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ORIGINAL RESEARCH ARTICLE

Can multiple fish farms be integrated within a semi-enclosed bay without causing acute ecosystem degradation?

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Summary The current study explores the possibility that multiple fish farms (FFs) containing sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) can be successfully integrated within a semi-enclosed bay in the Croatian Adriatic. The research focuses on determining principal environmental factors (EFs) that control the integration and attempts to estimate their individual and synergic ability to influence deposition and removal of organic matter (OM) and trace elements (TE) from the system. The complexity of the designated tasks demanded a comprehensive number of various datasets and samples to be used in the analysis. The ADCP data revealed strong wind induced currents forming within the research domain resulting in high system flushing efficiency (3.5—6 days). The sediment samples from all stations contained relatively inert minerals which contributed to overall low OM and TE concentrations and very limited variability found across the entire bathymetric range. The thermal advection effect recorded at two stations was attributed to specific seabed topography and the hydrodynamic response formed during *Maestral* wind episodes. The results indicate that a successful integration of four FFs has taken place within the research site (semi enclosed bay), and that the key EFs responsible for its success are strong wind induced hydrodynamics, favorable seabed topography and sediment mineral composition. The synergy of the principal EFs that formed within the

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system was found to have an attenuating effect regarding FFs chemical influence (OM and TE) and an amplifying one regarding spatial footprint which extended to ≈2000 m distance.

1. Introduction

The aquaculture industry has rapidly increased in the Mediterranean region over the past two decades (Apostolaki et al., 2009) and this trend is expected to continue. Fish farming (FF) of sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) has had the greatest annual growth rate of all aquaculture production types in the Croatian Adriatic (FAO FishstatJ, 2012). The excessive production of organic matter (OM) and certain trace elements (TE) typically associated with this type of industry (Cancemi et al., 2003; Delgado et al., 1997; Wu, 1995) caused significant concerns, due to the enclosed nature of the Adriatic basin. Although extensive research has already been conducted to elucidate the fish farming short term and long term effects, various aspects of aquaculture influence still require comprehensive investigation and description. The majority of the results point to a conclusion that FFs generate a negative biochemical pressure on the surrounding environment, though on relatively small spatial scales (Karakassis et al., 2000; Pergent-Martini et al., 2006). However, some scientific papers have reported that farming of sea bass and sea bream within the oligotrophic Mediterranean could be considered as tolerable for the ecosystem pending key environmental factors (EFs) support the integration (Karakassis et al., 2005; Maldonado et al., 2005; Puhr and Pikelj, 2012). The current study used the latter approach as a scientific foundation and went further by analyzing the ecological impact of multiple FFs located within a semi-enclosed bay in the Croatian Adriatic. Similar interactions between multiple aquaculture installations and a semi-enclosed system have been previously studied in the East Mediterranean with results having indicated medium to low impact on the ecosystem's nutrient stability (Neofitou and Klaoudatos, 2008; Papageorgiou et al., 2010). The first priority of the research was to determine the principal EFs that control the deposition and removal of OM and TE within the research site. These had to be primarily derived from *in situ* measurements as their scales of influences vary depending on site specific properties (Borja et al., 2009). Once identified, the principal EFs serve as a basis for investigating their synergic power which is expected to develop due to the enclosed nature and relative shallowness of the research site. This phenomenon is of particular interest as very little is known about its capabilities to amplify or attenuate aquaculture impacts. The complexity of the designated tasks demanded a comprehensive number of various datasets and samples to be used in the analysis. The datasets consisted of: *in situ* light and water temperature measurements, meteorological records of wind direction, intensity and air temperature, Eulerian current measuring device data (ADCP), and hydrographic data on seabed topography. Sediment samples were gathered *in situ* and analyzed for grain size, carbonate content, quartz, OM and TE content. Upon completion, the results of the study were expected to answer two very important questions: (1) can multiple FFs be integrated within a semi-enclosed bay without causing acute ecosystem degradation, and (2) are the prerequisites for a successful integration dependent on highly improbable combination of site-specific environmental factors or rather on set of conditions commonly found in numerous locations throughout the East Adriatic and the Mediterranean Sea?

2. Material and methods

2.1. Study area

The study area is located on the island of Ugljan (East Adriatic Sea, Zadar Archipelago, Croatia) and covers app. 2800 m × 1500 m section of the southern part of the island, including two large enclosed bays (Vela Lamjana and Mala Lamjana) and four small islands (Fig. 1). The entire area, which can be regarded as a semi-enclosed bay, comprises of 4 fish farming installations (containing sea bass and sea bream) and a small shipyard, making this location potentially susceptible to eutrophication and heavy metal toxicity. The site is partly exposed to *Jugo* (SSE-ESE) and *Maestral* (WNW-NW) winds, and is sheltered from *Bura* (NNE-ENE) wind which causes the wind driven hydrodynamics to be relatively attenuated. Seabed topography can be described as favorable due to the specific layout of the islands and the two enclosed bays (Fig. 1). From the geological point of view, the island of Ugljan belongs to the Zadar Islands group and is composed of thick-bedded Cretaceous limestones and Eocene foraminiferal limestones (Majcen et al., 1970). The seabed around the islands has a recognizable biogenic coarse-grained carbonate-rich surface sediment cover (Pikelj et al., 2016).

2.2. Data from the meteorological station

The meteorological data corresponding to the time interval of the *in situ* field measurement were obtained from the National Meteorological and Hydrological Service (DHMZ) Station in Zadar (10 km N of the research site). Wind speed [m s^{-1}] and direction (00-32) were recorded every 10 min by the sensor placed 2 m above the ground (7 m above sea level). Average values were then calculated to express prevailing wind direction and intensity for each hour of the day. Air temperature values were recorded in °C every hour by the thermograph.