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High-Resolution Modelling of Spread of Anthropogenic Contaminants in Marine Waters, Influencing Aquaculture.

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Master Thesis Report

Complex Assessment and Numerical Model Development of Impact Factors on Bivalve Mariculture in Coastal Areas

Aquaculture Farming in the Ebro River Delta

Mariya Perepelytsya

15th of August 2019

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Aquaculture Farming in the Ebro River Delta

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Mariya Perepelytsya

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15th of August 2019

Affirmation

I hereby declare that this work was written independently without any unauthorized assistance or sources not given credit within the work. All words, phrases, passages, and data taken from other sources have been properly cited. No parts of this work in the same form or a similar form have ever been previously handed in to fulfil an examination.

Delft, the Netherlands 15 August 019 Mariya Perepelytsya

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Abstract

Numerical model applications as Decision Support Tools for the development of solutions has proven its effectiveness over the last decades. Specific models are developed to address the various needs of stakeholders. Existing modern ocean models cover the sea areas with the large resolution, measured in kilometres. However, to get a precise understanding of complex processes that occur in the water column of coastal zones, high-resolution models are necessary.

Globally, coastal areas are vulnerable to anthropogenic impacts. Main sources are industrial waters discharges, run-off of agricultural rich in nutrients and pesticides waters along with urban wastewater and rainfall waters release in water bodies.

This has a detrimental effect on the objects of coastal and marine aquaculture, which often leads to the death of products, reduced growth or impaired health. Despite certain differences in their physiological characteristics, all the molluscs have a common feeding technique by filtering water through their bodies. Therefore, due to the lipophilicity of most contaminants and heavy metals, these compounds tend to be gradually absorbed and accumulated in soft tissues. Interestingly, this does not have a significant visible effect on the molluscs but in such a way, they become hazardous for the health and life of consumers.

To solve this problem, during my internship in Deltares, an integrated high-resolution hydrodynamic and transport model that takes into account the water physical parameters and propagation of anthropogenic pollutants in the coastal zone was developed in the new Delft3D FM 2019.02 HMWQ suite. The model uses the system of equations that consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. It is estimated that the modelled fluid is incompressible and therefore Navier Stokes equations with the Boussinesq and shallow water assumptions are solved. Simultaneously, this software package was tested that allowed the developers of the package to make operational adjustments to the program.

In this research the Ebro River Delta is chosen as study area as several aquaculture facilities are located in the Alfacs and Fangar Bays. The whole area is a natural reserve and, moreover, is one of the most vital natural wetlands areas in the Western Mediterranean zone (Köck et al. 2010).

The created model was set-up using measurements of the quality, flow rate and temperature of water from the Ebro River and irrigation canals, as well as the physical parameters of flow, temperature, salinity, water level and currents in the deep sea from the Copernicus system that uses remote sensing techniques. Calibration and validation of the model were carried out according to in-situ measurements of physicochemical parameters in local bays. The automatic data exchange with other open data services is implemented using the Copernicus monitoring system as an example.

Due to the fact that measurement techniques, data interpolation methods during the data gap-filling process and model assumptions create uncertainties, the necessity of in-depth uncertainty analysis is shown.

Due to the lack of available data, it is suggested to implement the neural network coupling with the model in further development. Thus, the automatic constant model calibration can be performed by training the model with the newly received data. Also, this approach will decrease the model uncertainties.

This research was conducted under the framework of the HiSea project, which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement № 821934.

This thesis is used to develop a forecasting system within the HiSea project. In addition, the thesis provides the necessary information to business entities in the field of aquaculture to ensure the possibility of sustainable decision-making management and development of risk response plans, since it provides a set of data on the physicochemical parameters of sea waters and the localisation of anthropogenic pollution.

Keywords: Hydrodynamic Modelling, Water Quality, COPERNICUS services, Data Analysis, Pollutants, aquaculture, heavy metals

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List of Acronyms

Al – Aluminium

As – Arsenic

BOD - Biological Oxygen Demand

Cd – Cadmium

CMEMS - Copernicus Marine Environment Monitoring Service

COD - Chemical Oxygen Demand

Cu -Copper

DO - Dissolved Oxygen

Fe – Ferrum

FM – Flexible mesh

IARC - International Agency for Research on Cancer

MFS - Mediterranean Forecasting System

MPIOM - Max-Plank institute Global Ocean Model

PARs - Precision Approach Radars

Pb – Lead

SI – International unit System

TAN - Total Ammonia Nitrogen

WQ – water quality

1. Introduction

According to the United Nations World Population Prospect population growth statistical data and predicted values, nowadays we face the rapid growth of the human population all over the world (UN, 2019). So, by mid-2050 9.8 billion people are expected, in comparison with the 2018 value of 7.7 billion inhabitants (UN, 2019). Therefore, the world faces also the increasing demand for food. Currently, among all the food sectors in the world, aquaculture is the fastest developing one with the prediction being the main one to respond to projected growth in the demand for seafood products (FAO, 2016; Kobayashi et al., 2015). Already, land resources, needed to meet the demand of on-land aquaculture production, are scarce (Duarte et al., 2009; Gentry, Froehlich, et al., 2017). Therefore, offshore aquaculture facilities are more beneficial than on-land or freshwater installations due to large ocean space available, and the rapid development of this branch of the food market is observed (Duarte et al., 2009). Mariculture – includes marine and coastal aquaculture, namely various marine species of fish, bivalves, crustaceans farming in coastal ponds, estuaries, lagoons, land-based installations and in the deep ocean (Clavelle et al., 2019). Unfed mariculture production of filter-feeding molluscs and bivalves prevails now over marine finfish, shrimps and prawns (Clavelle et al., 2019). Therefore, the presented research is focused on the assessment of the impact factors of the coastal bivalve farming, such as physical characteristics of the area and water quality. In particular, the oyster and mussel aquaculture facilities, based in two shallow estuaries in the Balearic Sea coast are studied. Local aquaculture farms produce the biggest number of oysters and mussels in Spain that brings 2 million euros annually per each kind of cultivated species. More details on the research problems and study area location and are provided in chapters 1.1 and 2 of this thesis.

Water quality is one of the foremost modern environmental issues. Dealing with it is one of the core points to reach the sustainability of ecosystems. Planet`s coastal areas are testified as being severely harmed by anthropogenic pollution, that significantly influences commercial coastal and marine fisheries (Islam & Tanaka, 2004). Due to the inland contamination sources, pollutants are washed to river deltas with floods and river waters and, as a result, coastal area. So, disruptions in local ecosystems take place and influence the quality of fish, shellfish and seaweed, and is a reason for their mortality in the worst scenario. Thus, real-time forecasting on hazardous chemicals concentration is required to improve understanding of the environmental situation and to enable tailored management and risk reaction plan development to enforce timely response measures implementation in case of hazards (HiSea, 2019).

There are numerous anthropogenic sources and types of contamination, such as agriculture that uses fertilisers and pesticides to enhance the growth and protect the products, urban discharges of wastewater, that contain antibiotics, organic compounds and urban run-off waters, carrying oils, heavy metals and microplastics. The most significant and hazardous pollution source is still industrial plants that, depending on the specialisation, discharge various kinds of chemical compounds that put ecosystems at risk.

Heavy metals are non-degradable elements that accumulate naturally in the coastal areas. They pose a high risk to the living organisms as they can bind with the carbon chains, so that bioaccumulation takes place, with the rapid annual increase of metal concentration year by year, if exposed to the heavy metal source continually.

1.1. Problem definition

Due to the aquaculture market growth, there is a high demand for developing new installations along with coastal areas. Besides, existing farms have the potential for an increase in their sustainability and, as a result, quality and efficiency of production. However, off-shore farms are highly dependent on local ecosystems, and bivalves are sensitive to the fluctuations in water quality, temperature and sediment`s background characteristics, such as the optimal conditions for the Pacific oyster growth are the temperature of 20 ^{o}C and 20-25‰ salinity rates (FAO, 2019). Contamination severely affects living organisms as a result of bioconcentration — when chemical compounds are absorbed from the environment to the body due to the lipophilicity of most pollutants and biomagnification — an increase in the concentration of elements in the food chain (Islam & Tanaka, 2004).

Legal demands addressing water quality are rising, and numerous policies and directives are developed, such as the Water Framework Directive, Drinking Water Directive, Nitrates Directive and many more. The decisions, made in accord with the given policies, have to be well-supported with respective documents and scientifically. So, numerical models are applied for the development of solutions and are used as Decision Support Tools (Neves et al., 2014). So, during the last decades, in accord with the introducing environmental legislation restrictions, the need for numerical modelling has raised significantly. Therefore, along with increasing accessibility to computer powers, various numerical models to better understand, reproduce and enable prediction systems of the water dynamics, quality, climate forcing, sediment transport and many more, were developed. Simple models are often used to understand the underlying causes of present phenomena (Murray, 2003), while complex models reproduce in details natural environment or have a multi-driven approach to the poorly understood physical processes (Nienhuis et al., 2016a). Therefore, the numerical modelling approach to understand and solve various issues, and, in this case, the hydrodynamics and water quality has proven its effectiveness over the years. Moreover, results of models prove to be acceptable for the decision-making, and now they are core tools for policy development (Neves et al., 2014).

Currently, coastal pollution is the biggest threat to aquaculture farms and, unfortunately, the main problem is the lack of proper water and sediment quality monitoring. As a result, these gaps in data that makes the knowledge regarding posed problems ambiguous and therefore complicate modelling process. Thus, adequate on-site monitoring is vital to ensure the proper scientific approach to the water quality, physical parameters and flow forcing analysis, needed to be done prior management and hazard response plans development for aquaculture sites.

Two main groups of pollutants affect aquaculture. The first one is nutrients, that triggers eutrophication and, as a result, phytoplankton excess development. The second one is pollution with pesticides and heavy metals. The first group of pollution problems for aqua-farmers is quite apparent. Moreover, in case of filter-feeder's aquaculture farms, research on the oyster impact on the nutrient cycle shows that due to the specific organism functioning, they cause denitrification of waters and sediments (Smyth et al., 2016). Also, some research suggests the application of oysters in algal bloom prevention due to their ability to transform bio-available nitrogen into the inorganic form (Grabowski et al., 2012). At the same time, modern monitoring methods of the nutrients contents in waters, especially inland, are quite reliable and highly operational. As, in addition to the possibility of the model set-up, there are remote sensing methods for accessing turbidity, content of Chlorophyll-a, and Precision Approach Radars (PARs), which are quickly using a large number of satellite images available through various sources, such as the European Union Program Copernicus, aimed to develop European information services based on satellite Earth observation data (Copernicus, 2019). At the same time, the problem of pollution with heavy metals and pesticides in coastal areas still has very low recognition, and on-line assessment of pollution by substances from this group is possible only by creating a high-resolution model.

Oysters and mussels are very vulnerable to various water quality parameters. Considering that a lot of research is being conducted on the concentrations of heavy metals, antibiotics and pesticides in the soft tissues of fish, bivalves and crustaceans ((Besada, Manuel Andrade, Schultze, & José González, 2011; Iamiceli et al., 2015; Ochoa, Barata, & Riva, 2013; Ochoa et al., 2012; Squadrone et al., 2016) and pollutants` effects on the health of organisms, these data are not directly related with the background water quality in the ecosystem. Thus, the absorption rates of various elements are practically not analysed. Oysters and mussels are widely used only as water quality bio-monitors. There is a lack of sufficient information regarding the concentrations and impacts of heavy metals in seafood. In this way, consumers are exposed to numerous potential risks. This creates a problem for aquaculture, as farmed products are sent to the market to consumers, which imposes stringent requirements on food quality. Accordingly, in the absence of a timely response to anthropogenic and natural incidents or neglecting the initial conditions when installing a new farm, aquaculture is at risk of high economic losses.

Despite the fact that hydrodynamics and water quality modelling is developing rapidly (Zalesny et al, 2017), existing models have been developed for slightly different purposes, namely, to gain a general understanding of current distribution, nitrification and algal blooms, effects of climate change and macro pollution analysis. These models, such as Copernicus Marine Environment Monitoring Service CMEMS, Max-Plank institute Global Ocean Model MPIOM and Mediterranean Forecasting System MFS cover the entire Mediterranean sea and global ocean areas, have low resolution, measured in kilometres. At the same time, aquaculture models require a high spatial resolution of 2 to 200 meters, so that small bays are covered in detail and all possible sources of pollution and biochemical processes are considered. With this approach the particular needs of existing farms are addressed, as highly precise model can show flow and contaminant propagation and it becomes possible to access vulnerability of each installation.

Also, the aquaculture farmers' own needs are not entirely clear for them. This is why HiSea project aims to connect stakeholders with scientists and model developers to create targeted, high-quality models for this sector.

1.2. Research objectives

Due to the intensive development of the coastal farming, respective assessment of the stakeholder`s needs is addressed in this research, in order to develop relevant management plans for the aquaculture sector. The main objective of this research project is to provide aquaculture enterprises with access to reliable analysis of information on the impact of external sources on temperature and physicochemical parameters of water. To address this aim, it is decided to take an area that is located within the Mediterranean basin. Two unique shallow bays in Delta Ebro, Spain, were taken as a case study area. This region is unique since the modern Ebro Delta was shaped within the past 200 years, as in the 4th century AD the ancient Amposta was a seaport (Fig.1) (Barcelona Field Studies Centre, 2018).

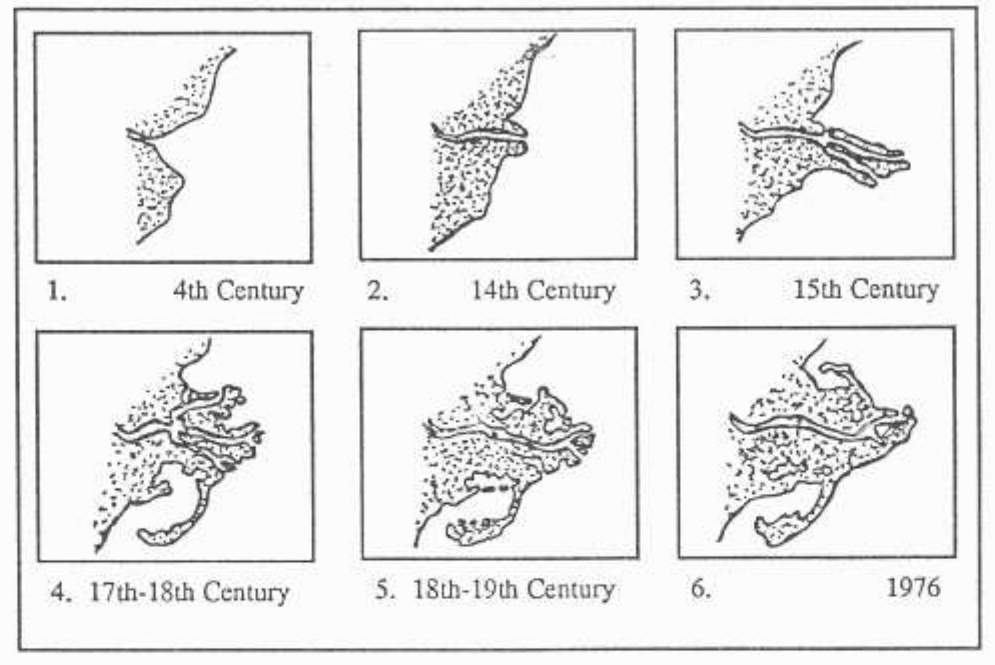


Figure 1. Ebro Delta alluvial plain evolution. Source: (Barcelona Field Studies Centre, 2018).

Still, local bathymetry is changing due to the constant sediment transport from the beaches, adjusted for tourism needs, and anthropogenic influence of the changing of river flow (Nienhuis, 2017). Therefore, local biochemical processes slightly vary due to changing conditions.

According to recent researches on the concentrations of hazardous compounds in tissues of produced in Ebro Delta oysters and mussels, mercury and lead and other heavy metals are accumulating in the products, that is related with the discharges from the Ebro river and discharge channels from rice fields. Therefore, in this research, the impact of these discharges input on the environment of both bays is accessed.

When issues of eutrophication and nutrient pollution are widely known and addressed, the problem of aquaculture products contamination with heavy metals is not obvious for stakeholders. So, in this thesis, the detailed analysis of the impacts of chemical compounds on aquaculture products is performed. Also, the distribution of the dissolved substances is accessed. The main objective is to provide local aquaculture farms with the relevant operational data on potential risks, related to the input of hazardous substances, and give solutions on the necessary response measures.

The general and final target of the HiSea project is to ensure the intensive development of local aquaculture farms, improve their product quality and increase of profitability. In the scope of this thesis, this comprehensive goal is addressed by creating a high-resolution deterministic model for visualising physical conditions in the aquaculture area and analysis of contaminant`s propagation in bays.

Moreover, an additional goal of this work is to test the new software package Delft3D FM Suite 2019.2 HMWQ, developed by the Deltares Research Institute. To do this, it is necessary to collect, assimilate and analyse data from open sources and local research institutes: the Institute for Agricultural Research and Technology (IRTA), the Spanish Center for Oceanography and the Ebro River Basin Administration. Further, using the obtained model, determine the effect of freshwater inflow on the aquatic environment of a closed bay and by its influence on the flow, temperature along with salinity parameters and analyse the primary sources and direction of chemical pollutants propagation.

1.3. Innovation and practical value

In this regard, the research is innovative because it is aimed at assessing the needs of oyster and mussel farmers in the first place and targets to enlighten all the problems mentioned before. So, the latest release of the Delft3D FM 2019.02 Suite HMWQ is the most up-to-date software that corresponds to the desired goals. This fact provides the add-on value to the conducted work, as it is an excellent chance for software testing for multiple purposes. It allows to model complex curvilinear and irregular coastal zones with high precision with its flexible mesh and possibility of application of σ-layering adds on the vertical process modelling precision. Thus, in this research I am making it possible to create an innovative model with a high resolution of 35 meters in the area of aquaculture installations, taking into account the temperature, salinity and water level oscillation, flow dynamics and assessment of external impacts on water quality in the region. An in-depth description of the used software suite and model set-up can be found in Chapter 3. This will give an insight on the quality and health of the local ecosystem and will confirm the necessity of more systematic monitoring due to human health hazards, resulting from the consumption of polluted aquaculture products, if safety measures are not taken.

Also, the technical possibility of online ensemble coupling of the used Delft3D 2019.02 with other open data platforms for data acquisition is analysed. All in all, the resulting system will be used to create a platform for predicting water quality with a target orientation on aquaculture needs.

2. Case study description – Ebro Delta, Spain

Ebro River Delta (Fig. 2, 3), located on the north-eastern coast of Spain, is taken as a study area for this research.

Figure 2. Research area location – Ebro River Delta, Spain. Source: earth.google.com

Figure 3. Ebro River Delta. NASA Earth Observatory image by Michael Taylor and Joshua Stevens, using Landsat data. Source: earthobservatory.nasa.gov

The Ebro River is the longest and main water supply river in Spain. Its catchment area occupies over 85 530 km^2 that counts almost 17% of the whole country's territory (Fig,4) (Nienhuis et al, 2017). It discharges into the Balearic sea (CHEBRO, 2019). At the same time, the delta`s area is more than 30,000 ha (Ochoa, 2013) and penetrates for 22 km into the Mediterranean Sea (MedWet, 2019).

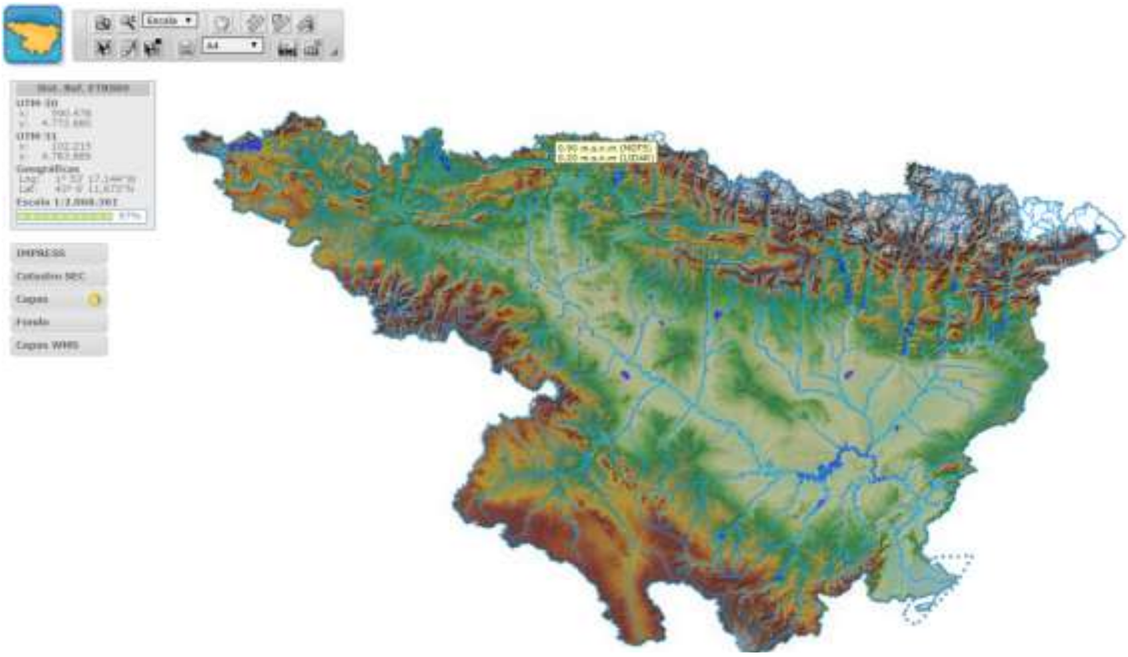


Figure 4. River Ebro catchment area. Source: iber.chebro.es

The final formation of the Delta occurred within the past 300 years and did not change dramatically since, from the sediment, carried with the Ebro river flow from the Pyrenees and the Cantabrian mountain ranges. River`s delta formation refers back to more than 6000 years BC, that has initially a form of an estuary that has faced numerous changes since then due to avulsion process (river channel modification), anthropogenic impact as dam construction along the river and past climate change (Nienhuis et al, 2017). Therefore, more sediment was brought with the river flow, that formed the modern shape of the Ebro Delta (Fig. 5).

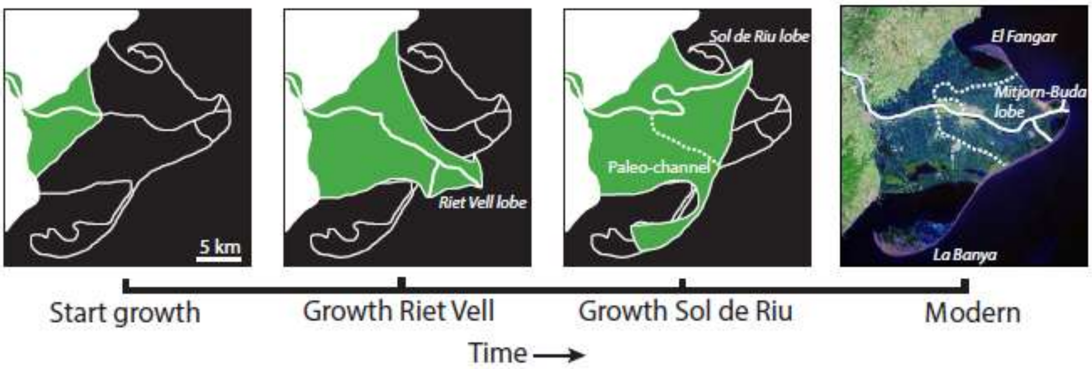


Figure 5. Morphologic development of the Ebro Delta, reconstruction. (Nienhuis et al, 2017).

Also, the Ebro River Delta is a natural reserve area and is an important wetland in the Western Mediterranean coast. Since 1983 almost 8,000 ha of the delta is a Natural Park and is a part of the Ebro Biosphere Reserve. Nowadays it has a high importance status as it hosts 8 rare plant species and is a nesting area for 316 bird species (Fig. 6) (MedWet, 2019).

Figure 6. Birds in the Ebro Delta wetland. Photo source: turismeamposta.cat.

The catchment and river flow were intensively changed throughout the years for agricultural and industrial purposes through land-use change. This caused the boost in the pollution rates over the whole Ebro basin (Mañosa et al. 2001). At the beginning of the 20th century, the prominent chloro-alkali factory was launched in the lower Ebro River, only 95 km upstream from the delta. The plant was discharging untreated waters directly to the river that triggered contaminant`s accumulation in the sediment (Carrasco et al., 2011; Bosch et al., 2009).

Moreover, due to the dam establishment right next to the factory, most of the sediment, counted in a range of 200,000 to 360,000 tons, was trapped. In accord with recent researches, deposits contain mostly high concentrations of heavy metals – Mercury (Hg), Arsenic (As), Cadmium (Cd), Chromium (Cr), Lead (Pb) and Selenium (Se) (Bosch et al. 2009). So, still, the pollutants are carried with the river flow down to the Delta area in the two shallow bays, formed during the last 200 years, in Ebro Delta, intensive mussel and oyster farming takes place. In the region, offshore aquaculture is the second economic activity after agriculture and counts up for more than 3,000 tons annually of produced crustaceans (Ramón et al. 2005; Ochoa, 2013).

Alfacs Bay

Figure 7. Alfacs Bay. NASA Earth Observatory image by Michael Taylor and Joshua Stevens, using Landsat data. Source: earthobservatory.nasa.gov

Alfacs Bay is a Southern semi-enclosed bay of the Ebro Delta (Fig. 7). It is approximately 16 km long from the mouth to its head, 4 km wide and the mouth to the open sea is 2.5 km. Depth varies between 2 to 10 m. Alfacs Bay has nearly stable stratification and is classified as a salt wedge estuary. During most of the year, 9-10 months annually, it collects the direct freshwater inputs from the drain channels of the rice cultivation (Serra et al. 2007). The contribution distributes into three periods:

1) Summer – rice fields are flooded between April and September with the discharge of 6 m^3/s;
2) Fall – discharge from fields September to January with $Q=7\ m^3/s$;
3) Spring – February to April is the dry period on rice fields (Cerralbo 2015).

Fangar Bay

Fangar bay is the shallow bay, located in the northern part of the Ebro River delta area. It is smaller than the southern one, with only 3m of average depth (Fig.8). Its length is approximately 5.5 km and width 2 km that makes it overall a complex ecosystem and an area, very suitable for aquaculture production, that is rapidly developing in the area (Fig. 9).

Figure 8. Fangar Bay. Source: google.com/maps

Figure 9. Fangar Bay aquaculture installations. Source: https://www.fepromodel.com/es/bahias-delta-ebro

Water quality

Water quality quantifies the water biological, chemical, physical and radiological properties in relation to environmental and biotic species constraints, as well as human necessities or anthropogenic use requirements. Frequently, it refers to a specific set of standards in accordance with the purpose of use. Commonly, water quality specifications are associated with ecosystem stability, drinking water and everyday domestic use (Diersing, 2009; Li & Liu, 2018).

Main water quality physical and chemical variables are Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Biological Oxygen Demand (BOD), pH, temperature, conductivity, water level, turbidity, water level and Total Ammonia Nitrogen (TAN). Considering dissolved chemical compounds, the list of prohibited ones and corresponding thresholds are constantly developing in accord with modern monitoring techniques and capacities of laboratory equipment. These regulations also vary, depending on the aims of water use. Nevertheless, maximum background concentrations of non-essential compounds in surface and marine waters in Europe are established by the EU Water Framework Directive 2000/60/EC. The inadmissibility of the heavy metals` presence in water is directly related to this directive.

Chemical oxygen demand determines the amount of oxygen that reactions can consume in the solution. In the International System of Units (SI), it is rated in mg/l as a relation of consumed oxygen mass to the water volume. Often by performing a COD test, it is possible to measure the amount of dissolved organic compounds. Also, the COD test is used to quantify the concentration of oxidised contaminants in the water column. Thus, it is one of the strict limitation parameters for the release of wastewater back to the water bodies.

Dissolved oxygen is one of the most critical parameters for the water quality assessment. It is vital for fish and zooplankton and variation of its concentration may cause anoxia or hypoxia. In aquaculture fish in low DO conditions are more exposed to various diseases. In literature, minimum recommended DO concentrations are 4-5 ppm. (Martınez, 1994).

Biochemical oxygen demand is the oxygen extent required by aerobic organisms to break down organics, present in water in specific temperature conditions and period. Same as COD, it shows the level of organic contamination, so evaluates the wastewater treatment effectiveness and is measured in mg(O_2)/l at 20°C in 5 days of incubation. Though, it is more specific than COD as it measures the level of biodegradable organic matter instead of accessing all the chemically oxidised compounds (Li & Liu, 2018).

Main chemical water quality indicators define it full value physiological characteristics and, what is more important, its compliance with standards, set in accord with purposes of use. They include the balance of Ca, Na, $(PO_4)^{3-}$, $(SO_4)^{2-}$, K, F that are essential for proper organism functioning. For the remaining compounds such as heavy metals, pesticides and other elements, specific regulatory concentration thresholds are set, that should not be exceeded in a clean and healthy environment.

Aquaculture production in the area

The region of Valencia developed into a Spanish national hotspot of aquaculture production, with the output growth of 26.5% in only one year in the season of 2010 – 2011 with more than 9278 metric tons of seafood valued at EUR 38 million. In 2010, the region's aquaculture enterprises also raised 199 metric tons of eel and Mediterranean mussels (*Mytilus galloprovincialis*) worth EUR 1.9 and 1.7 million, respectively, together with 4 metric tons of oysters (SeafoodSource, 2019).

DeltiMussel and Musclarium

DeltiMussel coastal farm is located in the Ebro River Delta Natural Reserve and shares more than 40000 square meters of its installations between the Alfacs and Fangar Bays. Musclarium has its installations in the Fangar Bay. This area is known as the second most valuable wetland zone of the Iberian Peninsula. Also, some installations are located in Valencia Port and now the productivity of the whole farm counts up to 25 metric tons of mussels and 16.2 metric tons of oysters per year. Average monthly production of 2000 to 5000 dozen of oysters (1 dozen=12 oysters) is sold directly on the Spanish and international market and to individual clients such as restaurants and hotel chains. Main farmed species are described below.

Mytilus galloprovincialis

Mytilus galloprovincialis, also known as Mediterranean mussel, are grown on the rectangular rafts of 200x15 meters that are attached to the seabed by concrete piles and hold 2-3m long mussel ropes. They are molluscs with the average body size of 10-15 cm with violet to black shells.

Crassostrea gigas

The Pacific cupped oyster is an estuarine species and is grown in the Alfacs and Fangar Bays in two ways. One is floating production on floating nets, covered from the sun and another is located in the Alfacs Bay mouth and is a type of water-column culture, grown on ropes. Once juveniles are settled for growth, they need from 18 to 30 months to reach the desired mass of 70 – 100 grams.

Nova Devimar

Also in the Ebro Delta Reserve in addition to offshore farms in the bays a mollusc purification company is based. Once oysters and mussels reach their commercial size, they are collected and sent to the purification and sorting facilities of Nova Devimar. Marine products are selected, washed, packed and conserved in accord with the end-user requirements. The total capacity of the installation is the treatment of up to 80,000 kg of molluscs daily (Nova Devimar, 2019).

Main species, processed in the farm and later through the purification processes are Galician, Mediterranean and rock mussels, Pacific and Flat oysters and razor, coquina and sea clams (Fig. 10).

Figure 10. Ebro Delta aquaculture products. Source: Nova Devimar.

3. Literature review

3.1. Mariculture market growth

In the year 2016, globally, the amount of farmed fish and products surpassed the volumes of captured ones. According to (Duarte, Marbá, & Holmer, 2009), offered on the market marine products are more diverse and the price range is expanded due to the rapid pace of aquaculture species farming.

During the past thirty years, aquaculture in the Mediterranean region has promptly developed. Aquaculture, due to the constant growth of production rates, from small land-based installations changed into large enterprises. At first, aquaculture farms were located on the coastline but lately, off-shore sites were created. Nowadays farms produce the most commercially important marine fish species such as gilthead seabream (*Sparus aurata*) and European sea bass *(Dicentrarchus labrax*) along with bivalves the European mussel (*Mytilus galloprovincialis*), the European flat oyster (*Ostrea edulis*) and the Pacific oyster (*Crassostrea gigas*) (FAO, 2014).

In the following tables (*Table 1, 2*) the production and economical value trends in Europe and in Spain can be observed. It is done according to the observed data and estimations by the Food and Agriculture Organisation (FAO), and it is seen that aquaculture production mass and stock value is upraising year by year since the last economic crisis time (FAO, 2019).

Table 1. Marine area Oyster and Mussels production quantity in Spain and Europe (tones)

	Year	2010	2011	2012	2013	2014	2015	2016	2017
Spain	Oysters	1301	1731	1170	927	926F	1024F	1013F	1033F
	Mussels	187967	208583	203664	162012	220449	225308	215885F	241785
	Total	189278	210314	204834	162939	221375	226332	216869	242818
Europe	Oysters	95742	93776	94256	92870	92387	82790	82726	85043
	Mussels	462074	483961	456399	411984	462219	477325	479531	498164
	Total	557816	577738	550655	504854	554607	580115	562258	583207

Table 2. Aquaculture economical value estimation in (USD 000).

	Year	2010	2011	2012	2013	2014	2015	2016	2017
Spain	Mussels	124225	154981	128890	106121	146621	127653	130499	147131
	Oysters	6429	7566	5190	5100	4861	4447	4324	4029
	Total	130654	162547	134080	111221	151482	132100	134823	151161
Europe	Mussels	533370	608076	539472	552716	544026	465390	466922	492899
	Oysters	513531	605264	583473	593977	545879	441035	433627	452799
	Total	1046901	1213340	1122945	1146694	1089905	906425	900549	945699

Nevertheless, there are still numerous issues that hold mariculture market development, as it is highly vulnerable to water pollution and climate change, so currently requires high investments that are barely paid off (Aydin, Aydin, Saydut, & Hamamci, 2009). Therefore, achieving the goal of precise and on-time water quality monitoring is one of the critical steps to develop sustainable regulations and frameworks for the aquaculture sector (Li & Liu, 2018), in order to increase the production efficiency and business profitability, rather than expanding farming areas.

3.2. Polluted coasts

The marine environment, in general, is exposed to global pressures that are invasive species distribution, pollution, overexploitation of resources, eutrophication, loss of the coastal habitat and climate change – global sea level and temperature rise, variation in chemical content and, as a result, biological processes disruption. Same problems are observed in the Mediterranean Sea that comes mainly from the anthropogenic activities – tourism, aquaculture and transportation (Fig. 11).

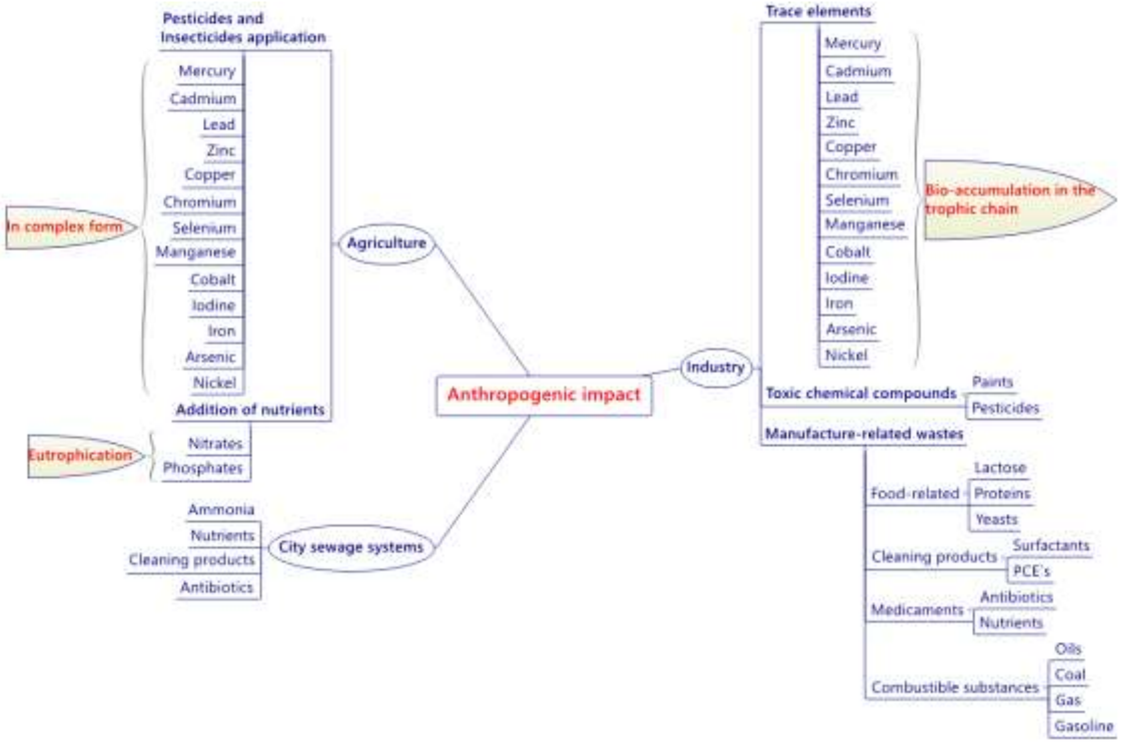


Figure 11. Scheme of anthropogenic pollution sources and their impacts.

According to the recent analysis, coastal pollution is a high-concern problem that influences offshore aquaculture farms. As a result, to reach the sustainable development goals and conservation of aquatic resources, marine pollution has to be under precise control (Islam & Tanaka, 2004). Shellfish species farmed in bays are often being exposed to the agricultural pollutants as it is common to use them and wetlands both for aquaculture and agrarian purposes (Ochoa et al., 2012). Also, sewage effluent poses a significant direct or secondary impact on ecology and living organisms, as it contains a wide range of harmful compounds, such as heavy metals, trace elements, viral, bacterial and protozoan pathogens, organic pollutants, toxic elements and a vast variety of other organic and inorganic components (Islam & Tanaka, 2004). Main problems and pollution sources are described below.

3.2.1. Nitrogen

Due to increased anthropogenic activity during the last several decades, the amount of bio-available Nitrogen, formed as a result of human activity, has increased drastically and almost reached the natural rate of creation. In the year 2000 reactive artificially-regulated nitrogen creation was 165 TgN/year. This equals to the 33-55% of global reactive nitrogen formation growth, taking into consideration the natural fixation rates. Land-based sources are the main cause of nitrogen in trophic estuaries. Thus, to measure the level of nitrogen sources growth, it is necessary to compare human-controlled nitrogen production rates to the on-land natural fixation. So, the recent assumption is that approximately 60 TgN/year flows into the ocean through the rivers that are twice more than 1860`s estimation (Boyer et al., 2006; Boyer and Howarth, 2002; Girardet, Herbert,2008)

Reactive Nitrogen is artificially created due to:

1. Synthetic nitrogen fertilisers production;
2. Stimulation of biological nitrogen fixation in agriculture;
3. Unintended release of chemically active nitrogen during combustion of fossil fuels (Galloway et al., 2004).

Out of the mentioned processes, the most influential developed and geometrically progressed one in terms of production rate in the manufacturing of the synthetic nitrogen fertiliser. It has developed a lot throughout the 20th century, and now the fixation of synthetic ammonia dominates in agriculture, as more than a half of the artificial fertilisers in the world has been produced since 1985 (Howarth et al., 2002a, 2005).

Also, the natural nitrogen cycle has undergone dramatic change due to the increased agricultural activity – especially flux of the nutrient into rivers and further to the sea. Even though riverine nitrogen flux is dependent on climate, as it is higher in the areas with the higher precipitation rate and discharges, the flux is firmly under the human impact. For example, in the areas of the low human activity, the background rate of the nitrogen wash-off to the rivers is around 100 (kg*km^2)/year, while in the regions, used intensively for industrial and agricultural needs, it is more than 10 times higher, for instance as in the watersheds that reach the North Sea, where the nitrogen flux is approx. 1500 (kg*km^2)/year or the Mississippi river that carries 6-fold of the natural concentration in waters (Howarth et al., 1996).

Interestingly, higher concentrations of nitrates are associated with lower values of conductivity. Irrigation waters from agricultural fields dissolve nitrogenous compounds from fertilizers and so they are washed off to the coastal areas. As waters, rich in dissolved nitrogen first discharge into coastal estuaries, it was possible to notice and experimentally proof the fact that contaminated lagoons have decreased levels of salinity that also caused a drop in the conductivity levels (Morales, Martí, Llopis, Campos, & Sagrado, 1999).

3.2.2. Phosphorus

The most often found form of phosphorus worldwide is phosphates (P-V), and it is ready for biological absorption, so it has always been used as a fertiliser and in pesticide in agriculture. Besides, phosphate and other forms of phosphorus are used in detergent production and as a food additive. As a result, over-fertilisation, industrial and domestic wastewater discharge leads to the excess phosphorus concentrations in surface waters that end up in the coastal area and open ocean waters. Thus, to avoid eutrophication of the aquatic media, it is necessary to monitor and access phosphorus content in media. Currently, it is 0.12% of phosphorus in the Earth crust, and it is mostly found in mineral form – vivianite, chlorapatite, fluorapatite and phosphorites. Apatites are considered as the most extensive stock of phosphate on Earth and are almost insoluble in water.

Phosphorus is known as the main nutrient for the aquatic environment and for now, is considered as the critical compound that influences marine productivity drastically. Most of the phosphorus in the seawater comes from its resuspension from the sediment that has a significant impact on the marine nutrient dynamics. In this way, water quality is under the considerable influence of the phosphorus concentration in the water column, which high level may lead to eutrophication. Thus, not all the phosphorus fractions cause eutrophication, so it is necessary to assess the content of various fractions in addition to the total phosphorus concentration measurement to predict the risk of eutrophication in the marine environment.

Major sources of phosphorus in seawater column are agriculture, untreated sewage water release and sediment. Impact of sediment resuspension on seawater is dependent on the chemical form of phosphorus-bonded compounds and has to be studied to understand if deposits act as a source of phosphorus release and in this way accelerate eutrophication process or it absorbs the nutrient (Aydin et al., 2009).

3.2.3. Eutrophication

Eutrophication is one of the foremost worldwide issues of the coastal area during several decades, that increases from year to year and boosts dimensions and occurrence frequency of harmful algal blooms, that causes also anoxic and hypoxic conditions, degradation of the natural habitat and, therefore, loss of biodiversity, disruption in the food-web (Howarth et al., 2000; NRC, 2000; Boesch, 2002). Mostly, this process is caused by a high concentration of nitrogen in the water column and also the availability of phosphorus, that is the reason for excess phytoplankton growth. In particular, coastal flora and fauna are exposed to harmful after-effects in closed estuaries and lagoons (NRC, 2000; Howarth et al.,2005; Howarth and Marino, 2006).

Coastal ecosystems respond to nutrient overload in two broad ways. Direct and the first-seen reactions are shifts in chlorophyll concentrations, primary production rates, algal biomass, algal blooms occurrence, and organic matter sedimentation patterns. Indirect responses include sediment biogeochemistry variations, transformations in benthos community structures and biomass, changes in food chain structure, alterations of dissolved oxygen and water transparency, and mortality of marine organisms (Cloern, 2001). Reduction of water transparency and intensity of light, passing to the deeper layers, is one of the indirect responses to increasing of plankton biomass. Though, it limits submerged vascular plants` development and growth. Intensive algae bloom cause hypoxia but the final collapse of algae leads to anoxic regime development and mass benthos and marine organisms` mortality. Due to this, changes in species composition, marine community structures and functions are quite likely to change. Moreover, one of the most hazardous consequences that follow seawater pollution is red tides – toxic algal blooms (Islam, 2005). The main species are dinoflagellates, which intensive growth may lead to the release of toxic substances and cause illnesses or lethal cases to aquatic organisms and people. In case of severe blooms, neurotoxins enter bivalves' bloodstream through the gills and fish die. For humans, red tide is a reason for respiratory problems development, but another threat appears through shellfish contamination. Shellfish, oysters, clams and coquinas in particular, can accumulate so many toxins that they become toxic to humans. All in all, eutrophication causes deterioration of the environmental quality and in such way has a negative impact on the amenity, recreational values and the tourist industry in addition to the ecological and biological losses (Islam, 2005).

3.2.4. Heavy metals

3.2.4.1. Sediment influence and contamination

Sediments are made of organic and inorganic particulate matter that has complex chemical, physical and biological characteristics. Some elements can be absorbed by deposit from the water column, and for this reason, it may have a much higher concentration of heavy metals and other chemical compounds. So, sediments are suitable for pollution monitoring. Nonetheless, deposits may also be considered as a source of contamination due to resuspension, redox reaction, adsorptive particles degradation, remobilization and desorption processes. For this reason, it has a long-term impact on the water quality and food chain, so well-timed quality monitoring and pollution source detection is necessary (Kalantzi et al., 2013).

Metals and phosphorus are binding to the sediment particles due to ionic exchange with iron and manganese coatings. Due to this, numerous bio-accumulating toxic pollutants are deposited to sediments and are also associated with organic carbon. It is transferred as river sediment to the estuaries. It was researched that almost 90% of phosphorus flux in freshwaters occurs due to the sediment transport in Europe and North America (Islam & Tanaka, 2004).

3.2.4.2. Land pollution

Agricultural pollution affects the environment by bioconcentration – when chemical compounds are absorbed from the surrounding environment into the organism due to the lipophilicity of most of the pollutants and biomagnification – increasing of the element concentration in a food chain (Islam & Tanaka, 2004).

Pesticides are chemical substances that purpose to kill pests, including insects, rodents, fungi and unwanted plants (weeds). This term incorporates all of the herbicides, insecticides, nematicide, molluscicide, piscicide, avicide, rodenticide, bactericide, insect and animal repellents, animal, fungicide, disinfectants and sanitizers (Li & Liu, 2018). In public health, Pesticides assist in destroying vectors of disease, such as mosquitoes. It is necessary to apply and dispose of pesticides appropriately due to their potential toxicity to other non-targeted organisms (WHO,2019). Moreover, more copious amounts of various pesticides are used recently. As a result, residual pesticides are infiltrated into groundwater tables, washed off to the surface waters and brought to the sea, that lead to toxic effects on organisms and plants (Li & Liu, 2018).

Impacts of pesticides are very complex and are regarded as an indicator of potential human health disruptors if any effects on the organisms or ecological level are found. One of the main issues is that these effects are hard to recognise, as they are mostly chronic. Mainly, they include cancer, lesion or tumour development, failure of the reproductive function, disruptions of the endocrine and immune systems, DNA, molecular or cellular damages, low red-to-white cell ratio in the blood, excessive slime on fish scale and gills or even fatal cases of organisms. Possibly, these effects are the result not of the pesticides, heavy metals or organic contamination but of combined exposure to the environmental stresses, that also include pathogens, eutrophication, oxygen depletion. In any case, the whole trophic chain is affected (Islam & Tanaka, 2004).

3.3. Heavy metal`s pollution sources

Mercury

Main sources of mercury (Hg) contamination are discharges from urban and industrial wastewater treatment plants, agricultural substances, mining, smelting and combustion (Zhang and Wong, 2007). In the Ebro river, Hg originates from the electro-chemical factory that was established at the end of the 19th century and produces chlorinated solvents. It is located 90 km upstream of the river delta, on the bank of the Flix reservoir (Carrasco et al., 2011).

Cadmium

The major source of Cadmium is also chemical compounds, such as pesticides, used in agriculture. This theory is supported with an example of the coastal area near the Mali Ston Bay to the south from the Istrian Peninsula. Local mussels showed higher cadmium concentrations than other closely located off-shore farms that occurred due to the influx of fresh water into the bay from the Neretva river. Contaminated river load with absorbed trace elements is brought with the flow, that disposes of in the bay (Kljakovic´-Gaspic´ et al.,2007). So, the same pattern is observed in the Mediterranean coast in general. Another source of this heavy metal is again the chloro-alkali factory in Flix (Bosch et al., 2009).

Lead, Arsenic, Cuprum and Zinc

Main source of lead contamination in the Ebro delta is the Flix factory (Bosch et al., 2009). Due to the long-time of its operation time, sediments, highly enriched with Lead, are dispersed over 100 km of the river until it is released into the sea. Other elements mainly originate from fertilisers and pesticides used in agriculture in the region.

3.3.1 Pollution sources in the Ebro Delta area

Overall, in the area surrounding the Ebro Delta, two main pollution sources are present. The main one is industrial plants, located upstream, that discharge heavy metals, especially Hg and Pb into Ebro river waters and over the past 50 years contaminated river sediment. Due to this, continuous resuspension and the additional load of contaminated sediments into the bays are present. The second origin of pollution is agriculture due to intensive use of pesticides, reach with trace metals and fertilisers, that are a source of excess nutrients (Ochoa et al., 2013). Moreover, because the ceramic industry located in the region of Valencia uses pigments that contain lead and cadmium, coastal sediments and waters are carrying these hazardous elements (Morales et al., 1999).

3.4. Health consequences

There is a list of elements that are essential for human body function – zinc, copper, selenium, chromium, cobalt, iodine manganese, molybdenum and the body regulates their absorption. They are vital for the proper enzyme and bioactive substances functioning. Due to this fact, deficiency of any of the elements expresses in a group of symptoms, so that deficiency identification of one particular element becomes problematic (Wada, 2004). However, an excess of metals leads to a negative impact on human health. In addition, there is a whole group of heavy metals, the damage from which is hard to overestimate.

Heavy metals are pollutants of crucial environmental concern due to the high toxicity rate and bioaccumulation, so constant monitoring is necessary (Morales et al., 1999). In accord with Davies, 1978 – ten main heavy metals were concerned as toxic and have been restricted in many countries but not worldwide. They were systematized according to their toxicity level and appear as follows: mercury, cadmium, silver, nickel, selenium, lead, copper, chromium, arsenic and zinc.

Mainly, heavy metals are associated with the metabolic processes' obstruction. Most of the heavy metals bind with sulfhydryl groups of the living organism – crucial proteins and enzymes. In phytoplankton and other marine algae metals also impact cellular integrity. Furthermore, metals tend to concentrate in the organism`s liver and muscles, that leads to numerous responses, such as lung pathologies, lymphocytic infiltration, fatty degeneration and decreasing nutritional state. Moreover, lead, mercury and cadmium are potential immune-suppressants (Islam & Tanaka, 2004).

According to Jezierska and Witeska (2006), Labile metal compounds are considered as the most hazardous ones to the fish health as they are classified as water-soluble heavy metals. So, environmental factors do influence significantly the accumulation rate of heavy metals in bivalves that include various ionic forms with different consumption bioavailability. This statement is confirmed by numerous researches and data assimilated, for instance heavy metal in fish organs accumulation studies by Ghosh and Adhikari (2006), Mohammadnabizadeh et al. (2014) and Velma et al. (2009) that proved the fact that most of the heavy metals present in water are in labile form.

Mercury

One of the metals that need particular concern is Mercury. This trace metal has a high potential level of neurotoxicity. Exposure to any water-soluble forms of this metal, such as mercuric chloride or methylmercury (CH3Hg), vapour inhalation or consuming metal with food results to the severe poisoning. Methyl-mercury (CH3Hg) is the most toxic form of mercury, and affects the immune system, alters genetic and enzyme systems, and damages the nervous system.

For marine mammals’ mercury concentrations of 100-400 µg/l of wet weight in the liver pose a high risk to their lives. This metal has a high level of bio-magnification in the trophic chain and age-related accumulation in the tissues due to its long persistence and high rates of mobility in the ecosystem (Islam & Tanaka, 2004). Until now the primary source of mercury for humans is marine fish (Ochoa et al., 2013). Fish is more likely to accumulate methylmercury in its muscle tissues and viscera rather than depurate it, so concentrations increase over time. Now, Mercury poisoning is called Minamata disease after numerous cases in Japan (Li & Liu, 2018).

Cadmium

Another non-essential metal for organisms is Cadmium that is also considered as a highly toxic compound for wildlife and the human body. Long-term exposure to this metal severely affects kidneys, brain, lungs and placenta. International Agency for Research on Cancer (IARC) has classified it to the first group of carcinogenic compounds as it affects kidney, lung and liver cells (FAO/WHO, 2011). Regarding this, divalent Cadmium ions ($Cd^{2+)}$ are particularly dangerous due to the fact that their atomic radius almost perfectly coincides with the radius of divalent calcium ions (Ca^{2+}). Thus, cadmium carries out its toxic impact, causes cells` death and destroys tissues of the organism by substituting calcium in cells, that is a vital regulator of intracellular processes. (Silkin, 2005) Moreover, vitamin D metabolism undergoes severe disruptions due to cadmium-induced failure of kidneys, that causes lower rates of calcium absorption and triggers osteoporosis and osteopenia progression, peculiarly for pregnant and multiparous women. It is the neurotoxic, genotoxic and nephrotoxic element. A strong influence on endocrine, reproductive, haematological and immune systems was determined, according to the recent public health researches ((EFSA, 2009), (ATSDR, 2012). Same patterns are observed and valid for marine mammals. Cadmium levels in kidneys of harbour porpoises in the eastern Scottish coast were linked with their age (Islam & Tanaka, 2004).

Due to all the above-mentioned effects, the use of cadmium is decreasing all over the world, as it is listed in the European Restriction of Hazardous Substances (Morrow, 2010). So, nickel-metal hybride and lithium-ion batteries substitute the nickel-cadmium ones (Li & Liu, 2018).

Nickel

Nickel is one of the essential for organisms and plants functioning metal, as it is one of the constituents of the enzyme`s active sites. Nevertheless, overconsumption and being a compound of hazardous alloys it may cause respiratory problems, dermatitis, retarded growth, degenerative disorders and hyperglycemia (Li & Liu, 2018).

Selenium

According to WADA (Wada, 2004), some symptoms of excess concentrations of Selenium in the human organism are central neural system disorders, selenosis, nail detachment and alopecia.

Lead

One of the most toxic elements that severely disrupt metabolism in Lead. This neurotoxin accrues in bones and soft tissues of lungs, liver, spleen and kidneys. Moreover, lead ions (Pb 2+) can overcome the blood-brain barrier and reach placenta (Gwaltney-Brant and Rumbeiha, 2002) and causes cell membrane destruction, enzyme function and tissue structure disruption. Also, lead causes blood disorders and mutilates the nervous system, that is especially harmful to children. They have a high risk of brain damages even when the blood level was normalized (Li & Liu, 2018). Nevertheless, it is rarely found in high concentrations in shellfish as bioavailable dissolved and the dietary lead is seldom with an exception for highly polluted zones and sediments (Ochoa, 2013).

Copper

Copper is also one of the vital metals in the diet as it is a main component of the cytochrome-c-oxydase respiratory enzyme complex. In crustaceans and molluscs, it is essential for the formation of the hemocyanin - blood pigment, whereas other vertebrates and fish have iron-based haemoglobin instead (Li & Liu, 2018). So, it has a tendency to bioaccumulation in fish tissues, having its toxic impact even at the molecular level and their level of copper accumulation may reach the concentration of hundreds to thousands of times above the concentration measured in the food, water and sediments (El-Moselhy et al., 2014; Kumar & Prabhahar, 2012). One of the important functions of copper is its use as an algaecide (Ajani & Akpoilih, 2010; Carvalho & Fernandes, 2006), which is globally used to kill algae and to prevent fish from being killed or harmed. However, this application is not safe for all aquatic organisms, especially fish as it can easily enter the fish's body regardless of its amount. Due to the fact that the liver regulates copper metabolism and is crucial for copper homeostasis (Das & Gupta, 2013).

Fish are relatively sensitive to the changes that occur in their surroundings, including an increase in pollution. The health of fish may thus reflect and display the health status of a specific aquatic ecosystem. Early toxic effects of pollution are only evident at the cellular or tissue level before significant changes can be identified in the physical appearance and behaviour of the fish.
Heavy metals accumulated in the gills will affect the respiration and osmoregulation processes, causing cellular damage to gill cells (Maharajan et al., 2016; Pandey et al., 2008). A study by Figueiredo-Fernandes et al. (2007) on *Oreochromis niloticus* treated with copper showed similar abnormalities in the gill tissues including epithelium lifting, interstitial oedema, lamellae fusion and lamellae aneurysm. Aneurysm and oedema were observed to be clearly related to short-term copper exposure, while lamellae fusion was related to chronic exposure of copper (Khabbazi et al., 2015; Padrilah, Sabullah, Yasid, Shamaan, & Island, 2018)

Excess state symptoms for human consumers are nausea, vomiting, heartburn, diarrhoea, jaundice, hemoglobinuria, hematuria, oliguria, anuria, hypotension, coma, melena (Wada, 2004) alongside the liver and kidney damage, anaemia, immunotoxicity and developmental toxicity (ATSDR, 2004).

Chromium

One of the metals which properties depend on the chemical form is Chromium. While trivalent chromium (Cr(III)) in trace concentrations is necessary for lipid, sugar and insulin metabolisms, its hexavalent form (Cr(VI)) is considered carcinogenic and toxic for organisms (Li & Liu, 2018), (Morales et al., 1999). Consuming this form of metal may result in skin and mucosa’s irritation, cause chromosomal anomalies in human bodies. Simultaneously, overconsumption of trivalent chromium may cause disorders in the central neural system, malfunction of kidneys and liver, growth retardation and nausea with vomiting at the early stage (Wada, 2004).

Zinc

Excess state symptoms of zinc presence in organism count in case of short-term exposure some Fe-Cu deficiency, nausea, vomiting, abdominal pain, hyperamylasemia, somnolence, hypotension, lung oedema and diarrhoea. Consequences of the long-term exposure are becoming chronic and include reduced reproductive function, dwarfism, taste disorder, hyposmia and anaemia and severe neurological diseases (Wada, 2004), (Hedera et al., 2009). Consumption of excess zinc can cause ataxia, lethargy, and copper deficiency. (Li & Liu, 2018)

Manganese

Manganese is a highly toxic, and several studies have suggested that ingestion of water and/or foodstuffs containing increased concentrations of this trace element may result in adverse neurological effects (ATSDR, 2012).

Ferrum

high Fe intake and/or Fe stores with an increased risk of chronic diseases such as cardiovascular disease, type II diabetes and cancer of the gastrointestinal tract (EFSA, 2004).

All in all, regular monitoring of metals and their various forms and compounds are essential for the safe and sustainable development of aquaculture. At the same time, research on the distribution of metals in coastal waters is currently extremely insufficient. Studies are generalized, and high-resolution mathematical models in the coastal zone, especially important and tailored for the development of aquaculture are not developed at all. Thus, one of the core goals of this study is the assessment of the distribution of heavy metals in coastal waters.

3.5. Cases of coastal areas contamination over the Mediterranean Sea

Several types of research, conducted during the past five years in lagoons and estuaries of the Mediterranean Sea confirm the necessity of continuous water quality and sediment monitoring to meet the requirements of the food safety standards for crustaceans and bivalves, massively produced in off-shore farms.

In 2016 (Esposito et al., 2018) conducted an assessment of heavy metal contamination in four lagoons of Sardinia, used for extensive aquaculture production. Researches used an autochthonous clam *(Ruditapes decussatus)* from off-shore farms as a biomonitor. The analysis of non-essential trace elements has shown high concentrations of Aluminum in samples, that corresponds to potential exceeding of provisional tolerable weekly (PTWI) level if and adult consumes 340 g and a child of 25kg only 120g of clams from Santa Gilla lagoon weekly. San Teodoro samples have shown twice lower concentrations of Aluminum that still poses a high risk, especially for children. This contamination is explained by the presence of the fluorochemical plant near the lagoon.

Another example is the Tagus estuary that receives the waters of the second biggest river in the Iberian Peninsula and, at the same time, is a major seaport and hosts commercial and fishing activities (Chainho et al., 2014; Duarte et al., 2014). The threshold for the maximum concentrations of chromium, nickel, cadmium and argentum were not exceeded, whereas lead and arsenic concentrations in Barreiro Bay were higher than allowed maximums for clams, that becomes a serious concern for the health of consumers. Nevertheless, sediments of estuaries showed that levels of As, Pb, Hg, Zn, Ni were higher than standards of permissible exposure limit (PEL) due to metallurgic and chemical industries in the area (Chiesa et al., 2018).

At the same time, statistical analysis of non-essential elements concentration in flat oysters (*Ostrea edulis*) and Mediterranean mussels *(Mytilus galoprovincialis*), produced on the aquaculture farms in the Croatian coast in Mali Ston Bay, Istrian Peninsula, Krka estuary and Novigrad Sea, was performed. The results show that continuous consumption of oysters produced on local farms poses risks for human health due to the fact that concentrations of carcinogenic element Cadmium exceed weekly intake limits by 32% (Bilandžić et al., 2016).

Lastly, investigation of Mediterranean mussels (*Mytilus galloprovincialis*) and Pasific oysters (*Crassostrea gigas*) from the aquaculture facilities in the Gulf of La Spezia (Italy) has shown that copper and zinc concentrations in oysters were higher than recommended values. At the same time, mussels could comprise risk for humans due to exceeding the tolerable daily intake threshold for aluminum (Squadrone et al., 2016)**.**

More researches, in addition to presented four above, confirm the necessity of constant analysis and monitoring of the trace elements in water and sediments in the vicinity of aquaculture facilities prior the assessment of heavy metal contamination in crustaceans and bivalves(Li & Liu, 2018).

3.6. Legislation and frameworks, regulations

Currently, surface water quality standards are regulated by the Water Framework Directive 2000/60/EC of the European Parliament and Council. It had set up precise standards for maximum allowable concentrations of substances and physical parameters that define water quality and has set goals for the sustainable development and reaching the so-called “good status” of surface and groundwaters.

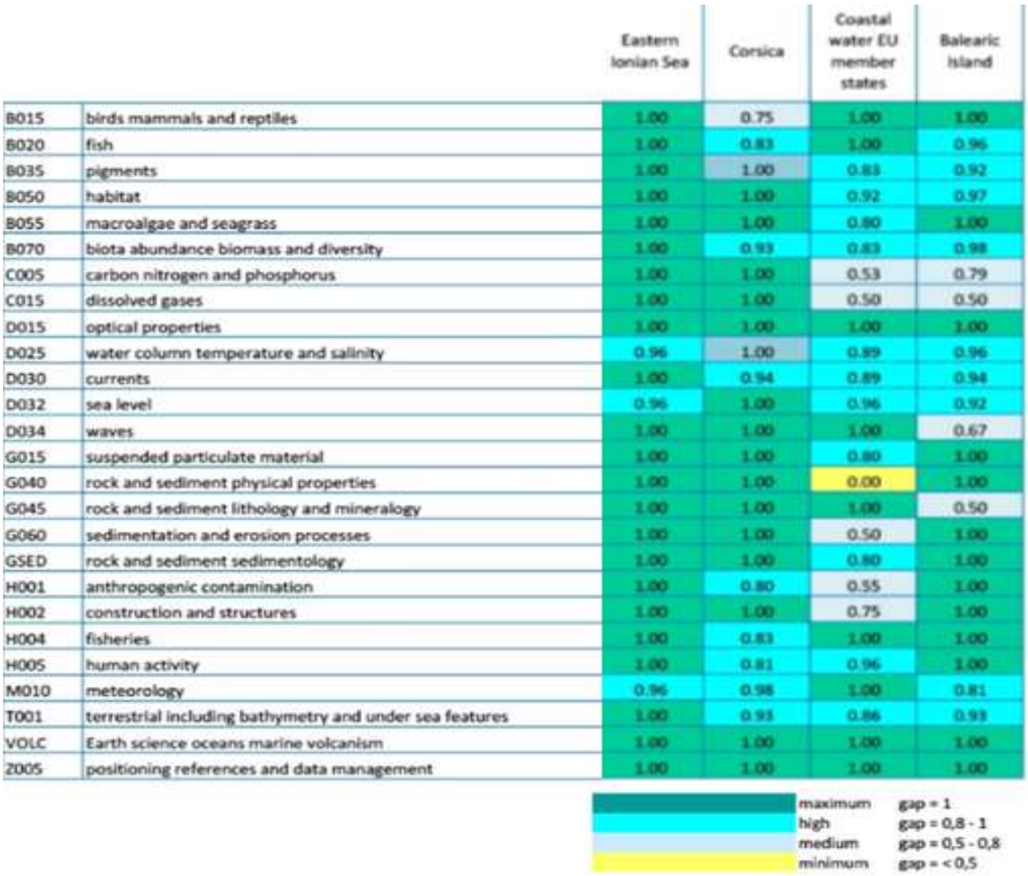
Maximum concentrations of elements in food products are listed in accord with the European Union legislation (no. 1881/2006 (European Commission 2006))/ So that the maximum limit for heavy metals in edible wet mass is 0.5 µg/g for Hg, 1 µg/g for Cd, and 1.5 µg/g for Pb. The Maximum Limit of Tolerance (MTL) recommended by the European Commission for Hg=3.3 µg/g, Pb=10 µg/g, and Cd=6.6 µg/g, assuming 85 % of water content. Maximum tolerable levels for essential elements such as Zn, Cu, and As are set yet neither on European nor on Spanish local levels (Ochoa et al., 2013). Though, European Food Safety Authority has set consumptions rate of the heavy metals of interest as follows:

- Copper – 5mg/day for adults,
- Zinc – 25 mg/day;
- Iron – recommended dietary intake levels are 45 mg and 40 mg for children and adults, respectively. Thus, the upper intake limit is still not decided;
- Manganese – 11 mg/day of the Upper Intake level for adults (ATSDR, 2012);
- Cadmium – 70 µg/day for an adult of 70 kg;
- Aluminium – 10 mg/week of a tolerable intake level.

In 1995 the Action Plan for the Protection of the Marine Environment and the Sustainable Development of the Coastal Areas of the Mediterranean (MAP Phase II) was implemented to substitute the Mediterranean Action Plan of 1975. The new plan of the Barcelona Convention developed seven Protocols to address specific aspects and set goals for the future of Mediterranean environmental conservation. Moreover, Horizon2020 initiative was based on the Convention with the main objective to determine and deal with the main pollution sources in the Mediterranean area.

3.7. Global models overview

According to the latest research on data acquisition and analysis of the existing models in the Mediterranean Sea, conducted by Dr Garcia (Garcia, et al., 2019), that included accessing 122 data platforms and almost 500 records, coastal water quality for the European Union member states receives some recognition. Though, least information is available regarding the status of fisheries and human activities in the Balearic area (Fig.12).



		Eastern Ionian Sea	Corsica	Coastal water EU member states	Balearic Island
B015	birds mammals and reptiles	1.00	0.75	1.00	1.00
B020	fish	1.00	0.83	1.00	0.96
B035	pigments	1.00	1.00	0.83	0.92
B050	habitat	1.00	1.00	0.92	0.97
B055	macroalgae and seagrass	1.00	1.00	0.80	1.00
B070	biota abundance biomass and diversity	1.00	0.93	0.83	0.98
C005	carbon nitrogen and phosphorus	1.00	1.00	0.53	0.79
C015	dissolved gases	1.00	1.00	0.50	0.50
D015	optical properties	1.00	1.00	1.00	1.00
D025	water column temperature and salinity	0.96	1.00	0.89	0.96
D030	currents	1.00	0.94	0.89	0.94
D032	sea level	0.96	1.00	0.96	0.92
D034	waves	1.00	1.00	1.00	0.67
G015	suspended particulate material	1.00	1.00	0.80	1.00
G040	rock and sediment physical properties	1.00	1.00	0.00	1.00
G045	rock and sediment lithology and mineralogy	1.00	1.00	1.00	0.50
G060	sedimentation and erosion processes	1.00	1.00	0.50	1.00
GSED	rock and sediment sedimentology	1.00	1.00	0.80	1.00
H001	anthropogenic contamination	1.00	0.80	0.55	1.00
H002	construction and structures	1.00	1.00	0.75	1.00
H004	fisheries	1.00	0.83	1.00	1.00
H005	human activity	1.00	0.81	0.96	1.00
M010	meteorology	0.96	0.98	1.00	0.81
T001	terrestrial including bathymetry and under sea features	1.00	0.93	0.86	0.93
VOLC	Earth science oceans marine volcanism	1.00	1.00	1.00	1.00
Z005	positioning references and data management	1.00	1.00	1.00	1.00

🟩	maximum	gap = 1
🟦	high	gap = 0,8 - 1
⬜	medium	gap = 0,5 - 0,8
🟨	minimum	gap = < 0,5

Figure 12. Information gap assessment. Source: Garcia, et.al. 2019.

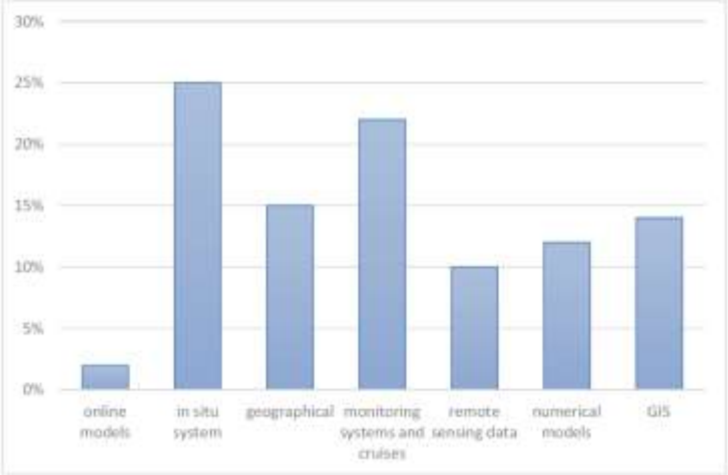


Figure 13. Variability in platform typologies. Source: Garcia et al., 2019.

Moreover, assessment of online platform typologies has shown that only around 2% of modern data platforms provide users with ready-to-use online models. Interestingly, numerical of remote-sensing models make an assessment on nitrate and phosphate concentration parameters in the water column and have open data occur only 4 times in databases while heavy metals data appear less than 3 times or are not mentioned at all (Fig.13).

3.8. Model in the research area

In the research area of Ebro river Delta the model that aimed to assess the hydrodynamic response of the Alfacs bay to local wind direction and seiches. Seasonal and spatial variabilities of the residual flow circulation were investigated for the year of 2013 – 2014 (Cerralbo, 2018). Thus, due to the fact that mentioned research had a different objective than the current one research and was not aiming the contaminant propagation model development, its results are used to gain a general understanding regarding the flow characteristics in the bay. Moreover, this thesis research takes into consideration, not the single-bay but has a sophisticated approach to the whole Delta. Therefore, to answer the posed questions and necessities of the aquaculture facilities in the area, the decision was made to set-up a new high-resolution integrated hydrodynamic and transport model.

4. Methodology

The posed problem requires a sophisticated approach. To fulfil the main task of studying the spread of pollutants in the area that is intensively used for aquaculture purposes, it is necessary to develop an integrated hydrodynamic and water models. Water quality models represent the movement of substances entering the domain through lateral inflows, point sources or boundaries, taking the already present background concentrations of substances as initial conditions. Simultaneously, the specific chemical and biological behaviour of pollutants are assessed. Groups of substances are included in modelling due to their interconnection. For instance, the sedimentation rate of adsorbed cadmium is associated with a sedimentation rate of inorganic suspended particles in the water column (Delft3D Flow-FM manual, 2019). In this way, the fluid dynamics are characterized accurately and freshwater influx, as well as chemical, biological reactions in the water column, are represented. Therefore, the integrated modelling approach is chosen for this research.

The following chapter describes the technical decisions that were made in order to address the research targets.

4.1. Data description

For the hydrodynamics and water quality model set-up, calibration and validation, several datasets are used. Derived products include remote sensing data, in-situ measurements, and continuously analysed and upgraded meteorological, hydrodynamic and ecosystem models. In this case, descent spatial coverage with data of the domain is reached and with supplementary in-situ time series model validation is performed.

Copernicus Marine Environment Monitoring Service (CMEMS)

For the hydrodynamics and water quality assessment, the datasets from the Copernicus services are used. Sea level, ocean colour and sea surface data are gathered by the Sentinel-3 satellite remote sensing. Then, it is further operated in the data assembly centres that develop and run near-real-time forecasting numerical models for normal and longitudinal currents, Chlorophyll-a, nutrients, water turbidity as well as climate change, ecosystems (phytoplankton, zooplankton, fish stock) and weather (CMEMS www.esa.int)

For this study the following datasets from Copernicus Marine Environment Monitoring Service (CMEMS) are used:

1. MEDITERRANEAN SEA PHYSICS ANALYSIS AND FORECAST

Hourly data of modelled current velocities (northward and southward), surface and sea bottom temperatures, salinity and sea surface above geoid time series of a horizontal grid resolution of 1/24 degree (approx.4.6km) with 141 unevenly distributed depth layers (Clementi et al., 2019). The hydrodynamics are supplied by the Nucleus for European Modelling of the Ocean (NEMO v3.6) while the wave component is provided by Wave Watch-III; the model solutions are corrected by a variational data assimilation scheme (3DVAR) of temperature and salinity vertical profiles and along-track satellite Sea Level Anomaly observations (CMEMS www.esa.int).

2. MEDITERRANEAN SEA- IN-SITU NEAR REAL-TIME OBSERVATIONS

In-situ observation data of the seawater temperature, direction of seawater velocity, practical salinity and other variables, not used in this project, is collected by the In-Situ Thematic Assembly Centre (INS TAC) and updated on the CMEMS portal several times per day.

3. MEDITERRANEAN SEA BIOGEOCHEMISTRY ANALYSIS AND FORECAST

Also, the sea surface height above the geoid, daily nutrients near-forecast-model data of satellite chlorophyll imagery in 3D with mass concentrations of chlorophyll, mole concentrations of phytoplankton expressed as carbon, dissolved oxygen, nitrates and phosphates along with primary production rate assimilation is used (Bolzon G., et al, 2017).

In-situ measurements

In order to represent dynamics and physicochemical processes in both bays in the most accurate way, the freshwater influx is taken into account. Due to this the Ebro river, canal De la Dreta del Ebre and canal de l`Esquerra del Ebre discharges, water level and temperature hourly time series were obtained from the SAIH (Automatic Hydrologic Information System) of the Ebro river basin portal. For the heavy metal and nutrients concentration semi-annual, monthly, weekly and daily datasets were obtained from the CHEBro analytical data portal CHEbro (chebro.es). In this case, the temporal resolution depends on the compound of interest and its monitoring frequency. The fifteen-minute time-series is available for nitrate and phosphate concentration in freshwater (on special request), that allows making a high-precision model and a near real-time prediction system. On the contrary, heavy metals and pesticides concentrations are measured once per half-year, as the heavy metal sampling frequency regulation in Spain is flexible and is accessed on monthly basis on 25-30% of sampling stations (EEA, 2019). In the year 2012 and 2013, though, these measurements are available on the monthly-basis, that allows to have the understanding of the background levels and estimate current rates of pollution, as agricultural methods did not change drastically in past 7 years.

As there is a high impact of the discharge canals of the rice fields in the Ebro area on the Fangar and Alfacs Bays due to the constant freshwater inflow, local discharge data for the model set-up is needed. Freshwater inputs have to be considered as it causes stratification in coastal sea waters, decrease in salinity and fluctuations in water temperature along with the sediment transport and run-off water from the fields that are rich with dissolved fertilisers and pesticides. Though, due to the lack of constant measurements, discharge rate time-series were generated based on the literature review that gives values of 6m^3/s (Navarro, 2009) and 10 m^3/s (Cerralbo, 2018) from each channel. So, the constant discharge time-series of 10 m^3/s were used.

Water flow, conductivity, transparency and salinity data inside the bays was obtained from the in-situ experiments, done by the IRTA researches. This data does not have constant temporal coverage but gives an indication of the dynamics patterns in the bays.

Last but not least, water quality measurements with nutrients, heavy metal and pesticide concentrations were gathered from the 25 observation stations in the Delta area we obtained on special request from the Catalan Water Agency.

4.2. Modelling Instrument

Delft3D FM Suite

The Delft3D FM Suite enables an integrated approach for hydrodynamic, water quality and waves modelling in one, two or three-dimensional applications.

Delft3D Flow Flexible Mesh

In order to model hydrodynamic and transport processes, that result from the tidal and meteorological forcing, the Delft3D Flow Flexible Mesh (Further D-Flow FM) module is used. The D-Flow FM solves the unsteady shallow water equations in two (depth-averaged) or in three dimensions. The system of equations consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. The continuity equation is solved implicitly for the whole grid when time integration is explicit for the part of the advection term. It is estimated that the modelled fluid is incompressible and therefore Navier Stokes equations with the Boussinesq and shallow water assumptions are solved. Vertical acceleration is neglected, so the hydrostatic pressure equation is used and vertical velocities in 3D models are calculated from the continuity equation.

In comparison with other software, it is beneficial due to the possibility of unstructured grid application consisting of triangles, quadrangles, pentagons and hexagons that allows to model complex areas, for instance, curvilinear coastlines, ports or lagoons (D-Flow FM UM, 2019). The structured grid representation is not smooth enough for curved land boundaries, that leads to irregularity in border representation and, thus, discretization errors. For the vertical grid set-up in this 3D simulation set-up, the σ - layering is used, as it better represents the stratification compared to fixed Z-layer coordinates, that are, though, also available in the package.

4.3. Model period

According to the assessment of the ecosystem impacts on oysters in both Alfacs and Fangar Bays and recent statistics, oyster mortality often occurs in the summer period, in May and June especially. This tendency is associated with the time of major use of pesticides in the rice fields of the Ebro Delta. Local agriculture uses up to 20,000 tons of approximately twenty-five chemical compounds with organophosphates being the major pesticide (Kuster et al., 2008; Mañosa et al., 2001).

Moreover, according to (Ochoa et al., 2012) mortality rate of oysters varies from year to year. For example, during the experiment period in June 2008, the oyster mortality rate was between 15-19% in Alfacs Bay and 7-25% in Fangar Bay, while in June 2009 mortality rate rose from 10% to 70% in Alfacs Bay and 20% to 80% in Fangar Bay.

At the same time, both bays receive fresh water from the drain channels that bring residual water from the rice fields, and their input discharge differs throughout the year. During the summer period between April and September average discharge rate from the channels is 6 - 10 m^3/s (Cerralbo, Espino, & Grifoll, 2016) (Cerralbo, Espino, Grifoll, & Valle-Levinson, 2019). Therefore, this research aims to model the summer period since the discharges from the drain channels are high at this season and pesticide use on rice fields is at the peak during June.

Also, as previous hydrodynamic models were made in the Alfacs Bay area in 2013 and now it can be seen that bathymetry profile has changed slightly since then, it was decided to model the period of 15 May to 15 September 2017. Moreover, due to the advances in remote sensing instruments, satellite data starting from January 2017 became more precise. It is important as the CMEMS modelled and validated output datasets of currents, salinity, turbidity, temperature and nutrient concentrations are used as boundary conditions inputs and are now available with higher time-frequency, as daily average measurements are substituted with hourly time series. Moreover, spatial resolution changed from 0.125x0.125 degree (13.5x13.5 km approx.) to 0.042x0.042 degree (4.5x4.5 km approx.) Also, generally, more data is available for this year.

4.4. Bathymetry adaptation

Figure 14. Real bathymetry of the Ebro Delta. Source: EMODNET, DTM of 2018.

Local bathymetry is one of the critical components for the real representation of the hydrodynamic processes. Sea bed profile of the research area was obtained from the EMODNET Bathymetry service portal as a DTM file (Digital Elevation) of 2018 scanning with 161 m grid resolution.

Though, in the area of the Ebro Delta, as it can be seen on the bathymetry map below (Fig. 14), there is a structure in the coastal area that elevates from the sea for more than 20 meters, while surrounding bed level varies between -11m to -20 m deep. Supposedly, according to EMODNET portal data and the form of the elevated area, this construction could be an airport. In the open map service, Google Maps this area is an open sea. Such an obstacle would cause local flow irregularities such as vortexes and also still zones. Since this artificial island is not located in the area of interest and, moreover, due to the secrecy of the construction for the public, it was decided to erase the construction from the bathymetry profile.

This procedure was done with the help of QGIS software, where the construction was deleted and then the interpolation of surrounding bathymetry was made (Fig.15).

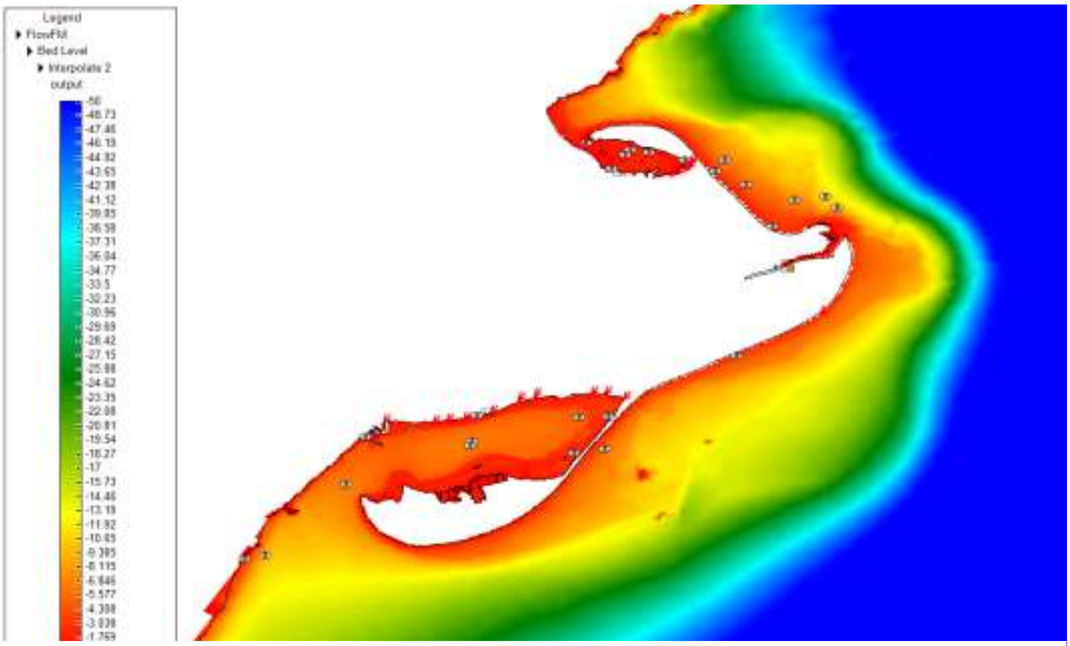


Figure 15. Adapted bathymetry profile.

4.5. Model setup

To address the aims of this research, the study domain of approximately 80x35 km was selected around the Ebro Delta area. Such a large spatial coverage is used to assess the influence of currents on the bays and to avoid computational instabilities and unwanted boundary effects that may occur if the boundary conditions are located too close to the area of interest. Initially, the regular coarse grid of 4500m resolution was created that was transformed into the irregular grid that has rectangular and triangular cells (Fig.16). With 7 levels of “Cells and Faces” grid refinement, that divides the grid cell into 4 (2-by-2), the 35m resolution in Alfacs and Fangar Bays areas was reached. Due to this, the resolution of the model grid is the following, from the outer coarse resolution to the inner higher resolution:

1. 4500 m
2. 2250 m
3. 1125 m
4. 562.5 m
5. 281 m
6. 141 m
7. 70 m
8. 35 m

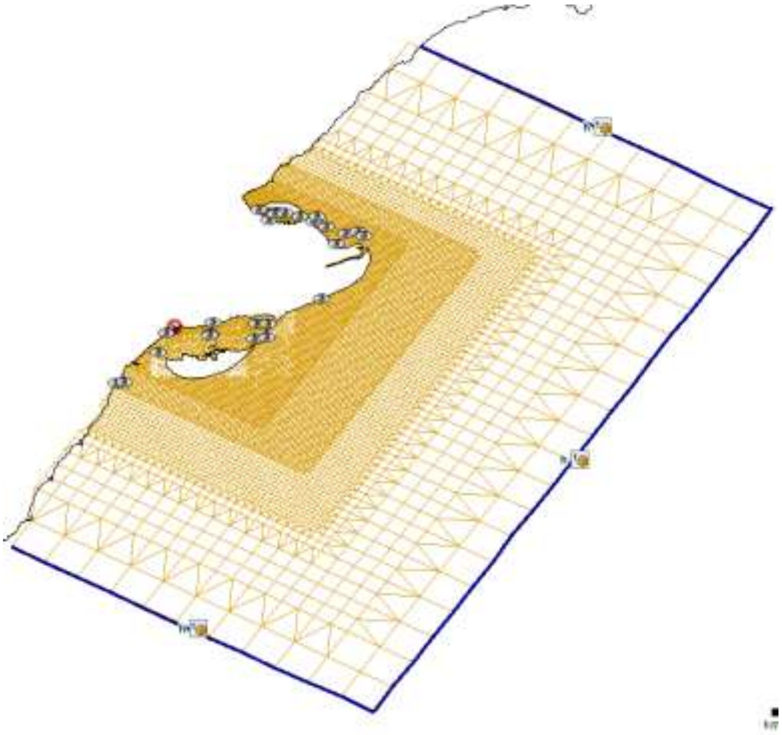


Figure 16. Unstructured grid over the domain.

It is also possible to continue refinement and reach a higher resolution in the area. Nevertheless, because aquaculture installations are at approx. 150 m from the shoreline and of 20-50 m width each, it is decided for the project purposes of keeping the resolution of 35 meters. In this way, the precise representation of local shoreline and complex geometry is achieved. Nevertheless, in case highest precision in the simulation of the transport and biochemical processes is required Delft3D FM Suite allows us to change the grid resolution without disruption to the model set up in the domain.

Initial conditions

Initial conditions of water level, temperature and salinity are uniform for the first model run, and are as follows:

Water level = 0m

Initial temperature = 19.5 ^{o}C

Salinity = 38 ppt

For the final set-up, the initial condition file data is used, that is the representation of the introduced salinity and temperature initial data over the whole domain at each grid cell.

Boundary Conditions

As boundary conditions the water level, normal and tangential velocities, salinity and temperature time series are assigned for the overall 2253 steps of hourly simulation that startы on 15 May 2017 and ends on 15 September 2017. So, corresponding time series of northward and eastward velocities, salinity, temperature and water level (steric and tide) are assigned on 12 points of South boundary, 21 points of the Long Boundary and 11 at the North Boundary, respectively (Fig. 17).

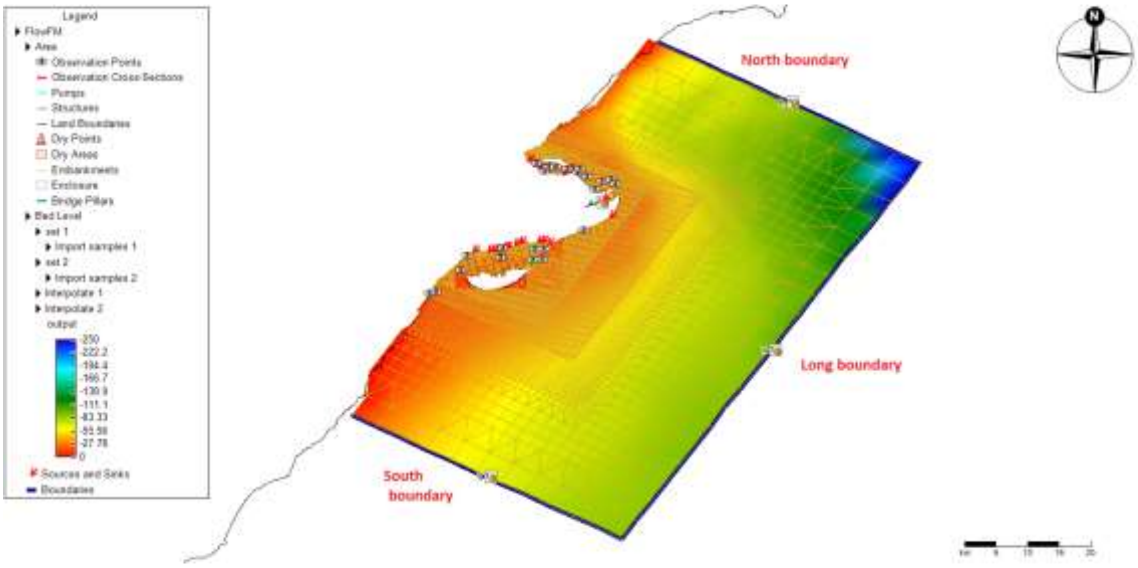


Figure 17. Domain boundaries.

These points represent the corners of grid cells and then data is uniform over the cell. Freshwater inputs represented with discharge, salinity and temperature are assigned as boundary conditions on the river delta. Source points are used for 11 discharge channels in Alfacs (Fig.18) and 11 in Fangar Bays (Fig.19). This decision was made due to the fact that channels discharge into shallow bays and these inputs are irregular, as during winter time there is no discharge at all or the number of channels can change with years. Thus, using source points for the irregular inputs representation provides more flexibility and accuracy. The discharge rate of channels is assigned with a 10 m^3/s value, according to the recent literature observation data (Cerralbo, 2018), due to the fact that on-site measurements were not taken in recent years.

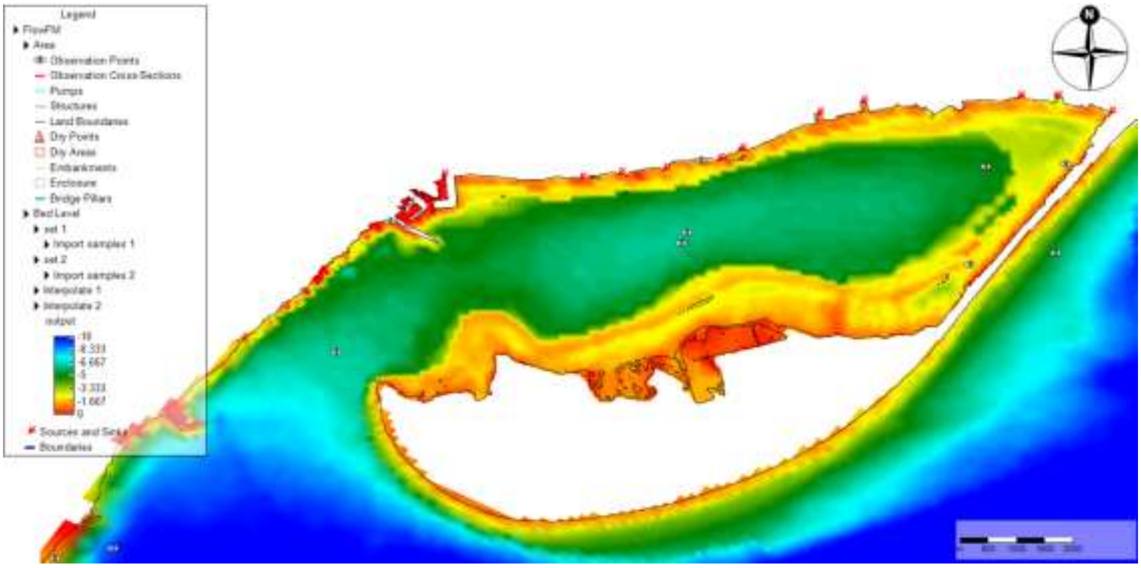


Figure 18. Observation points and irrigation channels discharge points in Alfacs Bay.

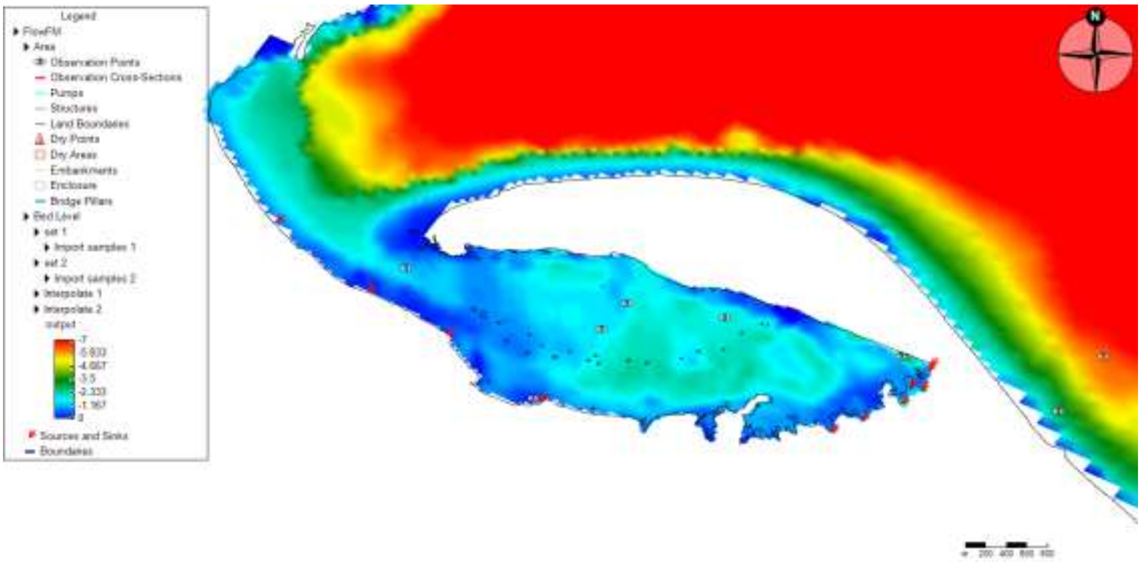


Figure 19. Observation points and irrigation channels discharge points in Fangar Bay.

Two main irrigation channels that start near Xerta 50 km upstream, Canal Margen Izquerda and Canal Margen Derecha discharges were set as source points too. As the river splits into two streams just prior falling into the sea but the discharge of the right split is not measured, the discharge rates of Canal Margen Derecha were assigned to that stream (Fig. 20).

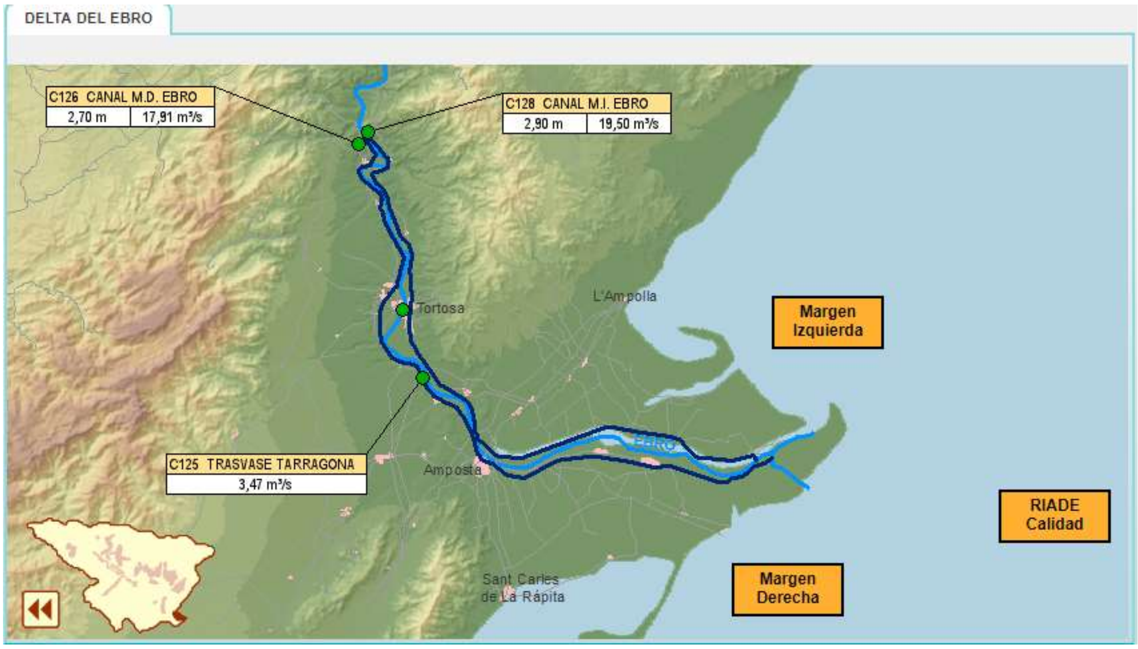


Figure 20. Canals of Ebro river Delta and Ebro River Split.

12 sigma layers are assigned to perform the 3D computation. This approach is chosen over the Z-layer vertical coordinate system due to its flexibility and the fact that it represents reality and reflects on physical flow processes with higher accuracy (Fig. 21).

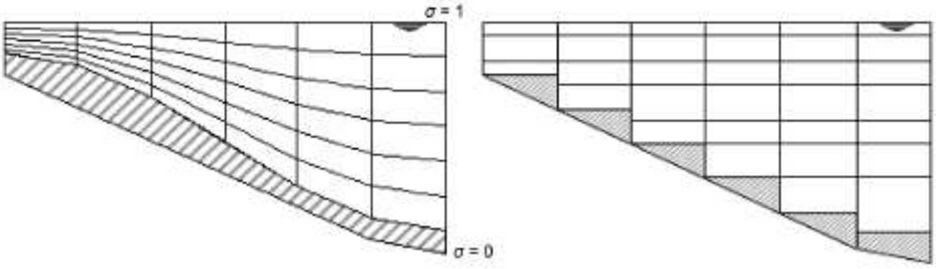


Figure 21. Representation of sigma and z-layering for the vertical coordinate system (D-Flow FM, 2019).

Boundary conditions are assigned on all the depth layers, respectively.

Online data acquisition from the CMEMS platform

During the model set-up process, the boundary conditions data assigning is an important step. At first, data of the northward and eastward currents, temperature, salinity and water level were separately retrieved from the CMEMS platform as *.nc files. As the grid, developed in this research, has different resolution and does not precisely correspond with the data-holding points of the obtained datasets, therefore data interpolation procedure was required. The nearest neighbour interpolation method was chosen due to the fact that the resolution of data holding grid and the assigned at the model boundaries are almost the same – 4670 m and 4500 m, respectively. Initially, to address this purpose, the Python algorithm was used (Appendix). Each boundary condition, naming water level, salinity, temperature, northward and eastward velocities had to be processed and retrieved individually. Therefore, despite the certain level of automatization, inserting data to the boundary points was very time-consuming. Moreover, the question of the possibility of using the northward and eastwards currents data in the graphical interface appeared. In this case, during the computation, the normal and tangential velocities should be assigned at each boundary point according to the software numerical grid, so that the rotation factor should be applied to the northward and eastward velocities data. Nevertheless, it was clarified that this is not a limitation of the software, as internal code treats the X, Y – direction data regardless the grid linearization but, in this case, data should be assigned in the software governing codes.

Moreover, during the process of the data treatment for the model set-up, the technical possibility of automatic data execution from the CMEMS database and conversion to D-FLOW FM boundary condition files was offered by Deltares colleagues. As a result, this script for automatic data retrieval from the Copernicus database was applied for the first time in the Mediterranean Sea during this model set-up. Therefore, now, for future flow models set-up that requires deep-sea data, instant data acquisition and interpolation, adjusted to the desired boundary condition point location, this script can be used.

Calibration

Model calibration is done by comparison of the model output data with in-situ observations. The observation data is assigned at 26 observation points (Fig. 22), located in the coastal area. This is done by executing salinity, temperature, water level and flow graphs from the observation points. Then, in Quickplot and Excel, obtained and real observation graphs were compared.

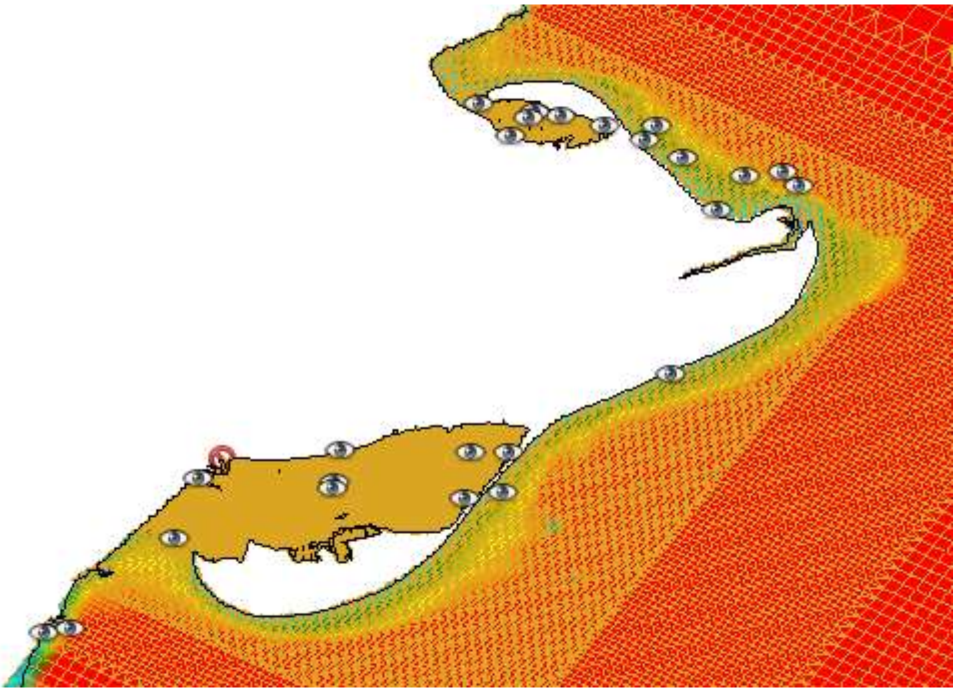


Figure 22. Observation points in the research area.

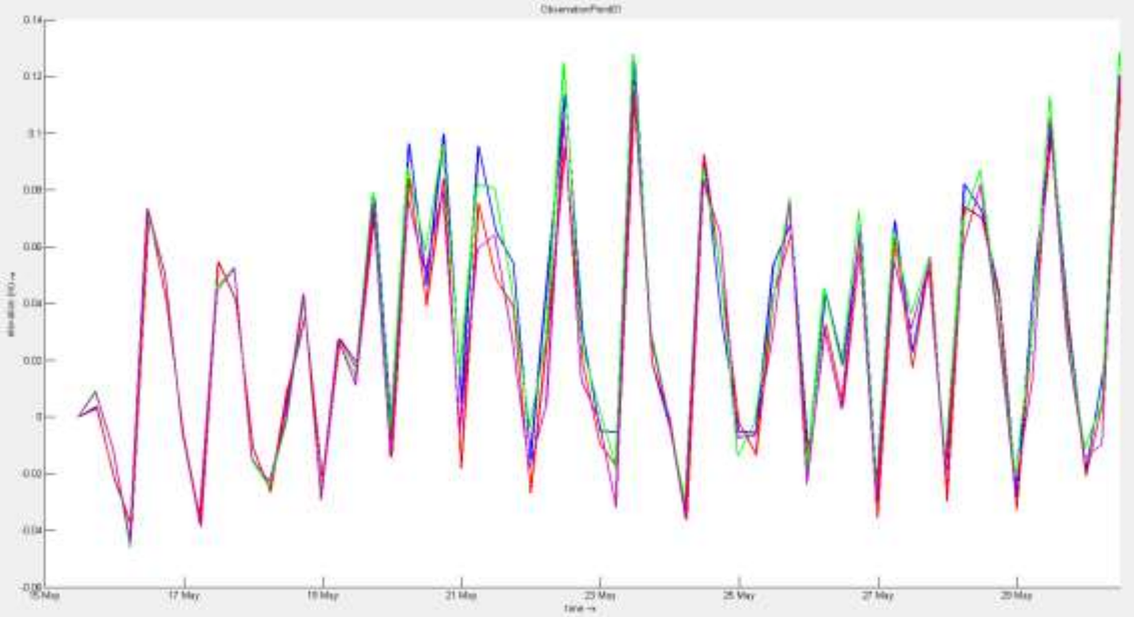
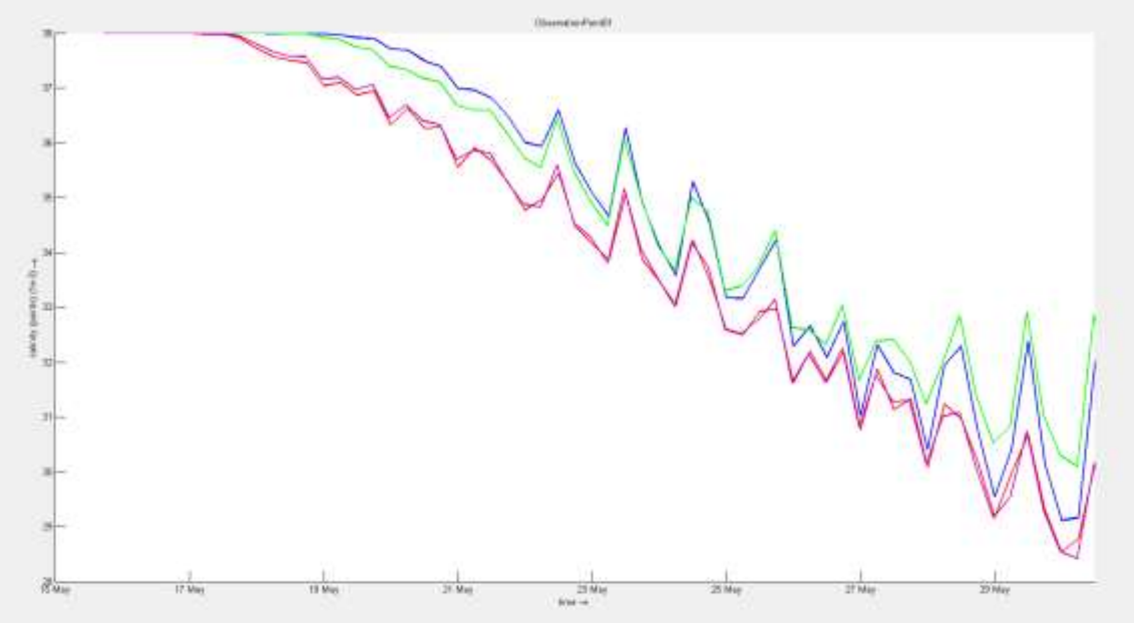


Figure 23. Water level fluctuation.

Firstly, as it can be seen on (Fig 23), the water level changes occur due to the tidal regime. Also, the rates are low, as generally in the Mediterranean area, so the maximum rise is of 10 cm and drop of 4 cm, in relation with the initial water level of 0 m, assigned to the domain.



On this graph the salinity fluctuation timeseries can be seen at the observation point 1.

This corresponds to the real observation data of the salinity in the Alfacs Bay.

The increase of salinities are observed during the tides due to the water exchange with the open sea.

According to the obtained result, the physical parameters of the model are adjusted:

Manning uniform friction coefficient = 0.023

This value of the bottom friction coefficient is chosen for the domain according to the bottom characteristics of the bay bed (mud and silt) and the presence of submerged aquatic macrophytes and ripples on some areas (Cerralbo et al., 2019).

Eddy viscosity **-** the coefficient of the relation between the vertical velocity gradient and the average shear stress in a turbulent flow (Argyropoulos & Markatos, 2015).

Uniform horizontal eddy viscosity = 5 m^2/s

Uniform horizontal eddy diffusivity = 4 m^2/s

For 3D model set up also vertical eddy viscosity =$0.5*10^{-4}$ m^2/s and vertical eddy diffusivity = $0.5*10^{-4}$ m^2/s were assigned.

Pollutant release

As the initial step, prior to the water quality model development based on the current flow dynamics, it was decided to perform a pollutant dispersion simulation. As one of the main objectives is to understand the impact of the freshwater inflow on the Alfacs and Fangar Bays, the tracer concept allows to gain the initial understanding of the dissolved particles and sediment transport patterns.

Therefore, compounds were released in 2 simulations to access the impacts of the Ebro river itself and then see, how do the irrigation channels, that discharge waters from rice fields directly into Alfacs and Fangar Bays, influence the water quality in the areas, used for mariculture. In this experiment, nitrates and copper were added to the model, in the Ebro river boundary and from the sources, that represent irrigation channels.

5. Results

In the following chapter the results of the described methodology application are presented.

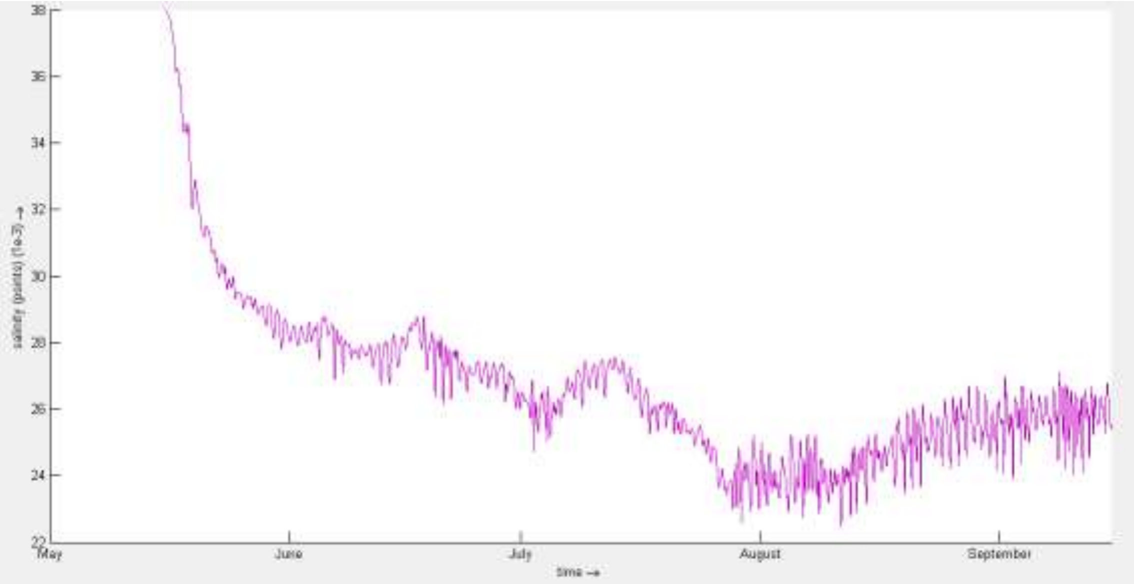


Figure 24. Salinity variation graph in Alfacs Bay, range between 22 and 38.

As one of the vital factors for the intensive growth of oysters and mussels is salinity, on the Fig. 24 it can be seen that the salinity in the Alfacs Bay drops significantly due to the freshwater input from the irrigation channels and Ebro river.

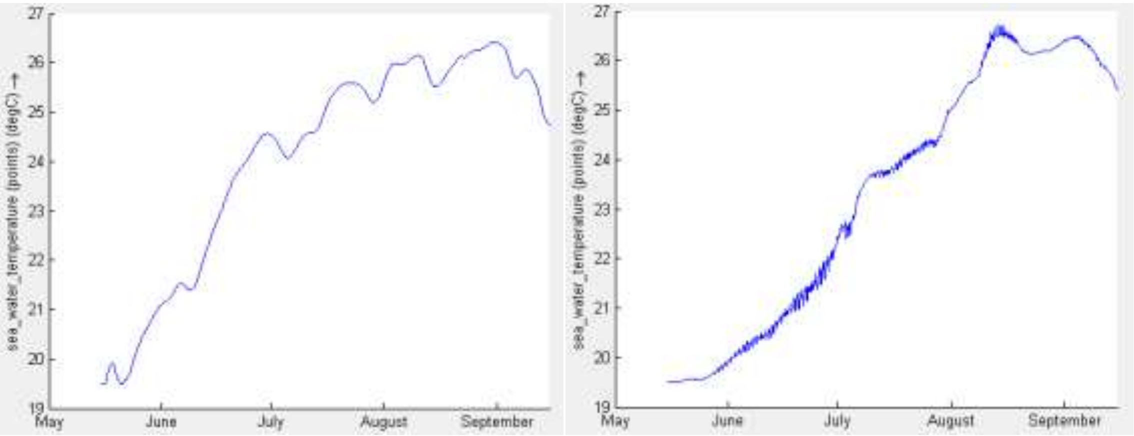


Figure 25. Temperature rise in the Fangar bay.

Also, the significant rise in the water temperature in both bays can be observed during the summer period (Fig. 25). Temperature dropping in the bays is associated with the days, when the temperature of the Ebro river waters drops, that may be associated with the rain events in the upstream areas. Therefore, we can see the impact of the river and also irrigation channels on this important physical parameter.

Also, on the Fig. 26 it can be seen that flow velocities are low inside both bays and higher flow velocities can be observed in Fangar Bay than in Alfacs, so the water exchange rate is higher in the Fangar bay.

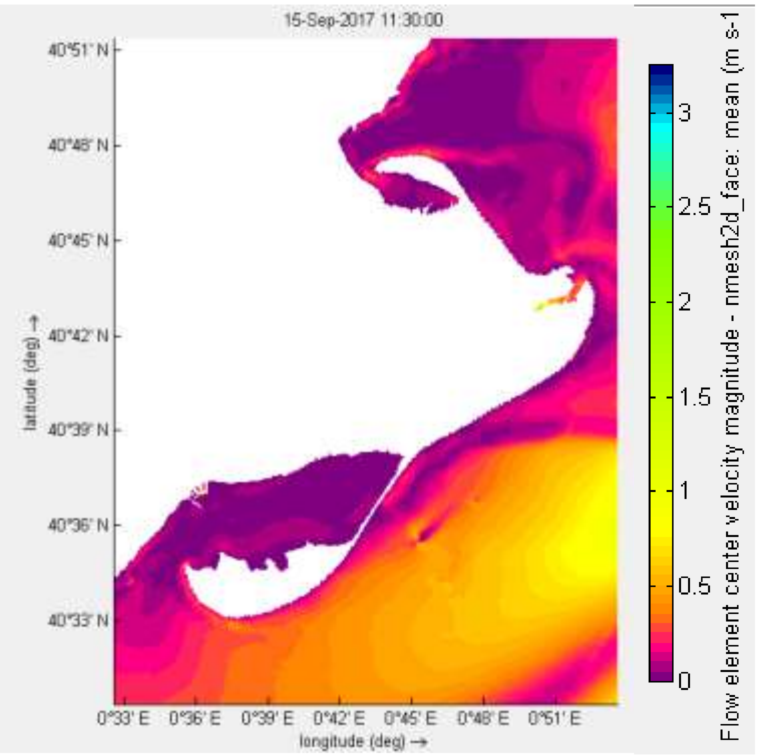


Figure 26. Flow velocity variation in the study area.

Impact of the Ebro river on Alfacs and Fangar Bays

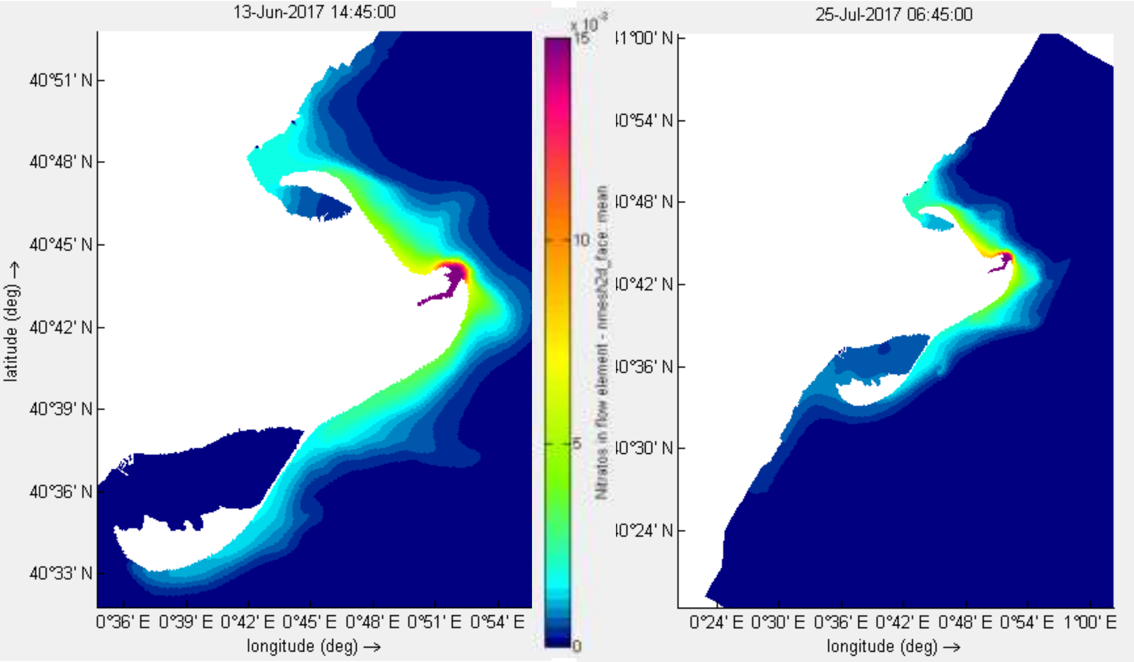


Figure 28. Nitrate dispersion from the Ebro river on 13 June and 25 July, 2017. Concentration varies from 0 to 15 mg/l.

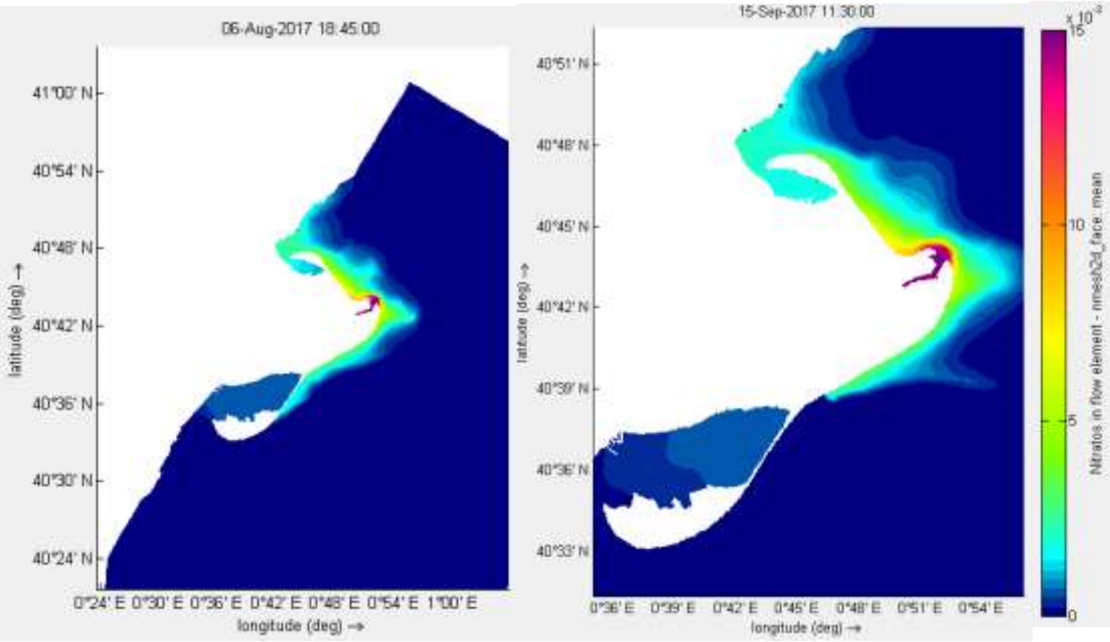


Figure 27. Nitrate dispersion from the Ebro river on 06 August and 15 September, 2017. Concentration varies from 0 to 15 mg/l.

On Fig. 27and 28 the dispersion of nitrates from the Ebro river only can be seen. At first, only Fangar Bay is being directly influenced by the freshwater input from the river, whereas in July the effect can be observed also in Alfacs Bay. Moreover, by the end of the simulation period on 15 of September it can be seen, that compounds are being trapped inside the Alfacs Bay.

The concentration, corresponding to the average observed value of 15mg/l access the research domain through the Ebro river delta. Due to the local currents most of the nutrients are brought to the Fangar Bay, whereas the Alfacs Bay is less vulnerable to the Ebro river water quality.

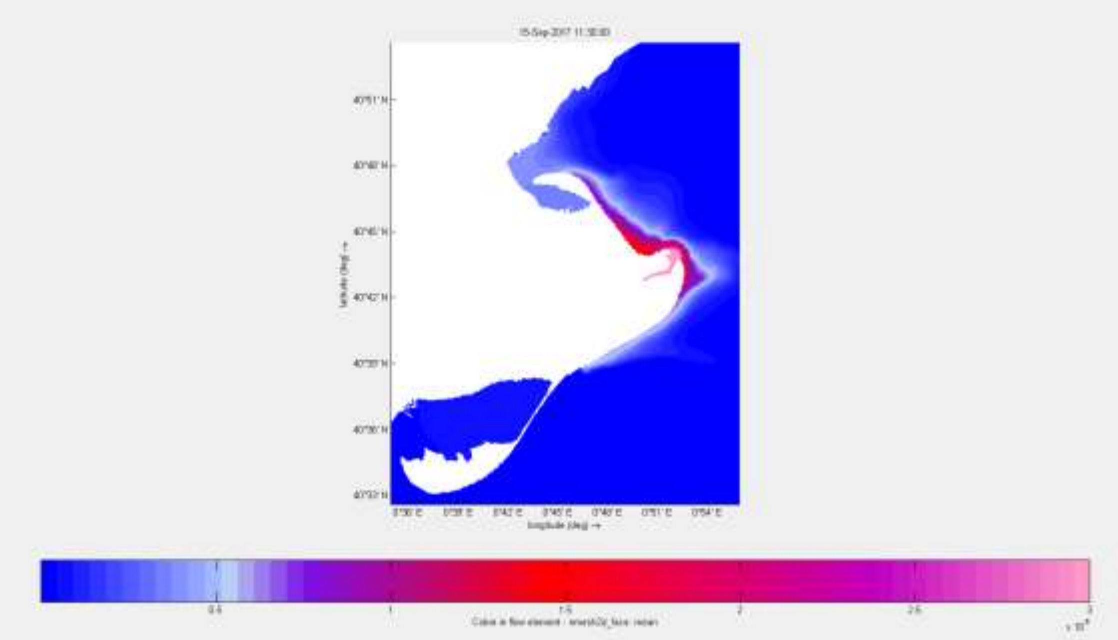


Figure 29. Copper propagation.

The same behavioral pattern can be observed for the copper propagation (Fig. 29), thus, higher concentrations are remaining near the actual river delta and again, the Fangar bay is impacted more, whereas Alfacs bay is not influenced at all. This is explained by the fact that initial concentrations of the element are almost 100 times lower, so mixing takes place and also due to its higher density and sinking to the bottom, rather than remaining in the water column.

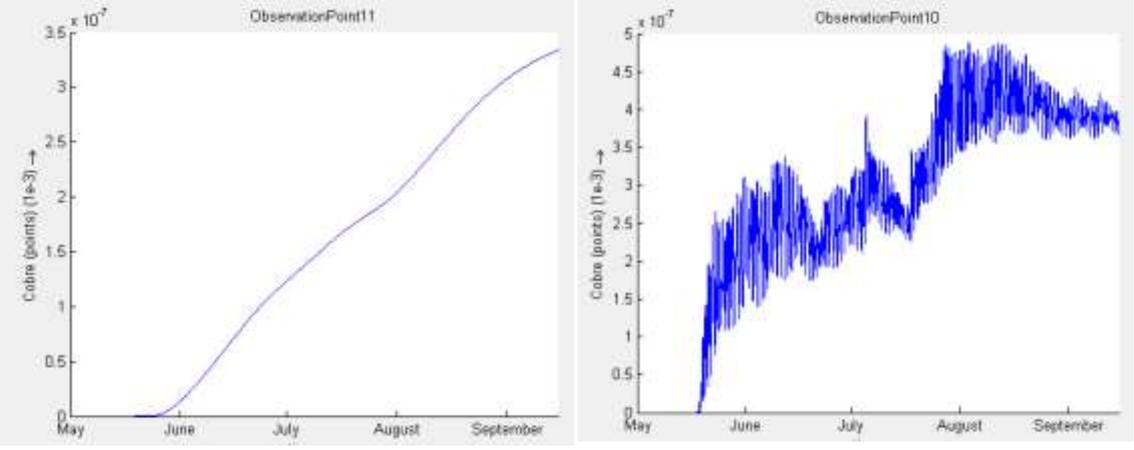


Figure 30. Copper accumulation tendencies point 10 and 11.

Moreover, as can be seen from the graphs, the accumulation of the compound takes place in the more still area of Observation point 11 (Fig.30). It is located in the end of Fangar Bay when in the mouth the trend of rising concentration takes place but due to the constant flow in the area, the graph is unstable and depends on the tidal regime.

The same statement is also valid for the observation points in Alfacs Bay. On the graph below (Fig.31) it can be seen that on the observation point 1, located in the mouth of the bay concentrations are changing, whereas on observation point 6 at the end of the bay, concentrations are lower but gradually rising (Fig.32).

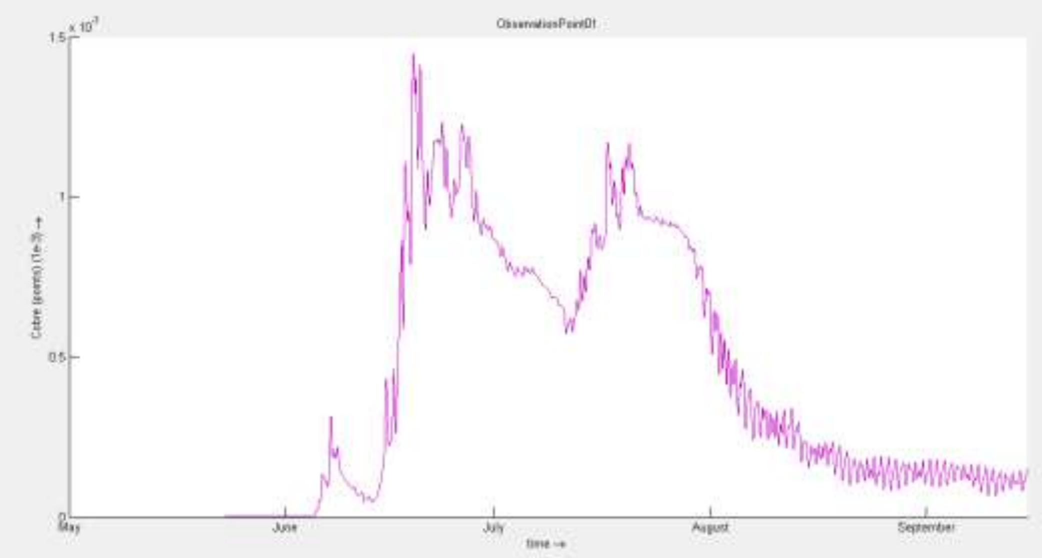


Figure 31. Timeseries of the Copper concentration fluctuation in the Alfacs bay mouth Observation point 1 from 15 May till 15 September, 2017.

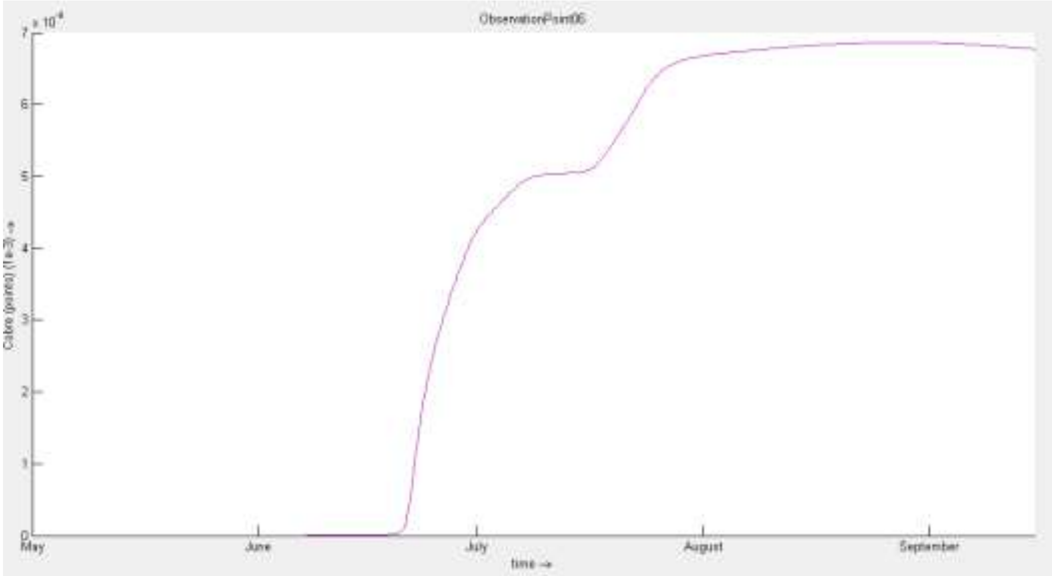


Figure 32. Timeseries of the Copper concentration fluctuation in the Alfacs bay end at the Observation point 6 from 15 May till 15 September, 2017.

The combined impact of the Ebro river and irrigation channels

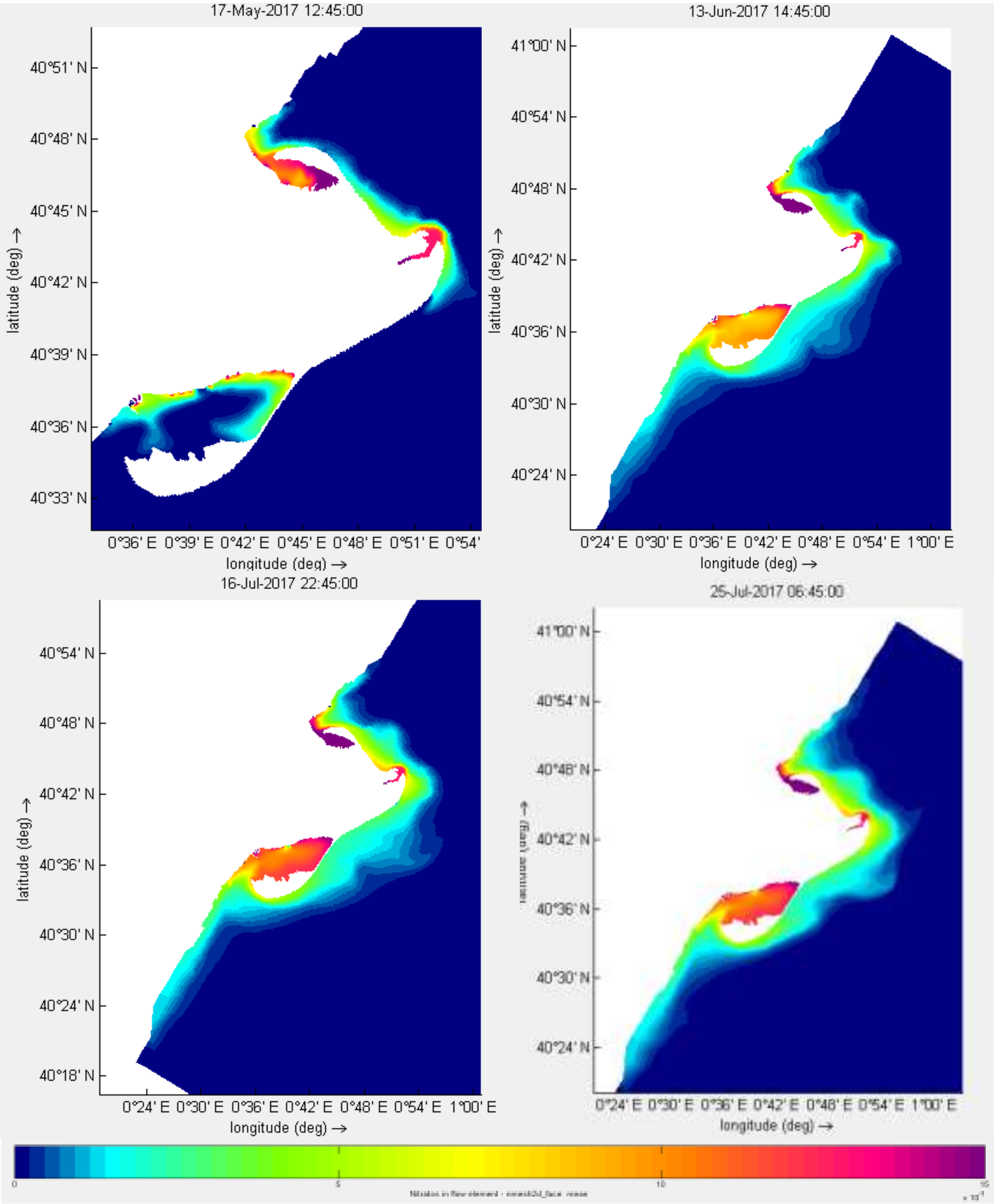


Figure 33. Nitrate propagation from discharge channels and Ebro river on 17 May, 13 June, 16 July and 25 July, 2017. Concentration varies between 0 to 15 mg/l. Retrieved from Delft3D FM 2019.02.

At the same time, the impact of irrigation channels on the water quality in both bays can be observed on the (Fig.33). Clearly, contaminants, brought to both bays with discharge water from rice fields tend to remain in Alfacs and Fangar Bays. Moreover, due to the low rate of the water exchange with the sea, the decrease in contaminant concentrations can be observed only in times when there is no discharge from the fields, as shown on the (Fig. 34), namely, in the winter period. Also, the Fangar Bay is more impacted by the contaminants, spreading from the river, than Alfacs.

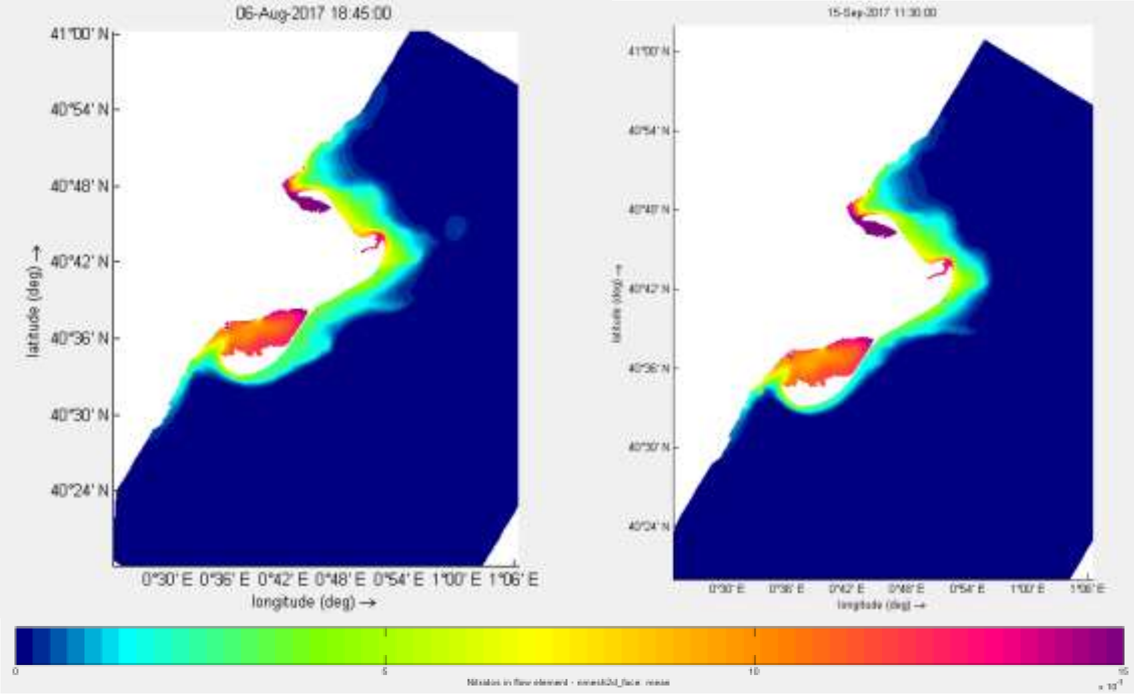


Figure 36. Nitrate propagation from discharge channels and Ebro river on 06 August and 15 September, 2017. Concentration varies between 0 to 15 mg/l. Retrieved from Delft3D FM 2019.02.

Also, the following graphs (Fig.35, 36) show that in the Alfacs Bay mouth due to the tidal forcing from the sea, the concentrations are fluctuating, whereas in the area of observation point 5, located at the end of Alfacs, accumulation takes place.

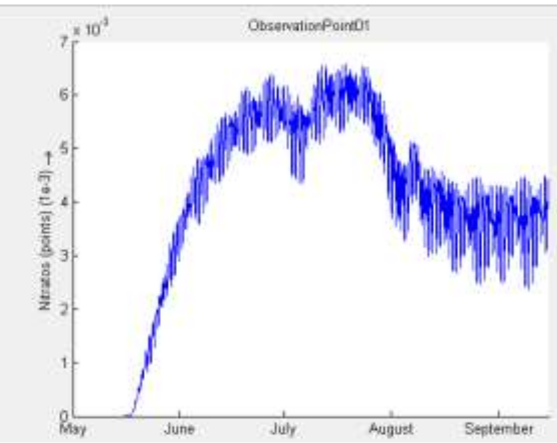


Figure 35. Nitrogen concentration fluctuation timeseries from 15 May to 15 September, 2017 at observation point 1 – Alfacs Bay mouth.

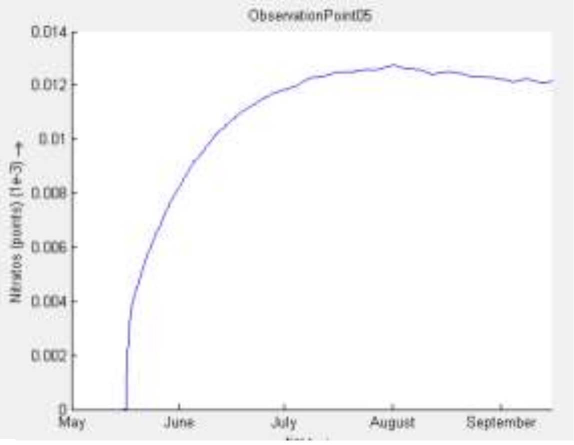


Figure 34.. Nitrogen concentration fluctuation timeseries from 15 May to 15 September, 2017 at observation point 1 – Alfacs Bay end.

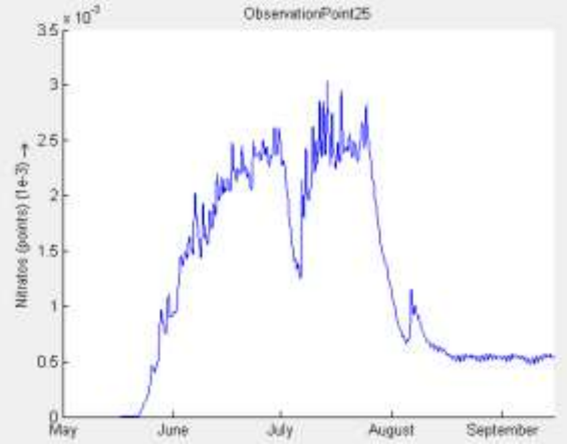


Figure 37. Nitrogen concentration propagation at the observation point 25. Timeseries 15 May – 15 September, 2017.

At the same time, on Fig.33, 37 it can be seen that contaminants from the Ebro river are also propagating along the coast southward during late June and July. Rising concentrations of pollutants can be observed on the observation point 25, located 5 km down from the research area. Despite the fact that concentrations are much lower than ones near the Ebro delta, in Fangar and Alfacs bays, this seasonal dispersion of pollutants, originating from the freshwater sources should be addressed in the water quality assessments along the Balearic coast towards Valencia.

6. Discussion

Overall, it can be seen that Alfacs and Fangar Bays are, in the first place, vulnerable to the freshwater input, as channels have the main impact on the environment in bays.

Due to the water surface heating and, on the other side, the freshwater influx from the irrigation channels to both bays, vertical stratification of the water column can be observed. This can be seen, in the first place, in the temperature (Fig.25) and salinity variation (Fig.24).

Therefore, in the future implementation of the developed model to the forecasting system, the temperature and salinity variation in the area of aquaculture farms will be addressed. This is a very important factor, as oysters are growing rapidly in the conditions of the water temperature between 15 and 25 °C and salinities in a range of 25-32 ‰ (FAO, 2019). Therefore, as the hydrodynamic model performs computation over 12 vertical layers, using the forecasting system will show the necessity of oyster installations deepening or upraising in certain conditions.

Regarding the impact of the freshwater discharge, both Ebro river and irrigation channels have a high impact on the water quality status in both bays. As it is shown on the dispersion maps before, due to the constant discharge from rice fields over the summer period, pollutants are getting trapped in the remote areas of the bays, especially in case of Alfacs Bay due to its structure and lower rate of the water exchange with the open sea than Fangar bay has. On the contrary, local currents bring most of the waters from the Ebro river to Fangar Bay. Therefore, it is more vulnerable to the water quality of the Ebro river rather than Alfacs.

Neural Networks

All in all, it can be seen from the data gathering process and model set-up, one of the main issues during the process is the fact that data is patchy, especially regarding heavy metal concentrations in water. Therefore, as now the water quality topic is gaining better recognition and Hydrographic Confederation of river Ebro along with the IRTA research institute have the observation points in the area that are currently inactive, or sampling is rare, no new expensive installations to obtain the desired data is required. Therefore, it is suggested to use an artificial neural network for automated accuracy improvement of the forecasting system. The modelled prediction data should be used as an input and then the neural network is trained with the real observation data, once it is available. In this way, it will be possible to achieve higher accuracy of the model not by changing the governing physical factors but by training the system.

Uncertainties

There are several sources of the model output uncertainties that influence the quality of the resulting hindcasting system and, therefore, should be introduced. Firstly, these are physical conditions due to the temporal and spatial coverage variability of the modelled parameters. Input data uncertainties – lack of data in the research area and its different spatial and temporal coverage makes the data operations and analysis necessary. At this step, it depends on the researcher which techniques are used for the data gap-filling process, such as various interpolation methods (linear, nearest neighbour, triangulation) but each of these provides the add-on value to the potential uncertainty of the model outputs. One of the influential core factors is the nature of the variable measurements. In the case of the in-situ measurements, the precision of analysing tools, such as flowmeters or spectrometers, and sampling techniques are vital to providing reliable data. On the other hand, the remote sensing imagery data has the global scale of spatial coverage but contributes to the potential model output uncertainty. To begin with the cloud occurrence during measurements and how this issue is addressed and, as most of this data is analysed and then used as the basis for the prediction models, the question of interpretation accuracy appears.

Last but not least, as computation methods vary between software, each numerical method (finite difference, finite volume) has its errors.

Model`s numerical computation errors appear from the combined impact of the truncation error, that is a difference between the real and approximated solutions, and the finite precision of the floating-point values that are representatives of real numbers with a fixed precision in accord with a used exponent base scale (2, 10 or 16). (Kahan, 2006)

In order to address the uncertainty estimation issue in modelled results, numerous uncertainty analysis methods were developed. The most known ones include the Bayesian Markov chain Monte Carlo (MCMC), generalised likelihood uncertainty estimate – GLUE method, Bayesian model averaging BMA and Integrated Bayesian uncertainty estimator IBUNE methods (Shi et al., 2019).

At the same time, last but influential forcing of uncertainties is understanding of processes. Simply, in water quality monitoring it is hard to access and estimate the dispersed sources pollution rates (Tashdighi A., 2013; Chen, Li, Zhong, & Shen, 2018) due to the fact that biochemical processes are not precisely understood and depend on many variables. Thus, the knowledge uncertainty source appears. For instance, in agriculture, different crop species absorb the fertilisers with a different rate, also depending on the external conditions on water availability, light or temperature, so run-off waters from fertilised fields will have different concentrations of nutrients reaching the water bodies. Chemical reactions of dissolved compounds in water that may have likelihood instant reaction and, thus, undergo a chemical transformation or react/degrade over time that leads to different water quality status of the same river between the measurement stations (assuming no external influx of chemical compounds takes place). Besides, not all the biological correlations between biota and elements in water or chemical reactions between contaminants are fully understood.

Therefore, it is necessary to consider and perform the predictive uncertainty analysis of the forecasting systems that are based on the integrated hydrodynamic and water quality models. Moreover, the uncertainty rate depends on the end-user purposes of the model application, as in many cases, the basic coarse results may be sufficient for the understanding of the current ecological, climatic or chemical background situation. So, as a result, the conclusion of the necessity of further in-depth analysis of the local ecosystem can be carried out. In this study, the uncertainty estimation is out of the scope of the master thesis work, but it is recommended to be addressed in the future and highlights the necessity to research this area.

7. Conclusions

To begin with, it is confirmed that Alfacs and Fangar Bays are highly dependent on the freshwater input from the discharge channels and Ebro river, even though actual delta is located within 5-7km from the mouth of both bays. In addition, a significant impact on water salinity and temperature fluctuation can be observed in the areas, where aquaculture facilities are located. Moreover, due to the differences in freshwater and seawater densities, along with salinity and temperature, the model shows that vertical stratification of the water column takes place. This is an important factor for local stakeholders, as the highest growth rates of oyster and mussel species occur at salinity rates of 32ppt and 17-20 ºC. In this case, the problem of the overheated environment is addressed, as the model uses 12 vertical depth layers. So, in the case of the predicted increase of temperatures, the deepening of farm installations is recommended. It is also possible from the production technique point, as molluscs are grown not being attached to the sediment but on ropes and floating installations. The same pattern can be applied to the salinity fluctuation, especially for the installations, that are located close to the discharge channels. Moreover, as pollutants release simulation has shown, the concentrations of hazardous elements are higher close to the channels discharge points, as these compounds are brought together with pesticides, washed off from the rice fields, and in the bonded form to the sediment particles. As heavy metals, that are the main compounds analysed in this work, have a tendency to sink down, it is shown that in the area of the discharge impact it is recommended not to grow aquaculture products near the Bay bottom.

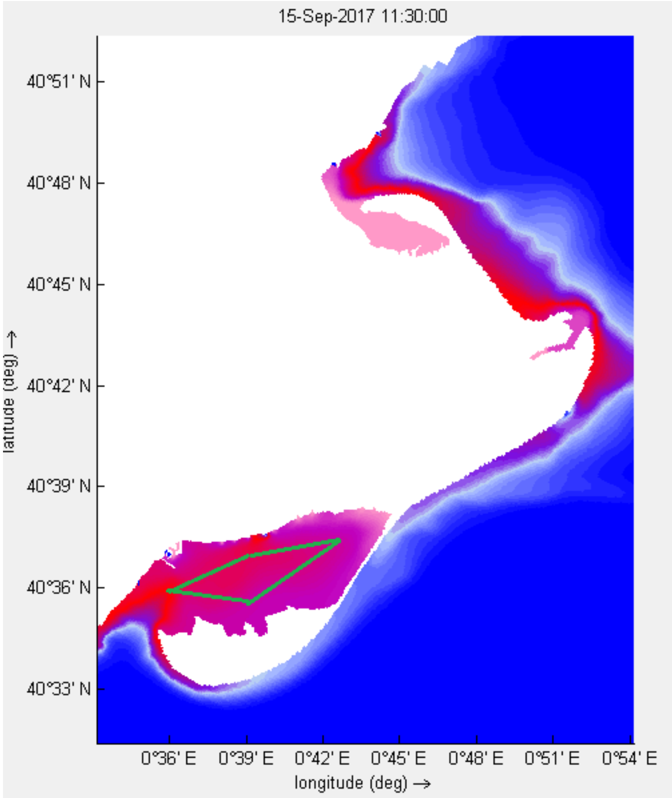


Figure 38. Recommended area for the mariculture installations placement (shown in green).

Overall, it is recommended to put aquaculture installations on the distance from the irrigation channels discharge points due to lower salinities and higher concentrations of pollutants. Also, regarding the temperature rates, more optimal for the pacific oyster growth can be found in the water column, so rope growth method is preferable.

Moreover, as mussels are less vulnerable to the existing currents and for pacific oyster optimal growth more still waters are needed, the rearrangement of the installation`s placement can be suggested. So that mussel ropes can be located closer to the mouth of both bays, where the water flow is constant. In this way, the production efficiency of the farm can rise without expensive measures implementation.

Floating installations require constant control on the temperature rates. In Fig. 38 the area or recommended farm installations placement is shown in green. That area is distant from the freshwater discharge points, so the drop in local salinities are still observed but it corresponds to the recommended values of 18-25 ppt. Also, as the middle area of the Alfacs Bay has depth in range of 4-6 meters, the water temperature remains optimal. Last but not least, the accumulation and trapping of contaminants take place at the end of the Bay, whereas in the middle the exchange rate with the open sea is higher. Regarding the situation in the Fangar Bay, due to the fact that it is shallow, water temperatures are higher in that area and due to the freshwater input salinities drop more, that in the Alfacs Bay, sometimes reaching 10ppt that is the condition in which oysters and mussels still can leave but their growth rate drops. Also, Fangar Bay is more vulnerable to the quality of the Ebro river waters, as due to the currents in the delta area, pollutants from the river are transported directly to the Fangar Bay. Also, the bay has higher rate of water change than the Alfacs Bay, that means that in case of the spills of hazardous substances from irrigation channels, its system can recover faster, than the Alfacs Bay`s.

So, the developed model provides detailed results for the physical parameter`s analysis within a short computation time. Moreover, it is possible now to simulate potential external impacts on the aquatic environment of the lagoons from floods or anthropogenic influence, that, in long-term perspective, allows to establish the forecasting system.

8. Recommendations

Due to the chemical and physical properties of the studied compounds, as heavy metals are brought to the domain through the irrigation channels and Ebro river water, the pattern of metal sinking and accumulation in bays can be observed. Mostly, metalloid compounds are bound with orthophosphate groups of pesticides and nutrients, that are washed off from the rice fields in the area and with sediment load. Sediment load, on the other hand, in both bays acts like a double source of contamination. Firstly, compounds are released back to the water column through resuspension from the bottom of the bays and secondly from the load, brought from the river and in the irrigation channels. Now, the developed propagation model provides us with a general understanding of flow propagation patterns, regardless of the particular chemical compound concentration.

Moreover, only the newly discharged hazardous substances propagation is accessed, so the initial concentrations of chemicals, already present in the area is not taken into consideration. Thus, it is vital during aquaculture facilities development to access the background concentrations of these compounds in the local sediment. In this way, with the application of the developed forecasting system, the alarm signal will be given to the local farmers regarding the weather disruptions and flood occurrence conditions. So, there will be enough time to move the installations up, as the oysters and mussels in the area are grown being attached to ropes that makes it possible to react on-time to the changes in water quality.

Now it is possible to understand the initial conditions of the ecosystem and transportation forcings. In this case, the oyster and mussel farms are expanding in the area and cleaning all the contaminated sediment load inside the bays and in the river, starting from the main pollution source, chloro-alkali factory, is not practical economically. Moreover, it will cause disruptions of the river dynamics and production rates of aquaculture farms, so the complex analysis of the biochemical processes in Alfacs and Fangar Bays should be performed. To address this task, 3-dimensional hydrodynamics, accessed in D-Flow FM module, such as water exchange rates, tidal forces and flows in the domain, along with the tracer propagation, is used as a part of the complex 3D model. Based on this, an integrated model that takes into account sediment transport, climate variation, algal growth, nutrients, pesticide, heavy metal resuspension rates over the whole year should be developed. Even though this is out of the scope of this Master Thesis, such a model is already in the development phase. The results obtained from the current model are used for the further set-up of the Deft3D FM D-Water Quality, D-Waves and D-Real Time Control modules in a form of communication-files. Moreover, as this model set-up configuration is only available now as the offline coupling, along with the mentioned future plan, the online simultaneous run of the water quality, climate and hydrodynamics modules is recommended. In this way, local stakeholders, using the developed model, transformed into the near-time forecasting system with a suggested resolution of 35 meters, will know precisely the area of contaminant dispersion and sediment resuspension rates. Therefore, farm installations could be moved around the bays or in the vertical dimension, to avoid contamination or mortality of products.

In addition to the above-mentioned positions, another global problem is recommended to be addressed in further research. Nowadays, due to the agriculture and aquaculture fields intensive development, more fertilizers and pesticides are produced and applied, with the current rate of 200,000 tones/year of compounds over the rice fields in Ebro Delta. In this way, most of the valuable components are washed-off the fields before they are absorbed by crops, or, in case of aquaculture farming – sink to the bottom or dissolved in the water column. So, both economically and from the resource point of view, we face only growing losses (Nienhuis, 2017). Therefore, it is required to address this problem and develop the re-use system. This problem is vital, as pesticides contain heavy metals and nutrients cause severe disruptions to the functionality of the aquatic environment. Therefore, this problem should be addressed by the development of the run-off water capturing system from the fields. As the broad net of irrigation and discharge channels is already available, it is suggested to install additional reservoirs for sedimentation and use of local filters or cartridges with active sites directly in channels. As an example, there is the decrease of bio-available phosphorus since only 0.12% of the Earth Phosphorus can be used for fertiliser and dietary supplements production (van der Grift, 2017; Van der Grift, 2018). Therefore, the Phosphorus-binding system is a solution to the posed problem. For instance, Aluminium and Ferrum hydroxides have the property to bind with phosphate $(PO_4)^{3-}$ groups, that allows capturing valuable compound before it is lost for reuse. In this way, the phosphorus circulation system can be developed. Moreover, phosphate groups undergo the process of chemosorption with colloidal ferric oxides on the sediment particle surface. So, finer sediments have higher phosphate absorption rates, so in-depth analysis of the sediment granulometry, properties and transport should be performed. Taking the similar principle of the compound capturing for the pesticides and heavy metal compounds in water, it is suggested to study further the technical possibilities and resulting chemical treatment and components separation. As a result, two global problems of valuable resource losses and water contamination could be solved.

Finally, numerous environmental issues were caused during recent years due to the exponential growth of aquaculture production in the Mediterranean Sea. Depletion of the water quality could be observed, but it is more influential on sediment in the area nearby the fish farms due to the residual organic matter and excess nutrient deposition, increased bacterial activity and seagrass degradation. Sediment and water phosphorus exchange are strongly dependent on numerous parameters: sediment granulomere, the concentration of P-binding elements such as iron, calcium, aluminium and manganese and dry weight (Aydin et al., 2009). The aquatic environment in the areas where cage aquaculture is based undergoes additional to the anthropogenic and natural background levels of metals, toxic influence from used for cage protective antifoulant paints, that are mostly copper-based (Arechavala-Lopez et al., 2013). Furthermore, metal concentrations in farmed fish flesh are synthetically increased by complementing their diets with essential metals – iron, copper, manganese, chromium and cobalt

(CIESM, 2007). This fact is proved by numerous researches that analyse and compare trace element concentrations in wild and farmed sea bream and sea bass (Arechavala-Lopez et al., 2013). Above mentioned facts should be addressed via the changes in the materials, used for the farm installations and cage production, for instance, carbon fibres instead of metals and plastic. Also, it is possible to implement the use of environmentally-friendly antifouling paints that do not contain heavy metals. Also, the legislation and normative regarding the composition of fish nutrition should be revised and tightened up.

In addition, it is recommended to address this issue in further studies and include nutrient and dietary supplements` dissolving in water and sinking into the integrated water quality modelling of the seas and bays.

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Appendix

NetCDF data interpolation example code

```
@author: perepely
"""
#pip install netCDF4 #This package is necessary to install the netCDF4
#pip install cartopy # This function is required if cartopy program is not intalled before
#============================================================================
==
import netCDF4
from netCDF4 import Dataset
import os
import numpy as np
import cartopy.crs as ccrs
import cartopy.feature as cfeature
from cartopy.mpl.gridliner import LONGITUDE_FORMATTER, LATITUDE_FORMATTER
import matplotlib
import matplotlib.pyplot as plt
#plt.style.use("ggplot")
#============================================================================
==
nc_path                                                                    =
os.path.abspath(r'C:\Users\perepely\Models\Raw_data\Copernicus\Fresh\currents_hourly.nc'
);
dataset = Dataset(nc_path)
#Interrogate netCDF file
print(dataset.file_format)
print(dataset.dimensions.keys()) #dimensions
print(dataset.dimensions['time'])
print(dataset.variables.keys()) #variables
print(dataset.variables['vo'])
print(dataset.variables['uo'])
print(dataset.Conventions) # Get conventions attribute

attr=dataset.ncattrs() #find all NetCDF global attributes
for attr in dataset.ncattrs():
    print(attr, '=', getattr(dataset, attr))
#============================================================================
==
timestep=100;
fh = Dataset(nc_path, mode='r')
time=fh.variables['time']
jd = netCDF4.num2date(time[:],time.units)
lons = fh.variables['lon'][:]
lons = lons.data[:]
lats = fh.variables['lat'][:]
lats = lats.data[:]
North_vel = fh.variables['vo'][:]
```

```
North_vel = North_vel.data[:]
East_vel = fh.variables['uo'][:]
East_vel = East_vel.data[:]
fh.close()
#===================================================================================
# Load the Pandas libraries with alias 'pd'
import pandas as pd
# Read data from file 'filename.csv'
# (in the same directory that your python process is based)
# Control delimiters, rows, column names with read_csv (see later)
data = pd.read_csv(r'C:\Users\perepely\Models\Delft_FM\Boundary_Conditions\Long_boundary\Mariya_long_border2.csv')
# Preview the first 5 lines of the loaded data
data.head()

#===================================================================================
#Gives the correct id number of lat and lon of the closest point!
lat_idx_lis = []
lon_idx_lis = []
#from numpy import absolute as abs
for i in range(len(data['X'])):
   loni = data["X"][i]
   lati = data["Y"][i]
   my_point = {'name': 'My_point', 'lat': lati, 'lon': loni}

   # Find the nearest latitude and longitude
   lat_idx = np.abs(lats - my_point['lat']).argmin()
   lat_idx_lis.append(lat_idx)
   lon_idx = np.abs(lons - my_point['lon']).argmin()
   lon_idx_lis.append(lon_idx)

values_lat = lats[lat_idx_lis]
values_lon = lons[lon_idx_lis]

#iy = lat_idx
#ix = lon_idx
for i  in range(len(values_lat)):
   print ('Exact Location lat-lon:', data['Y'][i],data['X'][i])
   print ('Closest lat-lon:', values_lat[i], values_lon[i])

#gives all timesteps and all depth layers

NORTH_FINAL = []
for i in range(len(lon_idx_lis)):
   North_vel_dataserie = North_vel[:,:,lat_idx_lis,lon_idx_lis]
```

```
    NORTH_FINAL.append(North_vel_dataserie)
    ###########change
EAST_FINAL = []
for i in range(len(lon_idx_lis)):
    East_vel_dataserie = East_vel[:,:,lat_idx_lis,lon_idx_lis]
    EAST_FINAL.append(East_vel_dataserie)
#==============================================================================
==
#PLOT map of North_vel
# Get some parameters for the Stereographic Projection
#Modify the range of i to obtain plots of several depths at an specific timestep
#Modify the number of plots that you require depending on the layer
for i in range(0,9):
    North_vel_plot=North_vel[timestep,i,:,:]
#Plot
    matplotlib.rcParams['figure.figsize'] = (10,10)
    proj=ccrs.Mercator()
    m = plt.axes(projection=proj)
# Put a background image on for nice sea rendering.
    m.stock_img()
    m.coastlines(resolution='110m')
    m.add_feature(cfeature.BORDERS)
    gl=m.gridlines(crs=ccrs.PlateCarree(), draw_labels=True,
                  linewidth=2, color='gray', alpha=0.5, linestyle='--')
    gl.xformatter = LONGITUDE_FORMATTER
    gl.yformatter = LATITUDE_FORMATTER
    gl.xlabels_top = False
    gl.ylabels_right = False
#Plot data for North_vel
    plt.contourf(lons, lats, North_vel_plot, 60,
                 transform=ccrs.PlateCarree())

    # Add Colorbar
    cbar = plt.colorbar()
    cbar.set_label(dataset.variables['vo'].units)
# Add Title
    plt.title('North Current Velocity Movement')
    plt.show()
#==============================================================================
==
#PLOT of East_vel
# Get some parameters for the Stereographic Projection
#Modify the range of i to obtain plots of several depths at an specific timestep
#Modify the number of plots that you require depending on the layer
for i in range(0,9):
    East_vel_plot=East_vel[timestep,i,:,:]
#Plot
    matplotlib.rcParams['figure.figsize'] = (10,10)
```

```
  proj=ccrs.Mercator()
  m = plt.axes(projection=proj)
# Put a background image on for nice sea rendering.
  m.stock_img()
  m.coastlines(resolution='110m')
  m.add_feature(cfeature.BORDERS)
  gl=m.gridlines(crs=ccrs.PlateCarree(), draw_labels=True,
              linewidth=2, color='gray', alpha=0.5, linestyle='--')
  gl.xformatter = LONGITUDE_FORMATTER
  gl.yformatter = LATITUDE_FORMATTER
  gl.xlabels_top = False
  gl.ylabels_right = False
#Plot data for East_vel
  plt.contourf(lons, lats, East_vel_plot, 60,
             transform=ccrs.PlateCarree())
    # Add Colorbar
  cbar = plt.colorbar()
  cbar.set_label(dataset.variables['uo'].units)
# Add Title
  plt.title('East Current Velocity Movement')
  plt.show()
```