Integrated SDSS for Environmental Risk Analysis in Sustainable Coastal Area Planning

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Abstract. The work deals with the development and implementation of a Spatial Decision Support System (SDSS) platform for coastal environmental risk analysis through the integration of multisource satellite data (Sentinel-1 and 2 and COSMOSkyMed) coupled with open source coastal hydrodynamic model addressed to flooding, erosion and pollution. The processing results allow us to cope with longshore pollutant dynamics connected to bathing use, to derive the shoreline changes and back-dune vegetation mapping, rocky coast movements detection as well as coastal area changes derived through advanced images segmentation techniques, multi-band change-detection and Persistent Scattered Interferometric Synthetic Aperture Radar technologies (PSInSAR). The SDSS provides cyclical production and updating in phase with satellite data acquisition frequency of the coastal scenarios for flooding risk analysis. All of these issues well enable operative products to be employed in the knowledge chain for sustainable coastal area planning activities. Moreover, self-consistent applicative tools, provided with proper graphical interface developed in IDL and integrated in SDSS, lead displaying and automatic extraction of the coastline sequence from Sentinel-1 data. Thus the comparison of two or more shorelines, even if multi-sources, provides the computation of coastal erosion and aggradation as well as the areas prone to coastal flooding. Finally, some interoperable tools for morpho-hydrodynamic modelling assimilation have been developed and implemented to reproduce flooding and pollution risk scenarios as well as coastal resilience assessment at different return time.

Keywords: SDSS · SAR · Change-detection · Coastal risk
Hydrodynamic modelling

1 Introduction

The increasing of coastal population density and the progressive growth of economic and touristic pressures, related to the exploitation and over-exploitation of marine and coastal resources, are some of the issues threatening the delicate natural framework of

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sea-side areas and in-shore coasts as well as the objective issues related to the management of coastal risks mainly concerning natural hazards and human activities.

In Basilicata (Southern Italy), with about 75 km of littoral (rocky and cliffs, sandy and stony), the coastal system is a precious and fragile resource of highly natural and landscaping significance to be protected and promoted through an economic and social natural-friendly development.

Coastal erosion occurs over the years mainly induced by drastic reduction of river sediment supply due to relevant and distributed interventions both all over the basins and along rivers [1–3] as well as increasing human pressure due to touristic and productive settlements [4]. The real spreading of such a phenomena have sensitively augmented public awareness to the opportunity to allocate resources for structural and not structural interventions addressed to risk prevention rather than emergency management. Such a smart governance approach might be based on an all-embracing and systematic analysis of coastal area vulnerability and resilience to identify appropriate mitigation and contrast measures and structural priorities to cope with sea aggression and seriously compromising the Lucanian coast [5]. In such a sensitive and vulnerable context appropriate resources to improve and implement conventional and innovative monitoring systems as well as modelling procedures able to continuously support management activities must be employed.

The paper proposes the results of the operative projects MATER and COMUINMARE addressed to the development of a general methodology of environmental and territorial analysis for the exploitation of natural resources. That is, the first operational results in terms of definition and implementation of a Spatial Decision Support System for hydraulic and environmental coastal risk forecast and prevention [6] are proposed. The main frame deals with the integration and use of ground and remote earth observation data, with particular reference to new satellite missions, such as Sentinel-1 and 2 [7, 8] as well as COSMOSkyMed. That is, among the operative products, the project shapes the structuring and implementation of an expandable SDSS based on open-data catalogues, enabling management and displaying of both basic information, including the relative metadata, and post-processing results obtained through open-source change-detecting codes and hydro-morphological modelling. The SDSS allows the development of integrative methodologies for systematic coastal monitoring and might be interfaced in an open source WebGIS environment dialoguing with the Regional Spatial Data Infrastructure. The SDSS provides the integration of ground and remotely sensed data with Open Source Information technologies for advanced analyses and web publishing geo-data for providing a simple and intuitive end-user consultation. The interoperability WMS (Web Map Service) standards, by the OGC (Open Geospatial Consortium) based on PSInSAR and Change Detection methodologies are used for geo-data analyses [9].

Finally, data processing validation for the developed procedures has been provided comparing the products to the ground data acquired by aerial surveys, carried on with a multi-sensor platform such as metric camera, thermal camera, hyperspectral systems and Laser. Such validated information are data input of morpho-hydrodynamic and pollutant dynamics numerical models in order to create several critical risk scenarios for coastal areas.

2 GIS and Spatial DSS Implementation

Decision Support Systems (DSS) are a specific class of computerized information tools and systems, which allow decision-making activities.

In general, DSS are interactive computer-based systems and subsystems proposed to help decision makers on communication technologies, data, documents, knowledge and/or models to identify and solve problems and make choices [10]. They should assist in formulating alternatives, accessing data, running numerical and/or conceptual assessment models, displaying and interpreting results [11].

A wide range of spatially distributed information on characteristic coastal areas, such as shoreline, beach morphology, land use/cover, topography, etc., are available enabling the Spatial Decision Support Systems (SDSS).

In such a view, the Geographic Information System (GIS) is generator for SDSS due to its high performing functions to store, retrieve, analyze, manipulate as well as display large volumes of spatial digital data and create thematic maps or logical frameworks.

The analysis of functional and architectural system requirements, supported by the research and identification of the reference solutions within the engineering software led to the design of a scalable and modular architecture.

The architecture modelling of the proposed system, highlighting its modularity through the robustness of software components and internal and external interfaces of the system identified, like SERVER FTP, CATALOGER, WEBGIS and DSS.

In a general view, the SDSS are new web-based software systems providing a series of functions of data and model analyses enabled in an simple interactive and expeditive way, increasing the efficiency and robustness of the decision-making through the creation of real-time or near-real-time alternative scenarios in the time-space domain [12, 13]. Comparing both systems, traditional computer based SDSS and web-based SDSS, the last ones present several advantages [11–19], such as:

- global, quick and user-friendly accessibility;
- high efficiency in real-time for model improvement and data update;
- independent platform compliant to virtual machine;
- centralized control coping with lower costs for hardware, software, distribution, maintenance and training.

These issues facilitate a wide community of stakeholders to access and participate in the public planning and decision-making processes, which can fruitfully impact the quality of their work even improving public awareness of the existence of spatial digital data and scientific models. In such a framework, a DSS evolution is made up of SDSS having the added value of the explicit consideration of the spatial dimension of decision-making problems which are intrinsic features to take into account in territorial system management and transformation. Thus, the proposed GIS-DSS platform is set up as a SDSS and deliberately implemented on the basis of open-source solutions extending its functionality.

Therefore, previous study and analysis of the state-of-the-art of available open-source solutions in GIS environment have been carried on addressing QGIS.

QGIS is an open-source system released under GNU General Public License and it is an official project of the Open Source Geospatial Foundation (OSGeo). The software is available for Linux, Unix, Mac OSX, Windows and Android platforms and supports several formats of spatial data. Furthermore, it allows us to process on spatial databases offering vector analysis tools, geoprocessing and database management. Finally, it is possible to adapt QGIS to specific needs due to the extensible architecture of plug-ins that can be created through specific libraries.

The SDSS module has been developed in Python (ver. 2.7) and set up as plug-in of QGIS (ver. 2.10 Pisa) on OS Windows 7 pro 64 bit.

3 Data Layers, Tools and Plug-in

The proposed QGIS project has been implemented with several informative layers, namely of new acquisition and so updatable by the user, and such implemented information layers are related to the multisource data as reported in Table 1.

Table 1. Currently implemented information layers

Information layers	Contents
Framework	All the information layers are raster type, except those of satellite data, and complain with official formats of the cartography released by the Military Geographical Institute (IGM)
Bathymetry	Archive data relative to the bathymetric campaigns in 2012 and 2015
Cartography	Historical data in raster format of the official IGM cartography at 25.000 edition 1949
DTM	Digital terrain models in raster format derived from aerial Lidar scans of archive and new acquisition refer to 2006, 2008, 2011, 2012, 2013 and 2015, all of them have been pre-loaded
Shoreline	Shoreline, in vector format produced by multisource data, both of archive and new acquisition. In particular, they have been extracted according to data availability in the following order of priority: laser data, digital orthophoto and historical cartography and relative to 1947, 1949, 1988, 2001, 2005, 2006, 2008, 2011, 2012, 2013, 2015
Orthophoto	Information layers refer to historical and of archive orthophotos, B/W and coloured ones, obtained with analogue technologies and orthophotos of latest production obtained with high-resolution digital cameras. The pre-loaded layers are relative to 1947, 1998, 2001, 2006, 2008, 2011, 2012, 2013 and 2015
Thermography	Aerial survey across the coastal strip performed with digital thermal camera
Satellite images	Sample catalogue containing some satellite images and related shorelines extracted from the same data. Radar Sentinel 1 and Optical Sentinel 2 data have been inserted. On the satellite data no cropping operation were performed but they have been included in the full coverage of the scanned images
Topographic survey	Ground survey 2015 available in the form of row measured points and coastline derived from the acquired points
Lidar data	Laser data of archive and new campaigns are available, after a careful clipping work and geographic homogenization

The system is able to process data through specific tools designated for such a purpose. That is, the Lidar Data were not directly pre-loaded into the system, because QGIS does not allow direct displaying in the native format and so, within the project, an ad hoc plug-in has been designated. The plug-in, named LAStoDEMCompare, manages the work-flow that, from the data in Lidar format, led to create the DEM in Raster format as well as the management and query of the extracted data.

3.1 Management of Geographic Datum

As one of the GIS system features is the management of information layers in different coordinate systems. The project enforces the management and processing procedure of the coordinates in QGIS environment in order to ensure the download and management of available, namely future, multisource data as specifically as possible.

The management of geographic datum in QGIS environment is entrusted to an "*on-the-fly*" testing algorithm (OTF) which automatically manages the datum conversions and geographic projections among information layers in different coordinate systems adopting some specific libraries produced and distributed by OSGeo.

These libraries contain, for almost all the reference systems, global and local, the geodetic parameters such as projection, ellipsoid, false origins and scale factors, etc., useful for the automatic re-screening of the associated geographic data.

This enhances the user to use geographic information coherently to several reference systems.

However, the precision on which data are re-developed, and thus overlapped, depends on the source data accuracy, moving from rigorous transformations for the most widespread global systems to approximate transformations for some local systems.

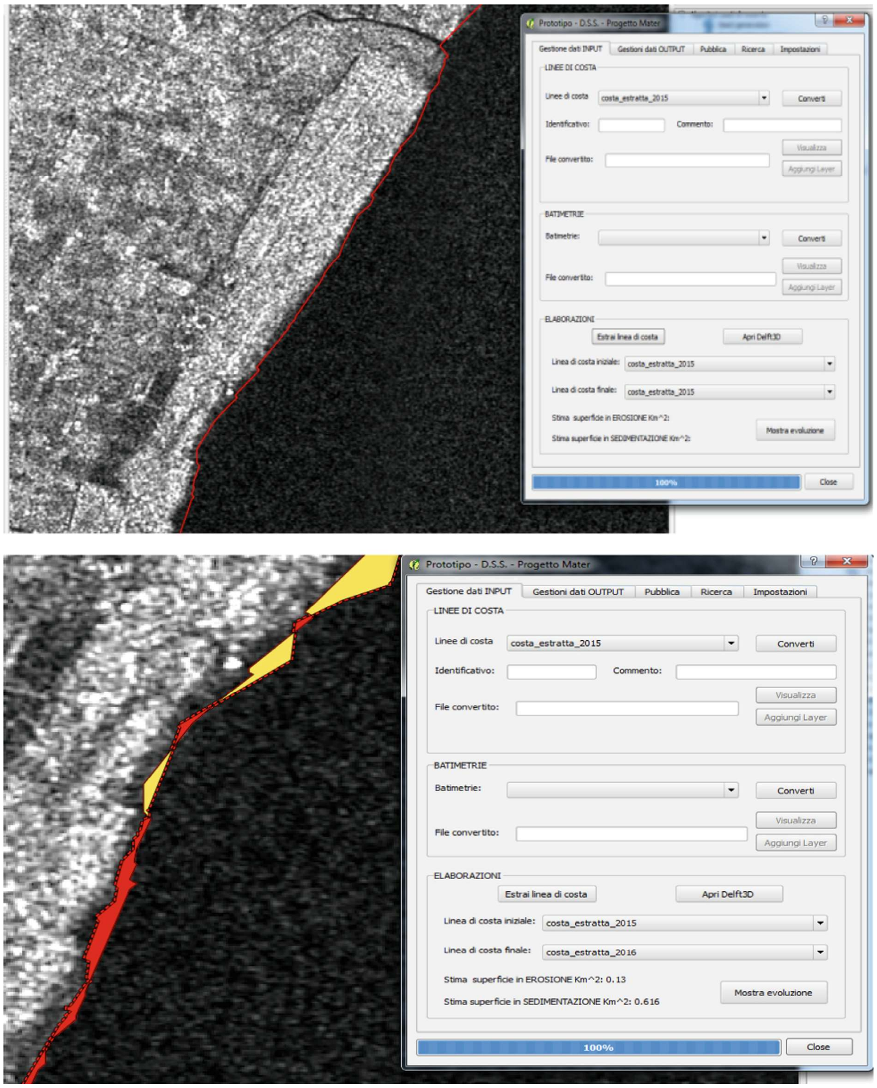
Considering that the most common systems in Italy are the Gauss-Boaga and ETRF89/ETRF2000 projections/ETRF2000, several GIS software including QGIS use simplified algorithms based on 7-parameters-Helmert transformation, and provide approximate transformation values with several meters of error according to altimetry.

Therefore, a new library has been published by recalculating these parameters in order to improve the precision of transformations at a regional level. The application of recalculated parameters on a sample of transformed points has led to average deviations in position of about 30 cm on the converted points referring to the grids of the Military Geographical Institute.

3.2 Self-extraction of the Coastline

The processing results include the coastline mapping, the back-dune vegetation mapping, the detection of rocky coast movements as well as new landfills, new buildings and spills. They have been produced by applying innovative images segmentation techniques, multi-band change-detection and PSInSAR (Persistent Scattered Interferometric Synthetic Aperture Radar) typologies, having the significant advantage of cyclical production and/or update with the same acquisition frequency of satellite data.

Through self-consistent applicative tools, provided with proper graphical interface developed in IDL and integrated in SDSS, and appropriate change-detection techniques, it is possible to display and automatically extract the coastline from Sentinel-1 data. Moreover, the system is able to compare two acquisitions, also multi-sources, e.g. by highlighting and calculating the eroding areas and those progressively emerged on the beach as shown in Figs. 1 and 2. The plots report the multi-source coastlines relative to the acquisitions in 1947-1949-1998-2001-2005-2006-2008-2011-2012-2013 and 2015 referring to the 2015 orthophoto base.



A

B

Fig. 1. Coastline extraction from Sentinel-1 data (A); Comparison between two available dataset (B).

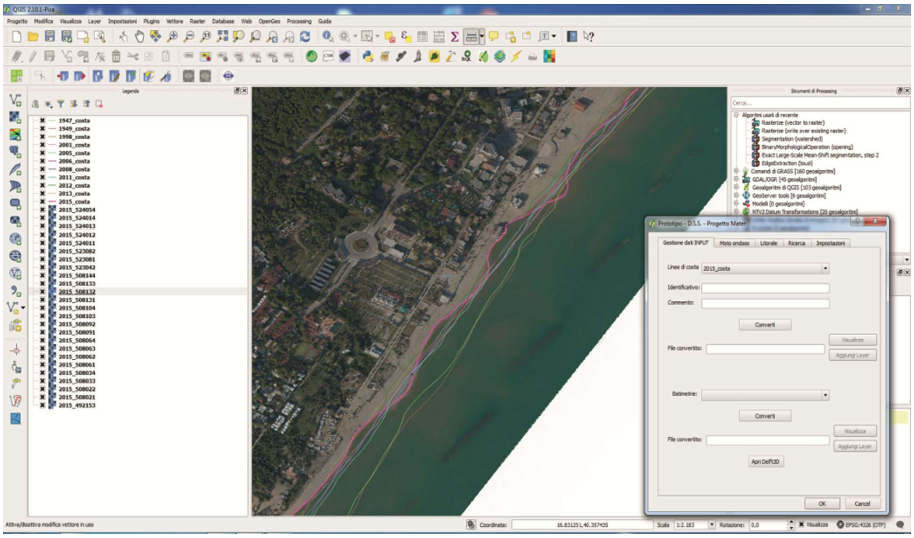


Fig. 2. Graphic comparison between two multi-source coastlines on orthophoto basis.

3.3 Morpho-Hydrodynamic and Water Bathing Quality Modelling

In order to reproduce possible alternative scenarios, to simulate the coastal system response at different natural and anthropic stresses, as well as to provide a valuable qualitative-quantitative support for decision-making, some tools able to make the SDSS interoperable by a morpho-hydrodynamic modelling software have been developed and implemented. For such a purpose, in the start-up phase, Delft3D (Deltares- NL) [20] was employed.

The Delft3D software (http://oss.deltares.nl/web/opendelft3d/home), produced and distributed by the Research Institute Deltares (NL), is available both in pre-compiled mode and open source, and is based on consolidated calculation algorithms resulting primarily from activities carried out by the Environmental Fluid Mechanics Section of the Faculty of Civil Engineering and Geosciences at Delft University of Technology (TUDelft-NL). The system is mainly composed of three modules grouping hydrodynamic simulation models, morphological and wave motion models as well as pre- and post-processing tools. The module relative to wave energy (Delft3d-WAVE) uses the SWAN (Simulating WAves Nearshore) [21] as a core processing code. This represents the state-of-the-art of so-called third-generation phase-averaged models, able to simulate, in steady or unsteady conditions the following issues:

– time-space propagation of wave motion
– shoaling and refraction for bathymetric variation and induced by currents
– wave generation, even considering the non-linear effects due to the overlapping of waves of different height and period
– energy dissipation due to the interaction between waves and seabed
– wave breaking and vegetation
– diffraction and reflection phenomena.

If necessary, the algorithm is able to process "*nesting*" operations, or may use different computing grids in a single run, nested one against another with a rising level definition. Such a frame results particularly useful whenever modelling of localized phenomena whenever detailed scales are required with a high computational outlay.

The hydrodynamic module, Delft3D-FLOW, is a multi-dimensional program based on Navier-Stokes equations for an incompressible fluid, under the Boussinesq assumptions for shallow water. It calculates steady or unsteady flows and transport phenomena, resulting from tidal and/or weather forcing, on a rectilinear and uniform or curvilinear grid.

The hydrodynamic module is able to simulate, with a highly accurate and defined unconditionally stable procedure, both in 2DH and 3D modes, even with diffusion and transport phenomena, taking into account the time variation of physical characteristics of the fluid. Furthermore, it is coupled to the transport module which allow us to identify the sediment transport induced by coastal currents, in time and space domains. Figure 3 shows the simulated effects in terms of bathymetric evolution of the Basento River delta due to a storm surge which event occurred in January 2015, while in Figs. 4 and 5 the average wave propagation direction and average bottom velocity distribution are reported respectively.

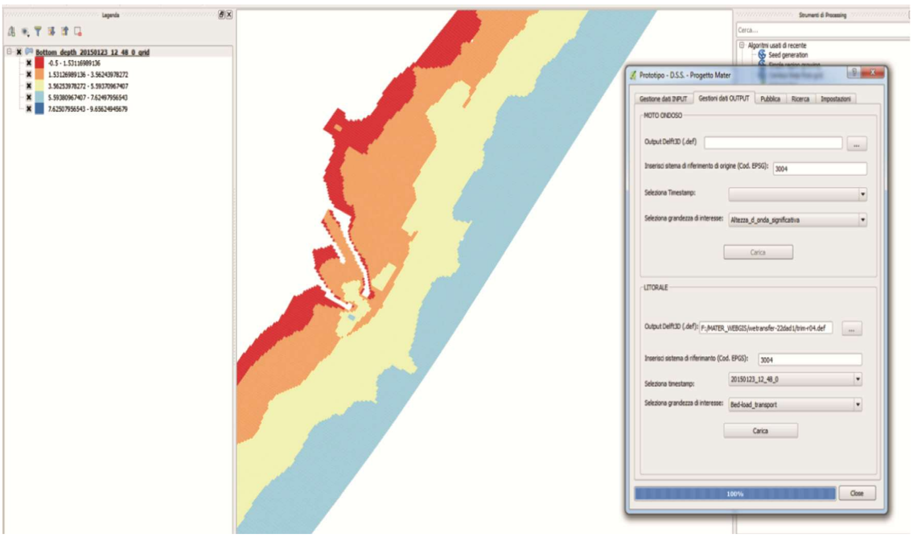


Fig. 3. Time representation of bathymetry.

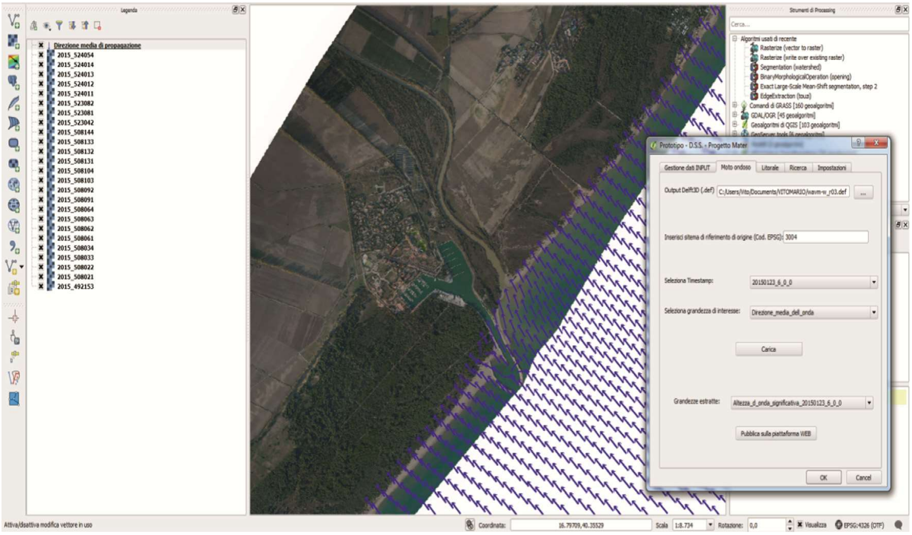


Fig. 4. Time representation of the average direction of wave propagation.

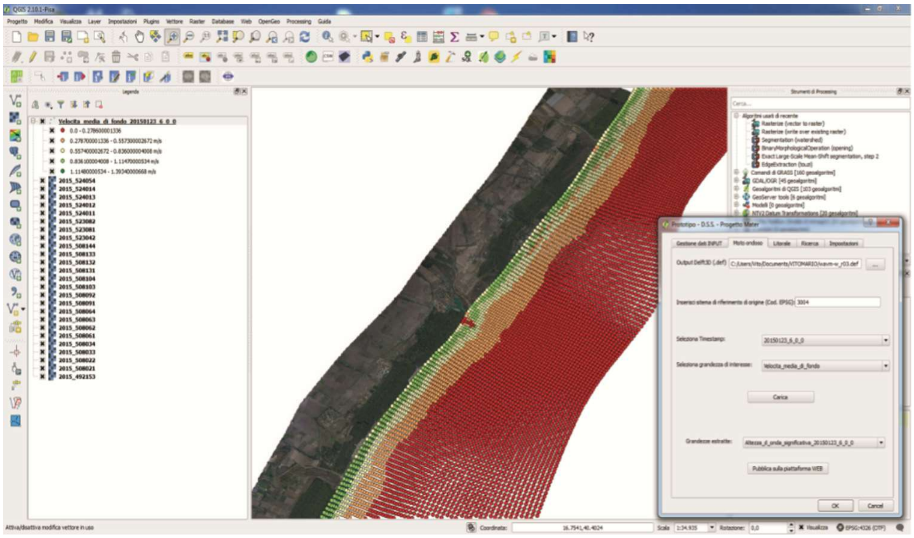


Fig. 5. Time representation of the average bottom velocity.

The main architecture of the implemented system switches on the SDSS to communicate with Delft3D code, both in terms of input for numerical computation and collecting the corresponding output for further analysis in QGIS environment. Indeed, the coastline can automatically be extracted and forwarded to pre- and post-processing data tools available in the Delft3D package. Although, the Delft3D code has a structured and complex output format which cannot be directly managed by QGIS, the developed and implemented set-up tool working in the SDSS allows us the extraction, displaying and multi-time management of the Delft3D output data. In reference to the sea wave propagation, the SDSS deals with significant wave height, significant period, average direction of wave motion and bottom velocity, as well as some data related to the coastal processes such as bottom sediment transport, suspended sediment transport, height averaged velocity, bottom shear stress and bathymetry variation in the time domain due to erosion and deposition.

Further, an integration between the Operative Project MATER and a coastal bathing water quality study, titled COMUNINMARE, has been proposed in terms of numerical simulation of spatial bathing water quality evolution due to the river discharge flowing in the delta area. The analyses have been carried on referring to the observed data measured along the coast during the ordinary water quality monitoring campaign performed by the research group during the bathing season 2017 (April–September 2017).

The Delft3d-Flow-Wave–D-Waq coupled model has been applied and the results have been assimilated into the SDSS giving detailed and suitable information about the area interested by the pollutant dynamics. More in details, both parameters Escherichia Coli and Enterococci have been monitored and simulated in order to obtain the space pollutant propagation in delta area. Figures 6 and 7 report the computation mesh and the space E.C. pollutant propagation in the area of delta Basento river.

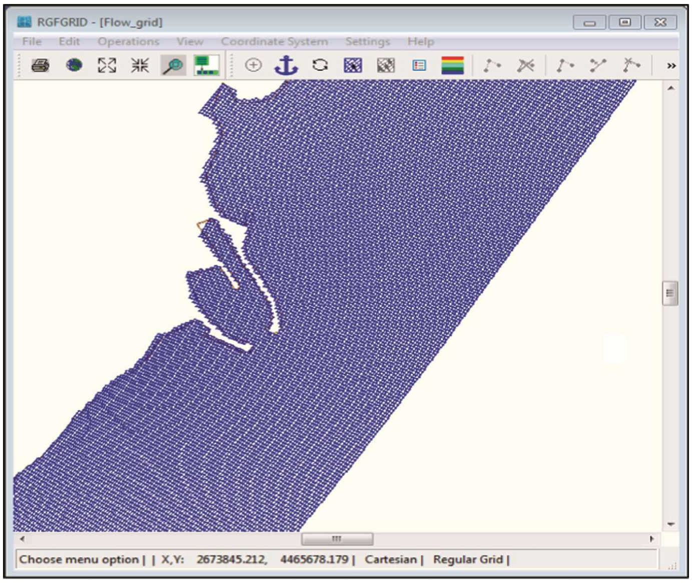


Fig. 6. Delft3D-flow computational mesh detail of Basento delta river

Fig. 7. Delft3d-Flow-Wave–D-Waq coupled modelling for Escherichia C. concentration space evolution in delta Basento river

3.4 WEB-GIS and Geo-Portal

The INSPIRE directive 2007/2/EC (INfrastructure for Spatial Information in Europe) aimed at harmonizing the organisation, accessibility and sharing methodologies of environmental spatial information among the EU Member States in order to support the EU environmental policies. Furthermore, according to such a directive, the information infrastructure might enable and ensure that spatial data obtained/collected from different sources should be supplied, stored and shared between users and applications. In such a context, the geo-portal represents the access point to the collection, management and distribution services of geo-referenced data for territorial analyses and/or downstreaming application domains. It does generally comprise a “Data Catalogue” for information download in local cockpit, providing a WebGIS tool with operational sections devoted to data publication, navigation and query. Such a WebGIS service is a geographic information system published online, which allows a mapping service of available data on the web. In such a way, it is indeed the extension into the net of specific applications designed and developed for digital cartography management. Thus, WebGIS leads the possibility of real-time interaction and the management of the access profile to the information at different levels (developer, simple user etc.). Furthermore, the access and consultation by the user is ensured even at low-level profiles without high technological upgrades.

The WebGIS-MATER platform, in such a scenario, is a Geoportal enabling publication, cataloguing, viewing and querying of information layers produced by the algorithms developed within the MATER operative project. In the framework of the INSPIRE directive, the platform should be used as SDSS and data-showing on interactive maps providing services for several integrated technologies (GeoServer for WMS/WFS/WFS-T/WCS, pycsw and CSW).

Figure 8 proposes the overlap between the DTM 2015 of the Cavone delta river area and the multi-source coastlines acquired in 1998-2005-2006-2008-2011-2012 supplying general and detailed information about the delta dynamics and beach evolution for further analyses: i.e. on delta migration velocity and local induced morphological changes.

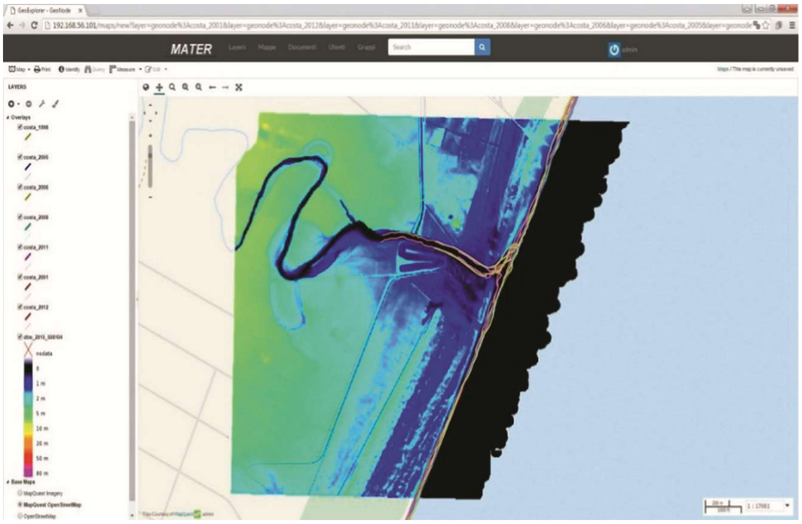


Fig. 8. DTM e multi-source coastlines for the Cavone delta river.

Furthermore, due to the high acquisition frequency of Sentinel-1 images, it is possible to perform interesting comparative analysis of multi-source data related to the coastline relief as shown in Fig. 9. In such a figure the overlap between the Sentinel-1 image acquired on February 13th 2016 and the shorelines collected on August 29th 2015,

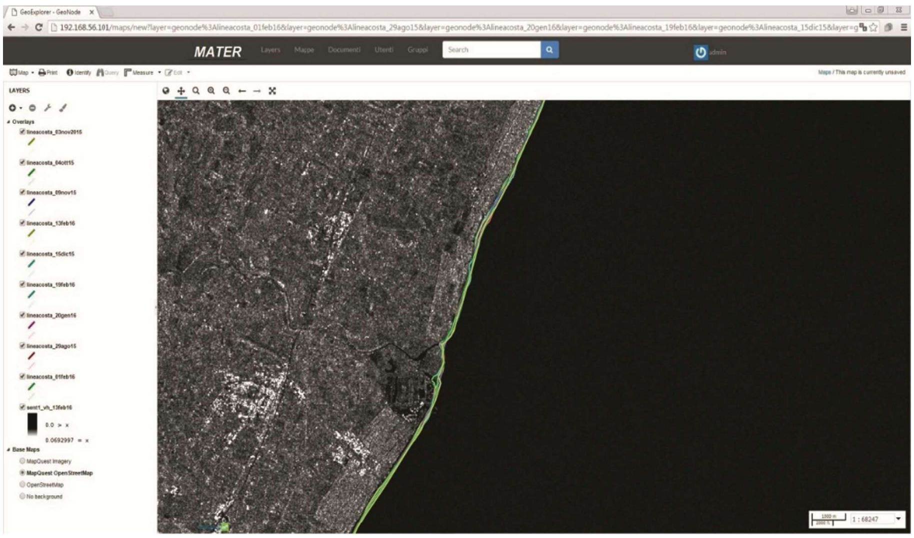


Fig. 9. Sentinel-1 data and multi-source coastlines around the Agri delta river.

October 4th 2015, March 11th 2015, November 3rd and 9th 2015, December 15th 2015, January 20th 2016, February 1st, 13th and 19th 2016 is reported.

Finally, the system also enables the viewing of maps produced by other organizations, even on their respective servers, via WMS (Web Map Service). In this way, the application is fully interoperable, ensuring both the publication of its own information layers, through OGC standards, and the integration and use of information layers derived from other sources with the same publishing standards defined by OGC as well.

4 Conclusions

The paper presents the preliminary results of the operative projects MATER and COMUINMARE, aimed at developing a methodology of environmental and territorial analysis for the exploitation of natural resources and supplying the first operational products for the definition and implementation of a Spatial Decision Support System for hydraulic-coastal risk forecast and prevention. The main issue deals with the integration and use of ground and remote earth observation data, with particular reference to the new satellite missions Sentinel-1 and 2 as well as COSMOSkyMed constellation data.

Among the operative products, the project provides the structuring and implementation of an expandable SDSS based on open-data catalogues, able to manage and display both the basic information, including the relative metadata, and post-processing results with open-source change-detecting codes and hydro-morphological modelling. The SDSS includes the development of integrative methodologies for systematic and continuous coastal monitoring, interfaced in an open source WebGIS environment dialoguing with the Regional Spatial Data Infrastructure in compliance with INSPIRE Directive. The SDSS also supplies the integration of ground and remotely sensed data with open-source information technologies, for the basic and advanced analyses, and web publishing of geographic data for a simple and intuitive end-user consultation.

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