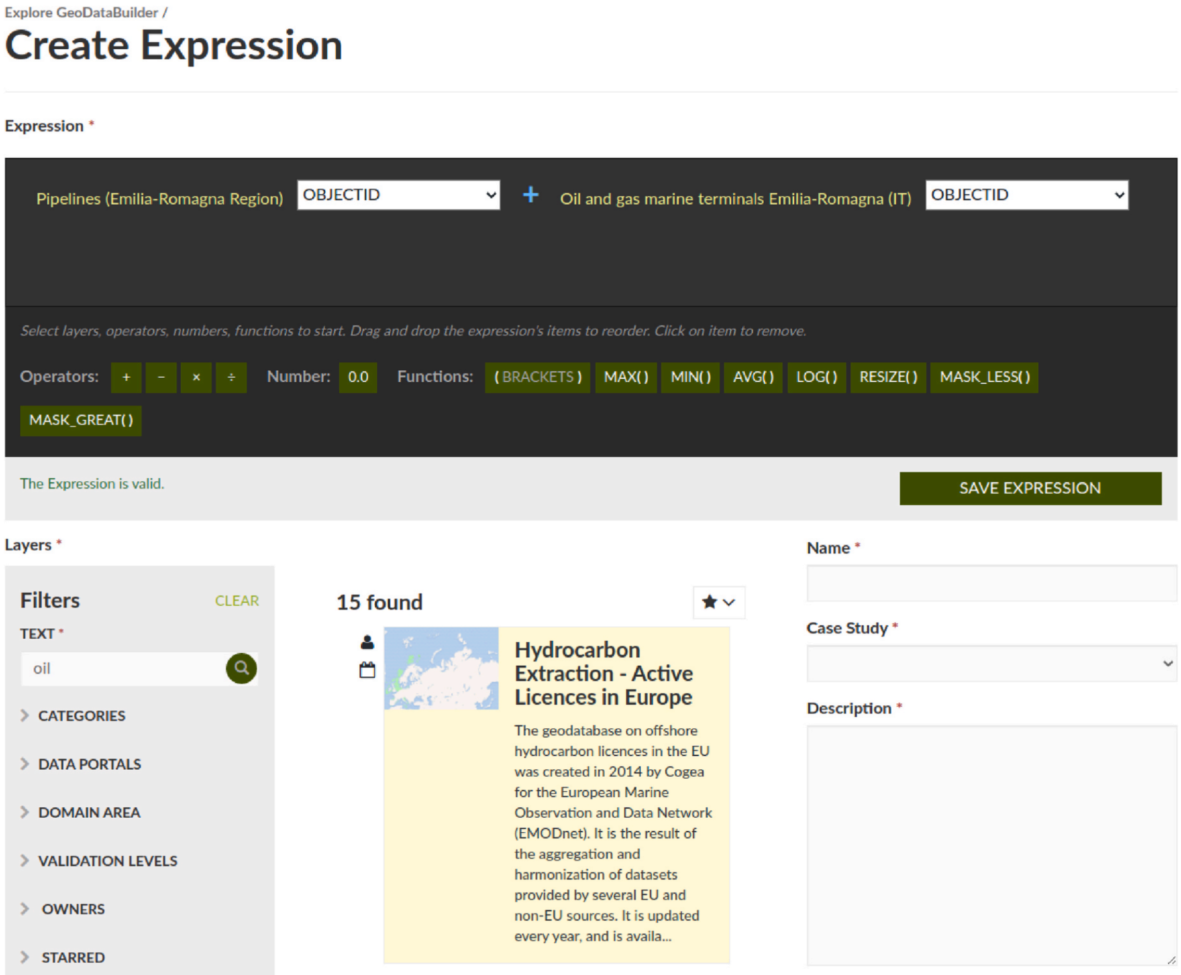

Fig. 3. GeoDataBuilder GUI for creating layer expressions through map algebra operators.

Access layer. External geospatial resources provided by "third-party" data repositories (e.g., EMODnet, Copernicus) are made available through the "Remote services" application. Remote services allow users to register external services, usually Web Map Services (OSGeo, 2010). Information on external published layers are automatically retrieved and the layers are made available through the platform similarly to the raster and vector geospatial layers stored locally (Corti et al., 2019).

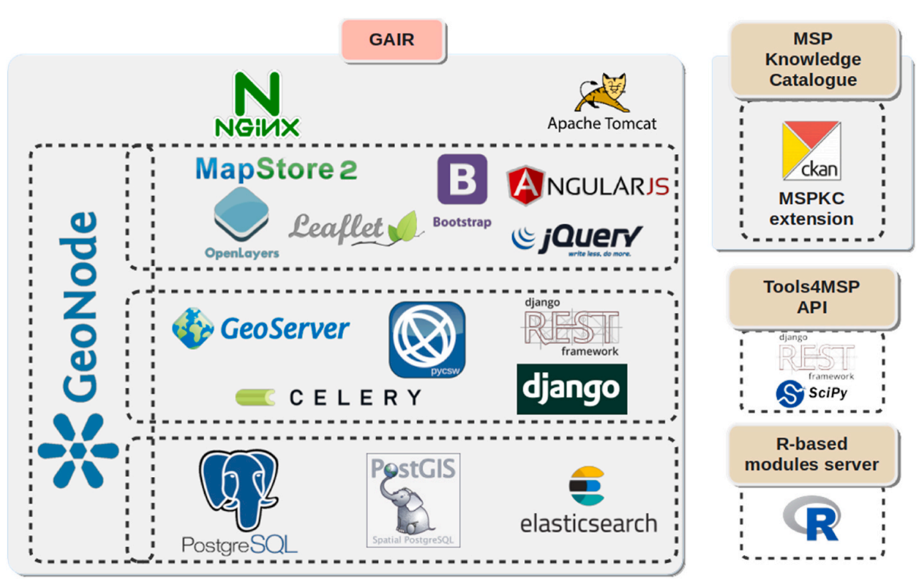

Fig. 4. Technological stack of the GAIR.

2.2. Technological stack

The technology stack is the combination of software products, development frameworks and programming languages used to build and run a complete application (Avgeriou and Zdun, 2014).

The GAIR adopts a Free and Open Source (FOSS) technological stack combining and integrating several software packages. Fig. 4 presents an overview of the software components used in the GAIR server and client implementations. Each element in the stack was carefully selected based on requirement fulfilment, robustness and size of the software community (e.g., number of developers and users), quality of support (e.g., public groups or forums addressing user queries regarding installation or other bugs), quality of documentation and software licence.

The GAIR has been developed on top of the GeoNode platform (Benthall and Gill, 2010; Corti et al., 2019; GeoNode Development Team, 2021, 2022), a complete suite for collaborative managing geospatial data that provides a significant number of required functionalities. Providing geospatial Content Management System functionalities, GeoNode facilitates the upload and management of geospatial datasets, making them discoverable and available via standard Open Geospatial Consortium (OGC) protocols and web mapping applications. GeoNode provides high level GUIs for spatial data discovery, uploading and managing (e.g., setting-up metadata and presentation form) and for composing and viewing interactive maps. GeoNode GUIs are built on top of Bootstrap (Bootstrap team, 2019) and AngularJS (Google, 2021) frameworks and MapStore2 (GeoSolutions, 2022) for the mapping applications. A highly interoperable access layer, based on GeoServer (GeoServer Development Team, 2022) and pycsw software packages (pycsw Development Team, 2022) provides access to stored resources through standardised interfaces (especially OGC-Web service). The resource layer is mainly implemented by PostgreSQL (The PostgreSQL Global Development Group, 2022), PostGIS (PostGIS Development Group, 2022) and Elasticsearch (Elastic NV, 2021) for supporting full-text searching. Overall, GeoNode has been developed on the top of Django (Django Development Team, 2018). In Annex 3 a summary of GeoNode and GAIR technological stack's software components is presented.

Beside adopting the GeoNode tech stack, the GAIR also leverages on additional FOSS libraries and frameworks such as jQuery (The jQuery Team, 2021) for the CaseStudy and the GeoDataBuilder GUIs and the Django REST framework (Encode OSS Ltd, 2021) for the CaseStudies API (see Figs. 1 and 4).

Tools4MSP API provides the model engine for CEA, MUC and PATRAC modules (Menegon, 2021). Finally, an R language (R Core Team, 2022) separate stack has been adopted to implement the R-based Modules Server that incorporates additional packages for dealing with geospatial data, such as the *raster* package (Hijmans, 2021), to manipulate and analyse gridded spatial data.

The MSPKC is based on CKAN (Comprehensive Knowledge Archive Network) web tool (Open Knowledge International, 2021), an Open Source Software for managing, organising, metadating and publishing collections of datasets. In addition, the "ckanext-mspkc" plugin (Menegon, 2018) has been developed during the SUPREME project and included into the MSKC implementation. ckanext-mspkc is a CKAN extension, which provides additional metadata fields to support an MSP-oriented resource categorization and description, and facilitates the linkage and coupling with the GAIR. The new extension introduces new metadata fields, such as MSP related topic categories and subcategories, domain areas (a spatially aware definition of marine areas - e.g., sea names), data portals (a reference to well established repositories and data portals), and validation level (a descriptive classification of dataset robustness and official level).

3. Data collection and geospatial datasets

Implementing a shared knowledge framework about the coastal and marine system is an essential requisite for creating the Case Studies and feeding the decision support module analyses. The inherent dynamic and collaborative nature of the GAIR facilitates the continuous improvement and refinement of collected datasets directly by the end users.

In total, 509 geospatial datasets and associated metadata information are stored into the GAIR (figure updated to March 2022). 302 layers were initially imported from the MSPKC (see following section - 4.1), while another 207 were later added into the GAIR by the project partners and the users. Fig. 5 represents the grouping of the geospatial datasets according to "Topic category", "Spatial scale" and "Validation level".

The "Type of Habitats" includes the majority of layers (79 layers/16%), followed by "Biological characteristics" (53 layers/10%), "Fishing" (47 layers/9%) and "Maritime transport" (40 layers/8%). In terms of spatial scale, the majority of datasets are of "Regional" scale (169/33%) followed by the "Country" level data (146/29%), then followed by "Mediterranean sea basin and AIR" level (82/16%). The dataset validation level refers to the source of the dataset and distinguishes among official data providers, such as competent authorities at different administrative levels including the European Marine Observation and Data Network (EMODnet), while research data is retrieved from experimental models and research studies (e.g. species distribution models, spawning and recruitment grounds, fishing effort estimations). The dataset includes 328 (65%) official and 181 (35%) research layers. It is to be noted that the official layers mostly refer to "Type of habitats" (70 layers/15%), while the research layers mostly refer to "Biological characteristics" topic (44 layers/9%).

Based on the "Domain area" metadata field, the spatial distribution of data availability in the AIR was calculated considering the number of layers related to different spatial scales (see Annex 4). Hotspots of data availability occur in correspondence to PORTODIMARE Case Studies, i.e., Emilia-Romagna, Istria-county, Slovenia, Montenegro and Kephalonia island.

4. Modules and workflows

4.1. MSP Knowledge Catalogue

The aim of the MSP Knowledge Catalogue (MSPKC) is to overcome time-consuming data preparation tasks during an MSP data gathering process by providing a web-based collaborative inventory and resource systematisation tool that facilitates the engagement with MSP data providers. The inventory includes spatial and non-spatial information such as reports, (geo-)statistical datasets, scientific publications, policy briefs, national MSP supporting documentation and Blue Growth Strategies. The MSPKC allows to improve the engagement of contributors, avoiding data duplications and fostering a collaborative approach for the catalogue filling-up and maintenance. A screenshot of the MSPKC home page is provided in Annex 5.

Data gathering in MSPKC was performed by 13 stakeholders—including research institutes, universities, local and regional authorities across the AIR (Italy, Greece, Slovenia, Montenegro, Croatia, Bosnia Herzegovina)—and was combined with data assimilated from other global, EU, national and regional geoportals, such as EMODnet Human Activities, Environmental Marine Information System (EMIS), SHAPE Atlas, Tools4MSP Data Portal (Annex 6). The stakeholders engaged into the data gathering process introduced more than 1000 resources including geospatial datasets, documents, maps, reports, etc. into the MSPKC, and categorised them into 26 MSP-oriented topics (e.g., maritime boundaries, biological characteristics, aquaculture, fishing). Each resource was described using dedicated metadata fields (e.g., reference date, owner, provider, licence, accessibility; Annex 7). As a next step, non-relevant or duplicated resources were removed, resulting in 994 resources (see Annex 5). A faceted-search and identification was performed by stakeholders to prioritise the geospatial data to be used by

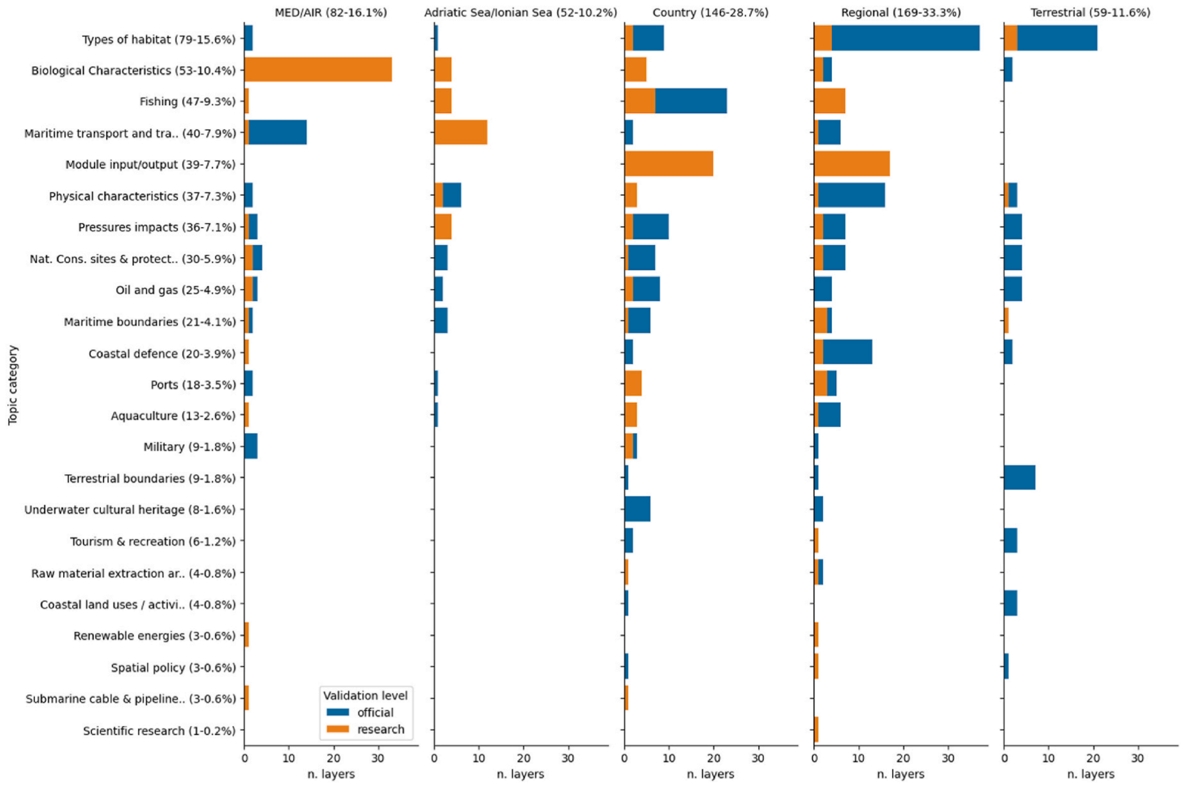

Fig. 5. Number of layers in the GAIR according to their spatial scale (Mediterranean to regional scale; terrestrial refers to non-marine data), to 23 "Topic categories" and to the "Validation level". The Validation level is a descriptive classification of dataset robustness in terms of official level data - data derived from official resources such as Ministries or Hydrological Institutes and research level data - data derived from scientific institutions and research projects.

the geospatial tools of the GAIR, based on the following criteria: *i*) data quality and reliability; *ii*) geographic domain; and *iii*) data availability. This resulted in the 302 high priority geospatial resources for the AIR that were imported into the GAIR.

4.2. Geospatial modules

4.2.1. Module identification and importance within MSP process

The identification of the geospatial modules to be incorporated within the GAIR platform was based on a combination of different criteria: i) relevance of the tools to support the different stages of the MSP processes especially in the context of the AIR region; ii) maximisation of project partners' experience in developing DSTs for marine management with particular reference to sector analysis of maritime activities and support to ecosystem-based management; iii) technological feasibility in integrating the tool within the GAIR platform; and iv) ease of use for stakeholders of the AIR and for non-expert GAIR user profiles (see Annex 1).

Although based on existing algorithms and tools developed by the partners, under the PORTODIMARE project the modules were improved and adapted to the specific needs of ICZM/MSP and to the need to achieve an harmonised approach among them. One of the goals of such adaptation and harmonization is to support integration among the modules themselves, for example, by allowing the outputs of one module to be used directly as inputs by other modules (e.g., the CEA module can use the outputs of the AZA, and SSF/MSF modules as inputs). Module results' integration can be performed using the GeoDataBuilder GUI described in section 2.1.1.

The relevance of the identified modules in supporting the different stages of an MSP process is illustrated in detail in Annex 8. The geospatial modules are mainly designed to support stage 2 (Gather data and define current ecological and socio-economic conditions), stage 3 (Identify issues, constraints and future conditions), and stage 5 (Evaluate alternative management actions). However, the AZA module can also have a significant use for building future scenarios and developing alternative management actions (Stage 4). Instead, the MSPKC and the GAIR core functionalities (i.e., data management and sharing, layers, maps) offer important support also to stage 1 (Define goals and objectives) and stage 7 (Refine goals, objectives and management actions).

4.2.2. Module description

Table 1 provides an overview of the geospatial modules available in the GAIR in terms of model, input data and output data requirements, module integration pattern and Case Studies application. GAIR geospatial modules differ according to adopted programming languages (Python and R), user interaction level, and level of long-term support perspective. This variability has led to the design of two different module integration patterns: "API-based" integration and "direct" integration (see Fig. 1 and Table 1). The API-based integration performs machine-to-machine communication with an external module/tool web service. This mode of integration was implemented for the Maritime Use Conflicts (MUC) module, the Cumulative Effects Assessment (CEA), and the Particle Tracking module (PARTRAC). In the direct integration mode, the GAIR common API communicates and executes directly with the module engine. This was implemented for the Aquaculture Zoning Assessment tool AZA, the Small Scale Fishery Footprint (SSF) and the Medium Scale Fishery Footprint and CEA module (MSF-CEA). A third mode of operation, implemented for the Coastal Oil Spill Vulnerability Assessment (OIL SPILL), does not require real-time analysis and end-users can explore, query and consult pre-processed layers and pre-configured maps. In Table 1 and in the following sections a detailed overview of the seven geospatial modules available in the GAIR is provided along with their main aims and documentation sources. In the supplementary material Annexes 9 to 13 we provide screenshots exemplifying outputs for each module.

Table 1
GAIR module overview, models input-output data, module integration pattern into the GAIR and case studies available.

Module	Model	Input data	Output data	Integration pattern	Case studies
MUC[1]	$\sum_{i=1}^{l}\sum_{j=1+i}^{l} c_{ij} p(U_i) p(U_j)$	Spatial distribution of the human uses (presence/absence) - p(U). Potential conflict score between each use combination - $c_{i,j}$	Spatial distribution of MUC scores. Summary statistics and graphs	API-based	Adriatic Sea; Emilia-Romagna Region; Slovenia
CEA[2]	$\sum_{k=1}^{n} d(E_k) \sum_{j=1}^{m} s_{ij} eff(P_j E_k)$ $eff = rf_{j,k}(\sum_{j=1}^{m} w_{ij} i(U_i, M_{ij,k}))$	Spatial distribution of the human uses - U. Spatial distribution of the environmental components - E Use-specific pressure weights - $w_{i,j}$ Sensitivity of the k-th environmental component to the j-th pressure - $s_{j,k}$	Spatial distribution of CEA scores. Spatial distributions of CEA score subdivided by MSFD pressure types. Summary statistics and graphs	API-based	Adriatic Sea; Emilia-Romagna Region; Slovenia; Kephalonia Island
PARTRAC[3]	$\frac{\vartheta x}{\vartheta t} = u_a + u_d$ $\frac{\vartheta y}{\vartheta t} = v_a + v_d$	u_a and v_a are the advective velocities in x and y directions determined by the SHYFEM hydrodynamic model; u_d and v_d are the diffusive velocity components in the x and y directions computed using a random walk technique	Spatial distribution of lagrangian particles position; particle trajectories; particle density	API-based	Emilia-Romagna Region; Kephalonia Island
AZA[4]	$SI_i = \sum_{j=1} w_j x_{ij}$	Suitability index of aquaculture – SI. Weight of the criterion j - w_j. Normalised criterion j in the i-th pixel	Spatial distribution of the aquaculture suitability index with superimposed constraints and sensitive areas Summary statistics and graphs	Direct	Default case study can be selected on a scenario-based mode
OIL SPILL[5]	$C = \sum_j w_j V_{ij} + w_B + w_D$ $OSR_i = \sum_1^{12}(C_i > 35)$ $V = E_v + H_v$	COMADEX Index - Weight of the criterion j - w_j. Criterion j for Vessel i - V_{ij}. Wind Beaufort value - W_B. Waves Douglas value - W_D. Oil Spill Risk (OSR) is the sum of COMADEX values over 35 by month for each pixel. Coastal vulnerability V is based on environmental vulnerability E_v and human vulnerability H_v.	Spatial distribution of coastal Vulnerability to oil spills and Monthly distribution of vessel oil spill risks from COMADEX Index	Preprocessed layers and maps	Adriatic-Ionian Region
SSF and MSF/CEA[6]	$FP_c = S_c \cdot A_c$	Fishing pressure (FP) index based on multi criteria analysis. coastal fishery suitability index (Sc) and the activity index (Ac)	Spatial distribution of fishing pressure, fishing suitability index and fishing activity	Direct	Kephalonia Island

1 & 2. Menegon et al. (2018b); Farella et al. (2021); 3. Ferrarin et al. (2019); Ribotti et al. (2019); 4. Brigolin et al. (2017); Porporato et al. (2020); 5. Lauro et al. (2015); 6. Kavadas et al. (2015).

4.2.3. MUC - maritime conflict analysis

The MUC is a geospatial instrument to identify sea areas where spatial conflicts occur between sea use pairs (e.g., commercial fishery vs. shipping). The methodology of the instrument was based on the COEXIST Project – Interaction in European coastal waters: A roadmap to sustainable integration of aquaculture and fisheries (COEXIST, 2013). The instrument was widely tested using the Tools4MSP Modelling Framework (Menegon et al., 2018c). For further details on the methodology applied in the Adriatic Sea and Northern Adriatic we refer to Menegon et al. (2018b) and Farella et al. (2021).

4.2.4. CEA - cumulative effects assessment

This module refers to the assessment and mapping of Cumulative Effects based on the Tools4MSP Modelling Framework (Menegon et al., 2018a). The module allows to assess the effects of single or multiple human activities on environmental components. The CEA was widely used across European Seas, namely Adriatic Sea (Farella et al., 2020, 2021), south-eastern Baltic Sea (Depellegrin et al., 2020) or North Sea (Gusatu et al., 2021). For further information on the methodological aspects we refer to Menegon et al. (2018a). Also section 4.2.7 exemplifies the application of the CEA module through the GAIR.

4.2.5. PARTRAC - module for particle/conservative contaminants dispersion

This module is a tool to evaluate the area of influence of a contaminant source. The tool simulates the dispersion of Lagrangian particles as a function of the hydrodynamic conditions simulated by the state of the art 3D SHYFEM oceanographic model (Bellafiore et al., 2018). The hydrodynamic field transporting the particles is calculated as multi-annual average by a finite element numerical model applied to the Adriatic Sea domain with higher resolution along the coast and including the main lagoons and rivers in the area (Ferrarin et al., 2019; Ribotti et al., 2019). This module allows to assess the dispersion of particles released in the Adriatic Sea. An advection-diffusion modelling tool for Lagrangian particles is proposed as a planning tool tuned to end-users and stakeholders. Its outputs and derived variables can be customised and analysed based on the end-user requests and can be used to evaluate events such as: impacts of aquaculture (larvae dispersion), tracking of floating debris and microplastic, point discharge and river plumes dispersion.

4.2.6. Aquaculture Zoning Assessment

The Aquaculture Zoning Assessment (AZA) module implements a spatially explicit multi-criteria methodology, namely SMCE (Spatial Multi-Criteria Evaluation) for identifying AZAs (Allocated Zones for Aquaculture - FAO, 2012), i.e., marine areas where the development of aquaculture is prior to other uses (Sanchez-Jerez et al., 2016). The SMCE applied for the AZA module can be carried out following the framework developed in Brigolin et al. (2017) throughout three steps: i) criteria normalisation; ii) weight assignment to each criterion; iii) suitability index calculation (Radiarta et al., 2008). All the criteria to run the AZA module, together with the weights and the constraints, are available for the users in the PORTODIMARE geoportal. For further details on the AZA module application we refer to Porporato et al. (2020).

4.2.7. OIL SPILL - Coastal Oil Spill Vulnerability Assessment

The module allows to represent, in the form of a dynamic map, the vulnerability to oil spills of environmental and socio-economic coastal resources of the AIR. The user can set the Map to the area of interest, activate one or more of the layers that summarise Oil Spill Risk and visually compare with the score for the coastal vulnerability in the area. Average values for the 2 components of vulnerability layers in the map are automatically calculated.

The instrument was originally developed as an Early Warning System within the HAZADR Project (Lauro et al., 2015), which aimed at strengthening the response capacity of the Adriatic Region against environmental and technological hazards due to collisions, shipwrecking and spillage of oil and toxic material into the sea that could seriously pollute the marine environment and damage the socio-economic activities of the sea and coastal communities.

The OIL SPILL is based on a combined index (COMADEX) composed by 5 different parameters regarding the ship dimension and conditions according to the annex 7 of the Paris MoU (vessel type, gross tonnage, year launched, flag and register), plus two values about the sea weather condition (Wind power by Beaufort scale and Waves height by Douglas scale) that can generate stress conditions on the ship structure.

The OIL SPILL was embedded into the GAIR as dynamic layers to explore the registered oil spill risk during 2019 and vulnerability across the Adriatic coastal areas. For further methodological details we refer to HAZADR 2015.

4.2.8. *SSF - module for Small Scale Fishery Footprint and MSF - module for Medium Scale Fishery Footprint and CEA - cumulative effects assessment*

These modules provide the tools for visualising fishing pressure for small and medium-scale coastal fisheries, and combine the multi-criteria decision analysis (MCDA) and geospatial techniques to quantify the synergistic effect of influential components (e.g., bathymetry, distance from the coast, Chl-a concentration, fishing effort, marine traffic activity, vessel capacity of ports, etc.) on defining fishing footprint. The modules were built within the fprmcda R-package by the Hellenic Centre for Marine Research (HCMR). For more information about the methodology associated with the fprmcda package, please see Kavadas et al. (2015). The CEA module integrates diverse pressures (e.g., SSF/MSF outputs, aquaculture, shipping, tourism infrastructures) to assess the

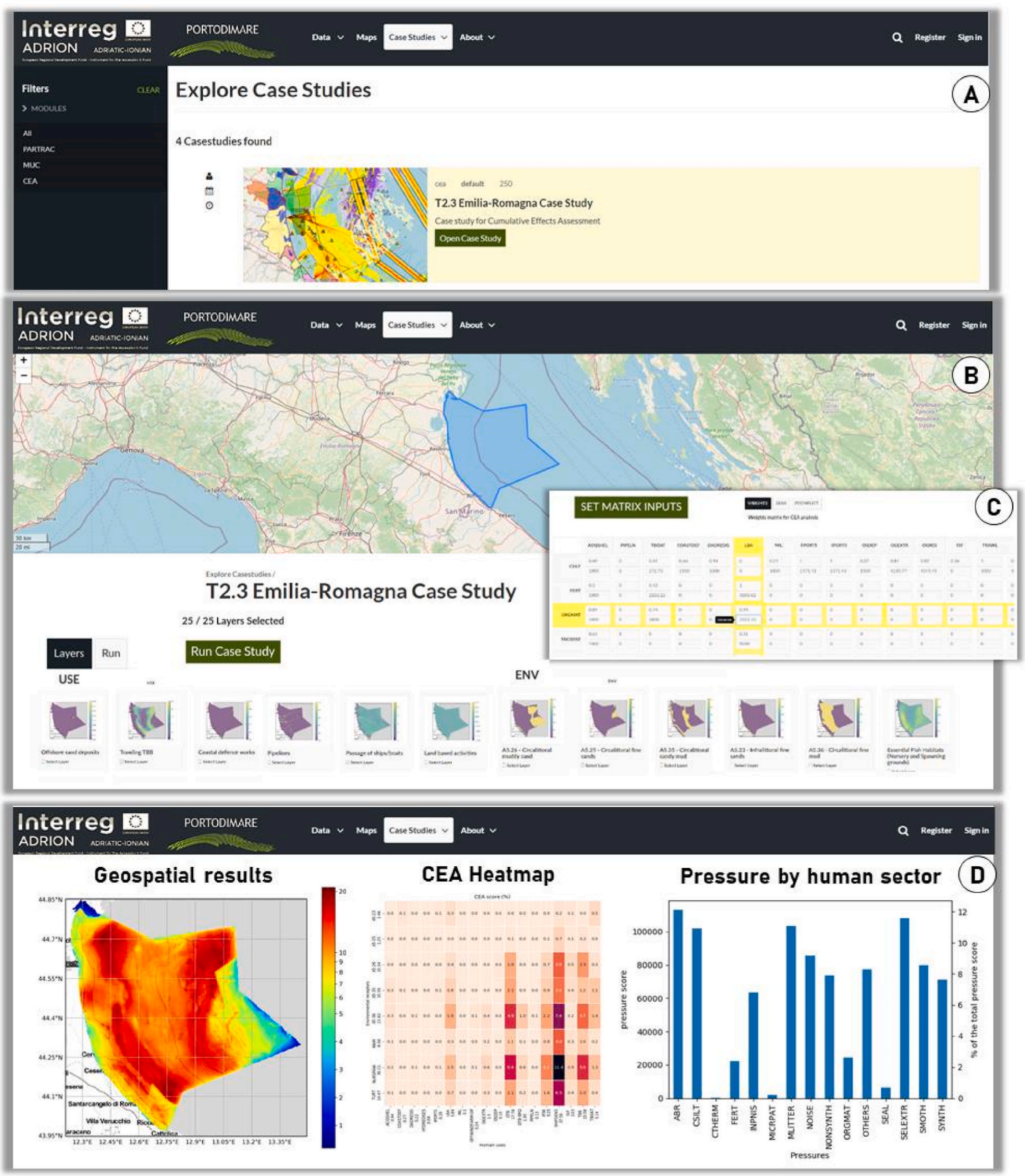

Fig. 6. Example of CEA model workflow implemented in the GAIR: A) Emilia-Romagna case study selection; B) model run setup in terms of selection of human uses and environmental components for model run definition; C) input matrix set up, in terms of sensitivity scores, pressure weights or pressure propagation distances and D) model run with geospatial and statistical outputs (geospatial results, CEA heatmap and pressure contribution by human uses).

spatial distribution of impacts exerted by these pressures on the selected ecosystem components.

4.2.9. Case study: CEA module workflow for Emilia-Romagna Regions

A typical user-driven module workflow for the use of the CEA is presented in Fig. 6. The aim of the case study is to perform this assessment by testing future aquaculture scenarios (expansion of 100 sq. km of new shellfish farms) in the Emilia-Romagna Region.

After the selection of the CEA module, the user can choose among the available case studies for each tool. A case study is a coherent and harmonised set of geospatial layers available at different spatial scales (AIR, national, regional, local, testing site or case study levels; see Table 1) and resolutions that can be used for module running (Menegon et al., 2018b). In the case study selection (Fig. 6A) we select the Emilia-Romagna Region (5260 sq. km) located in the Northern Adriatic Sea. The input parameter setup includes the selection of the geospatial features of the case study area (Fig. 6B). This includes the grid resolution layer (42080 grid cells; layer resolution 250 m × 250 m) that defines the spatial resolution of the input layers; the human activities (U; n = 16) relevant in the study area (e.g., shipping, fishery, military areas) and the environmental features (E; n = 8; e.g. marine habitats, turtles, marine mammals). The units of the spatial indicators U and E can be presence/absence (e.g., military areas), weighted dummy (e.g., land-based activities), and intensity indicators (e.g., maritime traffic). In addition, a shellfish aquaculture scenario was performed with the AZA module (see Annex 14; Perini et al., 2020b for detailed description) and incorporated in the CEA module considering a uniform distribution on areas with a high aquaculture suitability score (suitability ≥ 0.75).

Intensity indicators were transformed using log [x + 1] to avoid an over-dominance of extreme values and all datasets were rescaled from 0 to 1 in order to allow direct comparison on a single and unitless scale. Based on the selected layers, the user can compile a matrix of sensitivity scores based on 15 pressures adapted from the MSFD Annex III (2017/845/EU), pressure weights and propagation distance (Fig. 6C). The pressure weights are scored from 0 to 1 and are a measure of importance of a certain use in contributing to a specific pressure, while the distance refers to the area of influence of the pressure (in km). Sensitivity scores can have values between 0 (not sensitive) and 1 (highly sensitive) and correspond to the susceptibility of the environmental component to the pressure exerted by a human activity (Menegon et al., 2018a). The outputs of the model are presented in Fig. 6D, which includes geospatial results of CEA distribution, heatmaps representing CEA score for each human use and environmental component, and a bar-plot representing the aggregated value of pressures by human use for the study area. The server response time was approximately 5s, considering the full case study analysis (42080 grid cells, 25 geospatial layers, 15 pressures combinations), and a server having minimum hardware requirements of 16 GB and 2.2 GHz processor with 4 cores. For further details on the module setup and data components we refer to Perini et al. (2020a).

The geospatial explicit results show that the highest CEA scores (20) are located in offshore areas (approximately 20 NM offshore) in the north and in the south of the study area. In coastal areas, high CEA scores are located in the whole case study area between 3 and 12 NM offshore, in proximity to the Ravenna port. Areas showing medium-high scores (7–14) are largely distributed along the entire case study area, mainly due to maritime traffic and trawling activities. In the area, the complex system of marine transportation is the most influential source of anthropogenic pressures, such as the introduction of non-indigenous species, marine litter, underwater noise and polluting substances, and is impacting mainly Essential Fish Habitats (EFH), circalittoral fine mud (EUNIS Code A5.36) and marine turtles and mammals. The full set of trawling activities reaches a total CEA score higher than the one generated by maritime transport: bottom otter trawlers, mid-water pelagic and "rapido" beam trawlers impact the area mainly by generating abrasion, change in siltation, smothering and both selective and non-selective extraction of species. Land-based activities' pressures (e.g., microbial pathogens, marine litter, and introduction of organic and inorganic substances), strongly related to riverine inputs (e.g., Po River Delta in the north), have a significant influence on the overall CEA score. Coastal and maritime tourism influences the coastal water only within the 2 NM, being the source of a wide set of pressures (e.g., marine litter, underwater noise, introduction of both organic and synthetic components).

The contribution to total CEA of new shellfish farms (future aquaculture scenarios) is significant primarily at the local scale and, for some areas (e.g., between 3 and 6 NM in front of Riccione), the possible expansion of aquaculture may result in an overall decrease of the CEA score because the presence of higher impact activities (eg., non-compatible uses such as trawling) must be reduced or eliminated.

Another result of the module run is the CEA heatmap (Fig. 6D, centred) that calculates the CEA scores by pairwise percentage contribution by environmental receptor - human activity, respectively. Marine litter and pressures related to trawling fisheries (mainly seafloor abrasion, changes in siltation and extraction of species) are the pressures determining the highest contribution to the CEA score. The most affected environmental components are the species of high conservation interest (especially marine turtles), EFHs, and sandy-muddy seabeds (mainly circalittoral fine muds). The bar-plot in Fig. 6D (right) quantifies the contribution of each pressure to the total CEA score. Selective extraction, abrasion and marine litter are the human uses generating the highest pressure, with 12% and 11% respectively.

5. Discussion

5.1. Relevance of the GAIR for the Adriatic-Ionian Region

The GAIR supports all the four pillars of the European Union Strategy for the Adriatic and Ionian Region. Pillar 1 on Blue Growth, Pillar 2 on Transport and Energy, Pillar 3 on Environmental Quality, Pillar 4 on Sustainable Tourism.

The geoportal allows ecosystem-based investigation of the ecological resources of the AIR and analyses how current coastal and maritime activities may trigger adverse effects on the marine environmental status, which is one of the priorities of EUSAIR Pillar 3. This is ensured by the Cumulative Effects Assessment tool, which is widely used for ecosystem-based management of the marine environment across the globe (Clarke Murray et al., 2015; Griffiths et al., 2020; Hammar et al., 2020), and which is implemented in the geoportal through the Tools4MSP Application Programming Environment (API; Menegon et al., 2018a). Decision-makers and planners can use the tool to define planning strategies aimed at mitigating the anthropogenic impacts coming from multiple stressors, such as underwater noise, marine litter and abrasion.

The geoportal can substantially contribute also to EUSAIR Pillar 1 Blue Growth (European Commission, 2014). The geoportal implements a set of sectoral tools such as the Aquaculture Zoning Assessment (AZA) module, which enables the analysis of mussel aquaculture siting. In line with global trends, also in the Mediterranean 62% of fish food will be produced by aquaculture in 2030 (World Bank, 2013) and therefore the need for instruments that can support planners in the identification of the most suitable areas for this activity by balancing the demands for ecological protection with socio-economic needs will be required.

The MSP Directive (2014/89/EU) requires coastal EU member states to establish Maritime Spatial Plans by 2021. The geoportal provides a full suite of data and tools that can support the national MSP in AIR countries in a transboundary cooperation framework, according to art.11 and art.12 of the MSP Directive. In particular, the geoportal provides a set of tools to organise the sea uses, reduce conflicts and investigate environmental-human interactions to promote a sustainable development of coastal economies.

The Emilia-Romagna Region proposal within the Italian MSP process (Presidente della Repubblica, 2016) for the Adriatic Sea has been strongly supported by CEA results within the GAIR workflow (Perini et al., 2020b; resolution of the Emilia-Romagna Regional Council n. 277 of 01/03/2021). The regional focus given to the CEA analysis highlights the potential threats to species, habitats and ecosystems generated by multi-sector human activities in the regional coastal and marine space in order to inform the planning process on the present propagation of pressures and to assess the spatial distribution of impacts on one or multiple environmental receptors. Through the GAIR, the CEA operational tool has been made accessible through a graphical user-friendly interface available also for a wider non-technical audience, such as decision-makers, practitioners, Blue Economy sectors and civil society. The proposed CEA methodology and analysis for the Emilia-Romagna Region constituted a fundamental knowledge base for the regional MSP Pilot Plan, one of the earliest MSP pilot plans of the Italian sea space (Barbanti et al., 2018), which lead to the definition of management measures, in accordance with the areas of major impact and identifying the typology of sea uses responsible for those impacts. For further details on the pilot plan and its planning measures we refer to Barbanti et al. (2018) and Farella et al. (2020).

5.2. Limitations and future developments of the GAIR

The GAIR presents a series of limitations that can be the object of future development and improvement. User interaction needs to be improved (e.g., by enhancing the presentation of textual and graphical contents within the modules' pages, simplifying the management of all input parameters, allowing case studies to be created from scratch) and especially the GeoData Builder that is used for the creation of new input layers and to effectively connect the geospatial modules (i.e., incorporating the output of a module as an input of another module). The mechanism of data synchronisation (Data sync) between the MSPKC and the GAIR needs to be more robust through specific validators for uploaded or referenced user datasets. This could be ideally tackled by using error handling protocols.

As presented in the Emilia-Romagna case study, the modules were designed to be mutually integrated (mainly adopting a common grid-based approach for geospatial analysis and thorough systematic usage of the GeoDataBuilder), but this integration is not fully automated, because users still have to download the output of the previous module and manually upload it as new layer into the geoportal. Only after that, can the layer be used, for example, as a new input for CEA.

The performance of modules requires further improvement in terms of reduction of computational time. This is especially the case for computationally intensive modules such as PARTRAC for particle dispersion modelling. The GAIR is currently lacking a logical structure for defining the relevant layers to be used into the different modules; in the future, a fuzzy matching procedure will be tested to ease the identification of relevant layers to be used in the reference module and case study. The modules would benefit from asynchronous module runs to ensure more efficient user interactions and optimise the model run time. The modular architecture of the GAIR will easily allow adding other modules by using the API technology and sharing the same input data model.

At the current stage the software of the GAIR has a long term development perspective through ongoing and future international and national research projects such as ReMAP (Reviewing and Evaluating the Monitoring and Assessment of Maritime Spatial Planning, EMFAF, 2022–2025), MSP4BIO (Improved Science-Based Maritime Spatial Planning to Safeguard and Restore Biodiversity in a coherent European MPA network, H2020, 2022–2025) and the MSP4BIODIVERSITY (Biodiversity mainstreaming in Maritime Spatial Planning, Next Generation EU to establish the National Biodiversity Future Center, 2023–2025).

The project initiatives will further support the technological development of the GAIR through extension of tools, incorporation of new datasets, application in study areas outside the AIR (e.g., Western Mediterranean and Black Sea) and bug fixing.

6. Conclusions

The GAIR showcases to be a versatile instrument to support the development and implementation of the planning and management strategies in the AIR at regional, national and transboundary level. Indeed, its open and easy to use nature allows different users, also non-technical experts, to access and operatively exploit the provided services and the available data, thus making the GAIR a useful tool for public administrations, scientific and research bodies, as well as the civil society, and facilitates the engagement of data producers.

Being conceived and developed by a transnational network of research institutes and public administrative bodies, the GAIR possesses a shared and transnational character thus representing a collector of data and information coming from different sources and levels, from the scientific community research and monitoring activities to the public administrations repositories and is linked to different available thematic portals. This characteristic is of high relevance since it ensures a populated data portal thanks to data sharing practices at transnational level set up in the framework of the SUPREME and PORTODIMARE projects. The Geoportal becomes an instrument able to favour a knowledge building process by engaging multiple stakeholders and strengthening the science-policy dialogue.

Furthermore, the GAIR is expected to be a regularly maintained and validated source of knowledge and data for MSP, with data systematically controlled, filtered and harmonised to ensure reliable and useable products. The MSPKC provides mechanisms to engage the data providers who can collaborate in the inventorying, screening and prioritisation of data sources that compose the knowledge base of the GAIR and the analysis in the available case studies.

The GAIR provides a set of tools and services that can be used in an MSP context. The tools are already fed by a variety of spatial data in an effective and shared environment, where these services and the derived products can be integrated between each other to provide information relevant for the management. Both sectoral and multi-sectoral issues can be addressed thanks to the potential of adopting an integrated holistic approach, where one module can provide information useful to feed the application of a second module (e.g., AZA, PARTRAC, SSF towards CEA and MUC). As such, the modules offered by the GAIR can be customised and applied to satisfy the information needs and management issues depending on the context.

While the GAIR was developed to serve MSP in the AIR, the application of its modules is flexible for other geographic regions and scalable at different resolutions (local to sea basin level). For example, the CEA module has been tested in the North Sea (Gusatu et al., 2021) in the context of offshore wind energy scenarios for 2050, in the Lithuanian Baltic Sea (Depellegrin et al., 2020), in the context of marine ecosystem services threat analysis, as well as for transboundary CEA in the Strait of Sicily-Malta (Farella et al., 2019). Also the MUC module was applied outside the AIR, in an MSP-data stocktake in Bangladesh (Roy et al., 2022) for the identification of conflicts with nature protection, and in the Strait of Sicily-Malta (Farella et al., 2019), and the PATRAC module based on the SHYFEM Hydrodynamic Model was applied in the Mediterranean sea basin and Danube Delta (Black Sea; SHYFEM, 2022) (SHYFEM Development Team, 2022). The key advantage in these applications is the Case Study-driven approach that can be applied with adequate data to any geographic area of the globe. In addition, the GAIR, as an open-source platform for multi-user knowledge co-production, can be easily reused to support the development of maritime spatial plans from sub-national to transboundary marine waters in the European Seas and beyond.

Beyond the provisioning of spatial and quantitative data, the GAIR also provides information on the main existing strategies and legislative instruments that act at the AIR basin scale and allows the countries to be informed on the state of implementation of the management and spatial plans and the adopted approaches of their neighbours. Thus, the GAIR acquires an added value since it acts as a communication and sharing platform among the AIR countries, supporting the transnational coordination that is required by the MSP directive because it is recognized as a fundamental enabling factor for the achievement of an effective and sustainable use of marine and coastal resources. Indeed, the Geoportal ensures the transfer, the implementation and re-use of the outputs obtained by applying the provided modules.

Software availability

Name of software and products: Geoportal of the Adriatic-Ionian Region (GAIR) - PORTODIMARE GeoNode project.

Designers: National Research Council of Italy, Institute of Marine Sciences CNR-ISMAR (Venice).

Developers: Emilia-Romagna Region, Directorate General for Territory and Environment Protection. (Bologna); National Research Council of Italy, Institute of Marine Sciences CNR-ISMAR (Venice).

Maintenance: Emilia-Romagna Region, department, Directorate General for Territory and Environment Protection; National Research Council of Italy, Institute of Marine Sciences CNR-ISMAR (Venice).

Year first available: 2020.

Hardware required (web server): 16 GB or more; 2.2 GHz processor with 4 cores. (Additional processing power may be required for multiple concurrent styling renderings); a baseline of 50 GB–100 GB for production deployment. Additional disk space could be necessary according to specific needs, especially in relation with the number and size of spatial data. 64-bit hardware is strongly recommended. (see the GeoNode Quick Installation Guide (2021) for additional information).

Software required (web server): GeoNode 2.10, R-Server; Docker Engine and Docker Compose (optionally).

Software required (client/users): All modern internet browsers (e.g. Google Chrome, Mozilla Firefox, Microsoft Edge, Apple Safari) including mobile versions.

Software availability: GAIR: https://github.com/RegioneER/portodimare-gair.

Data availability:GAIR: https://www.portodimare.eu/

Software licence: GNU AGPL v3.0.

User documentation: https://www.portodimare.eu/static/docs/

Program language: Python (backend); JavaScript/React/Redux (frontend).

Program size: 100 MB.

Implementation: Official implementation for supporting Maritime Spatial Planning into the Adriatic-Ionian Region has been released within the Interreg ADRION - PORTODIMARE project (https://www.portodimare.eu/).

Declaration of competing interest

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

Data availability

All the data and metadata mentioned in the research are available at the following link: https://www.portodimare.eu/

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2022.105585.

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