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Spatio-temporal analysis of prodelta dynamics by means of new satellite generation: the case of Po river by Landsat-8 data

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A R T I C L E I N F O

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A B S T R A C T

This paper describes a procedure to perform spatio-temporal analysis of river plume dispersion in prodelta areas by multi-temporal Landsat-8-derived products for identifying zones sensitive to water discharge and for providing geostatistical patterns of turbidity linked to different meteo-marine forcings. In particular, we characterized the temporal and spatial variability of turbidity and sea surface temperature (SST) in the Po River prodelta (Northern Adriatic Sea, Italy) during the period 2013–2016. To perform this analysis, a two-pronged processing methodology was implemented and the resulting outputs were analysed through a series of statistical tools. A pixel-based spatial correlation analysis was carried out by comparing temporal curves of turbidity and SST hypercubes with in situ time series of wind speed and water discharge, providing correlation coefficient maps. A geostatistical analysis was performed to determine the spatial dependency of the turbidity datasets per each satellite image, providing maps of correlation and variograms. The results show a linear correlation between water discharge and turbidity variations in the points more affected by the buoyant plumes and along the southern coast of Po River delta. Better inverse correlation was found between turbidity and SST during floods rather than other periods. The correlation maps of wind speed with turbidity show different spatial patterns depending on local or basin-scale wind effects. Variogram maps identify different spatial anisotropy structures of turbidity in response to ambient conditions (i.e. strong Bora or Scirocco winds, floods). Since the implemented processing methodology is based on open source software and free satellite data, it represents a promising tool for the monitoring of maritime ecosystems and to address water quality analyses and the investigations of sediment dynamics in estuarine and coastal waters.

1. Introduction

River plumes play a fundamental role in the dynamics of coastal areas: with waves and currents they contribute to the distribution of organic and inorganic riverborne particulate thereby affecting not only the morphology, but also the ecology of coastal waters.

Catchment soils, mobilized by weathering and transported into the river network, are eventually transferred and deposited in the proximity of estuaries and deltaic systems (Davidson Arnott, 2010). Furthermore, rivers are a major route through which nutrients, sediments and pollutants, such as heavy metals and organic compounds, are transported (Qin et al., 2007; Rao and Schwab, 2007; Zhang et al., 2016).

In water bodies affected by rivers plumes such as lakes (Zhang et al., 2016) or semi-enclosed coastal regions (Kourafalou, 2001; Brando et al., 2015), the flow and associated suspended matter can alter the physical and biogeochemical properties of the basin, modifying thermohaline and dynamical properties (Horner-Devine et al., 2015), and affecting the exchange of nutrients and the migration of phytoplankton, zooplankton and fish (Rao and Schwab, 2007; Wang et al., 2012; Marini et al., 2008; Tesi et al., 2011). Different processes affect the river plume and its sediments load: advection and mixing drive the general structure of the plume while the along-coast transport of the riverine material is controlled by other processes, including stratified-shear mixing, frontal processes, mesoscale circulation, tide and wind forcing, as well as Coriolis effects (Hetland, 2005; Horner-Devine et al., 2015; Geyer et al., 2004; Nof and Pichevin, 2001).

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Understanding river plume dispersion in prodelta areas and its effects on the coastal environment is however quite challenging as suspended matter vehiculated by the rivers to the coast is highly variable over time depending on the hydrology and the distribution of the precipitation over the catchment. High concentrations of suspended matter in river plumes can affect water quality, generally decreasing light penetration with effects on the growth of aquatic vegetation and consequently the ecology (Kirk, 1994; Gippel, 1995; Milliman and Farnsworth, 2013; Cannizzaro et al., 2013; Dogliotti et al., 2015). For these reasons there is a mounting interest in monitoring the turbidity as an indicator of water quality in estuarine and coastal areas, (i.e., Marine Strategy Framework Directive (MSDF) or Maritime Spatial Planning Directive (MSPD)). Cristina et al. (2015) studied how the remote sensing can play a fundamental role in supporting the MSFD, by the use of MEdium Resolution Imaging Spectrometer (MERIS) sensor products.

The mapping of prodelta area by remote sensing has proven to be a successful methodology for water quality monitoring (Dogliotti et al., 2016, 2015; Braga et al., 2017; Brando et al., 2015; Petus et al., 2014; Nechad et al., 2010) and tracing river plumes (Shen et al., 2010; Falcini et al., 2012; Petus et al., 2010). Earth observation methods provide the synoptic perspective required to identify the plume changing features both in time and space overcoming the problems of spatial and temporal relevance of conventional monitoring techniques.

Satellite sensors such as Advanced Very High Resolution Radiometer (AVHRR), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS) have been widely used to describe the dynamics and physical characteristics of river plumes, their interaction with coastal forcings and seaward dispersion (Brodie et al., 2010; Doxaran et al., 2012; Filipponi et al., 2014; Dogliotti et al., 2016). Despite the low spatial resolution of these sensors (from 250 m to 4 km) they have provided valuable information on the evolution of river plumes at frequent revisit time from 1 to 3 days (Robinson, 2010). The integration of sea surface temperature (SST) with ocean color radiometry also supported the characterization of these transition ecosystems (Falcini et al., 2012; Otero et al., 2009). Other sensors with better spatial resolution such as Landsat, SPOT, permit more detailed investigations, but their low revisit frequency may reduce the number of available scenes (Zheng et al., 2015; Aldabash and Balik, 2016).

The availability of wide free-access data catalogues encouraged their use in the study of spatio-temporal variability of river plumes in estuaries and coastal waters (Zhang et al., 2010; Nechad et al., 2011; Chen et al., 2011; Shen et al., 2013, 2011; Petus et al., 2014; Filipponi et al., 2015; Dogliotti et al., 2016, 2015). These datasets support the monitoring of river plume dispersion, quantifying their relation to main natural forcings as discharge, waves, current and wind (Zhang et al., 2016, 2014; Ruddick and Lacroix, 2006). However, Pahlevan et al. (2012) evaluated the performances of Landsat-7 imagery for coastal analysis but found that low signal to noise ratio (S/N) and radiometric resolution were not sufficient to perform the analysis with good quality.

River mouth plume-dispersion patterns can be now observed with unprecedented resolution because of the most recent generation of satellite imageries such as those provided by Landsat-8 and Sentinel-2 (Irons et al., 2012; Pahlevan et al., 2014; Gernez et al., 2015; Lavrova et al., 2016). Furthermore, Landsat-8 provided continuity to multi-decadal time series of Landsat scenes allowing to perform long term analysis (Lymburner et al., 2016). Recently this data has been used by Brando et al. (2015) to characterize the Po river plume over the prodelta using SST and ocean color during the flooding event of 2014/11/19.

On the same time there are several processing algorithms devoted to carry out apparent and inherent optical properties and water quality parameters (Chlorophyll − Chla, suspended particulate matter − SPM, and colored dissolved organic matter − CDOM) (Odermatt et al., 2012; Lee et al., 2016a,b herein after). Dogliotti et al., 2015 obtained good performance of the algorithm for retrieval of turbidity from remotely sensed data in different regions using field data in estuarine and coastal waters. This algorithm was then implemented in the software ACOLITE for atmospheric correction and processing of Landsat-8 and Sentinel-2 data (Vanhellemont and Ruddick, 2016, 2015, 2014).

Even if the earth observation products cannot fully replace buoy monitoring or field investigations with oceanographic vessels they reveal multi-scale surficial spatial patterns in different time frames otherwise not observable with conventional methods. The combined use of remote sensing and *in situ* data, and more recently theoretical models, are quite promising for quantifying coastal processes (Bonamano et al., 2016; Brando et al., 2015; Lee et al., 2016a; Braga et al., 2017). Indeed, the integration of satellite-derived product with other multidisciplinary data can become a useful tool for a long-term monitoring system capable of building large data sets for studying these environments (Bonamano et al., 2016; Filipponi et al., 2015). The link between earth observation and models has actually been identified as a critical step in achieving effective integrated ecosystem assessment (Malone et al., 2014).

The development of a new generation of satellite data for ocean color and new data policy for free use of NASA and ESA images significantly extended the amount of information available on different spatial and temporal scales for the study of oceanographic processes and marine ecosystem monitoring. In this context, satellite big data processing is becoming a challenging task due to the extensive nature of the analysis, combined with the large amount of data handled (Ma et al., 2015). Therefore, the capacity to develop specific retrieval algorithms and robust processing techniques for time series analysis is crucial. It is thus necessary to define a reliable processing chain to perform temporal analysis for estuarine and coastal zones.

This paper is part of a research focused on the Po River prodelta, a complex environment located in the northern Adriatic Sea (NAS) Italy, by means of Landsat-8-derived products. This coastal system is dominated by riverine inputs and hydrodynamic forcings, and their interactions influence the physical and biogeochemical processes of the whole basin. The turbidity maps on a shorter temporal range has been just presented by Braga et al. (2017) in order to describe the Po river plumes and provide some interpretation to the controlling factors through time and space. Brando et al. (2015) characterized the river plumes in the NAS during significant flood event in November 2014 adopting Operational Land Imager (OLI) sensor, Thermal Infrared Radiometer Sensor (TIRS) data and hydrodynamic modelling obtaining good correlation between turbidity, SST and salinity showing how they change between different rivers in the NAS. Finally, to complete this research we considered other quantitative indices to extend the analysis of controlling factors, in particular this contribution describes a multi-temporal processing chain based on a workflow written in R language which adds new outputs and maps also introducing the thermal analysis and peak detection methods. The paper is organized according the following sections: the first introduces to the study area providing the environmental setting, the second defines the satellite data and the processing chain. Then the results describe the outputs based on two approaches: punctual extraction of time series from temporal hypercubes and spatial pattern analysis. Finally, we discuss these results in light of comparison with literature and previous researches.

2. Study area

The study area is located in the prodelta of the Po River, the major Italian river for discharge and extension of the drainage basin. The Po River is also the largest tributary of the northern Adriatic Sea (NAS) and its delta extends seaward for about 25 km with five major distributaries characterized by different and variable partitioning of water discharge and sediment load. From North to South these branches are called Maistra, Pila, Tolle, Gnocca, and Goro (Fig. 1). More than half of the total flow and sediment load are carried by the Po di Pila whose outlet