FISH HABITAT AND ENVIRONMENTAL EFFECTS OF TIDAL VARIATION IN THE LOWER RHÔNE RIVER, RHÔNE RIVER DELTA, AND MEDITERRANEAN SEA UNDER EUSTATIC CLIMATE CHANGE SCENARIO

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DOI: 10.2478/trser-2025-0020

KEYWORDS: land use and climate change, sea level rise, delta flooding, fish, risks.

ABSTRACT

Warming climates induce Mediterranean Sea level rise, which is destined to have major impacts on Rhône Delta habitats, biocoenosis, and escorting biota, including fish. Based on their bioecological features, a number of fish species in the Rhône Delta will be affected by such sea level rise. Others will adapt and positive ecological feedback loops may fuel further changes. Sea level variation was and is likely to be one of the key stress factors for fish in the Rhône Delta.

RÉSUMÉ: Les problèmes environnementaux liés aux marées basses et hautes dans la zone de basculement du Rhône, du delta du Rhône et de la mer Méditerranée, ainsi que les habitats piscicoles qui s'y trouvent, seront affectés par les scénarios de changement climatique.

Les changements climatiques induisent une élévation du niveau de la Méditerranée, un contexte qui laisse présager des impacts importants sur les habitats, les biocénoses et les organismes associés du delta du Rhône, notamment les poissons. Selon leurs caractéristiques bioécologiques, certains espèces piscicoles de ce delta seront affectés par cette élévation tandis que d'autres s'adapteront. Leur rétroaction positive sur l'écosystème pourra engendrer de nouvelles dynamiques écologiques. La variation du niveau de la mer a été, et reste probablement, l'un des principaux facteurs de stress pour les poissons de ce delta.

REZUMAT: Probleme de mediu legate de maree joase și înalte în zona plăcii turnante a ecosistemelor peștilor din regiunea râului Rhon-deltei Rhonului-Mării Mediterane, într-un scenario de schimbări climatice de tipul "apa va veni".

Schimbările climatice induc creșterea nivelului Mării Mediterane, un context care anticipează influența acesteia asupra habitatelor deltei Ronului, biocenozei și biotei însoțitoare, inclusive a peștilor. Pe baza caracteristicilor lor bioecologice, unii dintre peștii acestei delte vor fi afectați, alții se vor adapta.

INTRODUCTION AND BACKGROUND

The wetlands where the sea converges with major freshwater sources (e.g. the deltas of the Rhône, Rhine, Tiber, Po, Danube, Tigris, Euphrates, Jordan, Indus, Nile, Yangtze, Ganges, Brahmaputra rivers, etc.) have been inhabited by agricultural civilizations for more than five millennia and have played a major role in some of the major human developments of the Upper Holocene (Bănăduc et al., 2016). All of these civilizations emerged in wetlands because they were advantageous in terms of protection, trade, agricultural production, and economic raw material availability (Mark and Macklin, 2015; Kappelman et al., 2014; Williams et al., 2014). In the 20th century, delta and estuary wetlands have taken on further value in terms of ecological health (Popa et al., 2016; Cameron and Matless, 2011; Prichard, 2004) and public perception (Zare-Shahraki et al., 2022; Hurd, 2001).

As a subset of wetlands, deltas have distinct features and forces. They are formed and shaped when the source of sediments to the coast by a river is richer than the dispersion vectors such as water and wind, or sometimes by human technological interventions. Complex and mutually interacting natural and anthropogenic stressors constantly impact the ecological features of deltas (Bănăduc et al., 2024, 2022a, b; Nõges et al., 2016; Navarro-Ortega et al., 2015). Certainly, each delta is unique and every enduring human presence influences them, creating networks of forces and counterforces that must be considered at the most detailed level possible. As a result, only in-situ tailored assessment, monitoring, and management activities can be successfully planned and implemented.

Europe's deltas (i.e. those of the Rhône, Ebro, and Danube Rivers, etc.) began to be studied through an eco-economic lens in the early 20th century (Bănăduc et al., 2016; Prichard, 2004). In the context of global climate change, two main questions are addressed here: first, whether there are some phenomena that cause changes in terms of the specific elements of deltas more quickly than the resilience capacity of those deltas; second, whether fish belong to these changing elements. To find the answers to these questions, certain fish species in the Rhône River basin and adjacent Mediterranean coastal zones were selected as study cases.

The Rhône Basin is crucial due to its geographical, biological, ecological, and human historical and present significance (Tockner et al., 2009). The valued natural resources of the Rhône Basin wetlands induced multifaceted and enduring patterns of interaction, as well as indirect impacts on aquatic and semi-aquatic ecosystems components, including fish. This has occurred in spite of some recent conservationist policies, strategies, and actions (Loucks, 2019; Caro et al., 2015; Poulin, 2012; Höhener et al., 2010; Roche et al., 2009a; Buet et al., 2006; Torenq et al., 2003; Mathevet et al., 2003).

Both the biotic and abiotic elements of wetlands are present on every continent (Davidson, 2014) and are integrated with in very complex biological and geological structures. They are characterized by intricate functions, in high terms of both spatial and temporal dynamics, determined by natural and anthropogenic causes a situation amplified by the dynamics of the so-called Anthropocene (Keddy, 2010; Fraser and Keddy, 2005; Davidson et al., 2005; Adamus et al., 1999-2000). All of these features characterize the Rhône Basin wetlands from the 19-21st centuries (Poulin, 2012).

In the Rhône Basin, there are complex and shifting physicochemical conditions having to do with salinity in its transitional waters. Both its upstream and downstream zones have formed highly complex ecosystems, which are now facing significant human-induced stressors (Seyer et al., 2023; Dole-Olivier et al., 2022; Lepage et al., 2022; Martin et al., 2019; Diaz et al., 2018; Pruski et al., 2015; Frayssee et al., 2014; Eyrolle et al., 2012; Mikhailova and Isupova, 2006; Arnaud-Fassetta et al., 2003; Suanez and Provansal, 1996).

Some of the main human changes are the result of the drainage channels (Fig. 1) with regulatory hydraulic works (Fig. 2) intricate engineered systems for agricultural land reclamation to the detriment of wetland landscapes. In the same area, sea dykes built along the coastline of the Rhône Delta stretch over many tens of kilometers and stand two meters above sea level. These constructions are designed to stop in the late autumn and winter the intrusions of sea water into adjacent lands (loccaly called "salvade"), which prevented terrestrial agricultural development in the southern Camargue in the past. Hydraulic works in the form of openings installed along the dykes (Figs. 1a-d) regulate water exchanges between the sea and the regional lagoons, fragmenting natural habitats and spatial-temporally modify the natural cycles. At the same time, dykes were elevated along the Rhône River and the entire area became restricted and human-controlled, allowing some economic development but interfering with the flows and exchanges of natural material, energy, and information.

Sluice gates are structures that only partially facilitate the circulation of water and aquatic organisms between the Mediterranean Sea and brackish lagoons, as well as the upstream freshwater habitats of the study area. The hydraulic operations of the embanked delta have been managed by humans since the 19th century. These anthropogenically manipulated water exchanges between habitats (Figs. 2a-b) partially enable young marine fish in particular to enter upstream into the Rhône Basin, where they mature, and then leave to reproduce in the Mediterranean Sea. Even so, this fragmented, uneven journey is not without risks. Along shorelines, piscivorous fish, such as sea bass, hunt near these few openings, while fish-eating birds, such as herons, terns or cormorants, wait around the sluice gates in anticipation of a catch (Seyer et al., 2023; Dole-Olivier et al., 2022; Lepage et al., 2022; Martin et al., 2019; Diaz et al., 2018; Pruski et al., 2015; Fraysse et al., 2014; Eyrolle et al., 2012; Mikhailova and Isupova, 2006; Arnaud-Fassetta, 2003; Suanez and Provensal, 1996).

Figures 1a: Drainage channel in Camargue; b. Regulatory hydraulic works in Camargue drainage channel; c-d. Hydraulic work opening in the dyke in Camargue (photos Angela Curtean-Bănăduc and Doru Bănăduc).

Figures 2a: Flooded habitats through hydraulic opening in the dyke; b Unflooded habitats through hydraulic opening in the dyke (photos Angela Curtean-Bănăduc and Doru Bănăduc).

The southern coast of France between the two arms of the 1,450 km^2 Rhône Delta is characterized by a wide network of permanent and ephemeral freshwater, brackish, and saltwater, taking the forms of lagoons, lakes, ponds, reedbeds, marshes, wetlands, etc. The Rhône River and its coastal delta (Fig. 3) make a complex transitional area, even if heavily fragmented by the actvities, forming a unique complex of ecosystems (Tockner et al., 2009).

The composite structure of the ecosystems of this area have been influenced by the proximity of both European and African ecosystems. This also has to do with a unique long-term mixture of inherent abiotic and biotic forces of both the river and the sea with interrelated spatial-temporral effects. In this way, it is a good example of how an extremely dynamic, rich, and multifaceted "ichthyosystem" developed by providing opportunities for the establishment of a large number of ecologically and/or economically important fish species, some of which will be considered here. Unfortunately, this paper deals mostly with the negative impacts of a large diversity of human-induced stressors (Villsen et al., 2022; Grimardias et al., 2017; Ernoul et al., 2012; Arnaud-Fassetta and Provansal, 2005a, b, 2003; Darnaude, 2005, 2003; Carrel and Rivier, 1996; Cauwet et al., 1990; Lochet and Leveau, 1990).

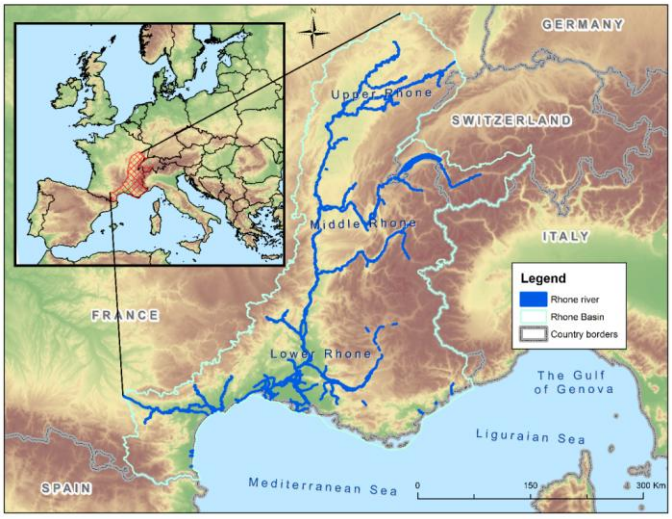

Figure 3: The Rhône River-Rhône Delta-Mediterranean Sea area.

It should be stressed that the diverse and permanent negative anthropogenic influences resulting from hydropower systems, dyking, drainage, river canalization, and nuclear power (to name only a few) have induced severe alterations in the Rhône Basin ichthyocenosis in terms of species diversity and relative abundance (Carrel and Rivier, 1996).

In these composite contexts, interrelated ecosystems comprise four main categories of fish species, namely potamodromous (fish born upstream in freshwater ecosystems, migrating downstream as juveniles to grow before migrating back upstream to spawn), anadromous (fish born in freshwater, migrate out to the sea as juveniles where they grow before migrating back into freshwater to spawn), catadromous (fish born in saltwater, migrating into freshwater as juveniles, where they grow before migrating back out to sea to spawn), and amphidromous (fish born in freshwater/estuaries and deltas, then drift out to sea as larvae before migrating back into freshwater to grow into adults and spawn). With its crucial transitional position, this delta has developed a key evolutionary and ecological role for many fish species. Some of such species are the focus of this study in terms of their ecological status and potential trends in relation to the impacts of climate change-induced sea level.

Relative sea-level rise results in frequent and sometimes permanent saltwater intrusion into wetlands previously characterized as brackish and/or freshwater. Saltwater intrusion can significantly affect resident and transiting organisms, including fish. It is well known that salinity is one of the most significant environmental parameters influencing feeding, reproduction, growth, and distribution of fish (Boeuf and Payan, 2001; Holliday, 2001). It affects their growth and survival, for example by decreasing fish feeding (Boeuf and Payan, 2001; Fielder and Bardsley, 1999) and by modifying their energy costs for osmotic and ion regulation (De Boeck et al., 2000). Fish populations from brackish ecosystems show increased tolerance to dynamic salinity stress relative to those from freshwater environments, a characteristic genetically acquired and transmitted through specific genetic adaptation from one generation to the next. Natural selection plays a key role in the responses of resident brackish-habitat fish to increases in salinity (Purcell et al., 2008). Clearly, the either higher or lower rate and speed of sea level rise may or may not give these species the time they need to adapt. Consequently, some fish populations may follow an adaptive path in the future, whereas others may be adversely impacted in various ways by sea level rise in the study area.

Long-term historical human-induced and inherited disruptions and their force within the modern/present period of time greatly affect the aquatic and semi-aquatic natural and semi-natural habitats, these processes being speeded recently due to the effects of climate change. Sea-level rise in response to global climate change is permanently relentless and its impacts, combined with an increased frequency of large storm-surge events are sudden and episodic hazards. The assessment of global average sea-level rise results by 2100 range between 0.29 and 1.10 m, but with continued climate warming, however, sea level will continue to rise well above, by 2300 levels are expected between 0.6 to 5.4 m (Allison et al., 2121).

By consequence, this study aim is to work based on varied predictable scenarios in which sea level rise induced by global climate changes may influence fish more or less sensitive to this potential impact through salinization of brackish and freshwater wetlands, and through the fragmentation and loss of their habitats in the medium-long term future, as well as the identification of species which have or do not have a relatively good chance of adaptation due to their populations adapted to salt stress in brackish and/or salty habitats. Regional potamodromous, anadromous, catadromous, and amphidromous sea-delta-river fish species populations are expected to be more or less sensitive due to their biological and ecological

characteristics and needs, in the complex context of their local and regional ecosystems overexploitation, degradation of natural capitals and services, environmental distresses, and variations in their ecological resilience, abundance, and last but not least diversity.

The Rhône Valley is an ecological attractor and a corridor for the natural and anthropogenic biotic and abiotic elements of the watershed, influenced by all the effects of its basin tributaries, the Mediterranean Sea and further afield, and its delta has a strategic natural location, structure and functions as an ecological filter and damper area; and above all especially for the purpose of our study, it is a place for fish feeding, refuge, reproduction, nursery, development, etc. Last but not least the authors try to prove here that this delta turning plate region is also an adaptation ground for different fish species, and it provides an intricate buffer and transitional complex of ecosystems with a key role for the Rhône Basin and its adjacent marine coast area. Problems of habitats quality and biodiversity of aquatic and semi-aquatic habitats in the entire Rhône River basin due to anthropogenic effects are in the end mirrored in this delta ecosystems status and their associated biota. Despite these problems, the Rhône Delta, located at the biogeographical crossroads of Europe and Africa and created by the Mediterranean Sea and the Alps proximity influences, with its large diversity of ecosystems, habitats, and biodiversity, remains an unique integrated landscape formed by the dynamic paleo-climatic and near-present climatic conditions. This amazing eco-bio-geographical complex node formed of river, fluviolacustrine, lagoon-marine and maritime landscapes and ecosystems, plays a major role in the region connectivity, providing a point of transition and stepping stones to surrounding geographical areas, with a key role for fish in this particular case approach.

Can the effects of climate change push this area into another state of dynamic ecological equilibrium with significant changes in all its non-living and living components? Can this transition area be the cradle of future resilience through adaptation of some fish species?

Fish are a worldwide traditional, trade and industry commercial foodstuff source for wild and domestic animals, and people and have a significant role in the aquatic and semi-aquatic ecosystems functional structures. For countless humans, fish are the needed major protein basis, and for even more, fish represent a weighty portion of their nutrition (Bakhsh, et al., 2023). Climate change is even now modifying aquatic habitats, with noteworthy effects for capture fisheries in the wild. Across the planet, the profits, food safety, occupations, and employments of aquatic resource-reliant groups of people are at risk, as the effects of climate change loom over safe food management, overexploiting imperiling fish (Bakhsh, et al., 2023).

Fish are key elements of aquatic ecosystems and support ecosystem services, due to their very large number of taxa and their variety of ecological niches in spite of their worrying risk of loss and increasing human-induced stress on aquatic ecosystems; they are thus of extraordinary value to nature and humans (Levêque et al., 2017).

We focused here on the Rhône River-Rhône Delta-Mediterranean Sea area fish because their ecological and economic importance is substantial on a regional and global scale (Carrel, 2002; Lebel et al., 1999; Changeux and Pont, 1995; Pattee, 1988; Leger, 1945; Kreitmann, 1932). The familiarity with fish and their habitats for fishing has existed since the rising of humans, a situation that has gathered much information and makes fish an ideal group of organisms for long-term studies of the ecosystems in which they live (Bănărescu, 1964; Giurescu, 1964). The value of fish fauna in the Rhône River-Rhône Delta-Mediterranean Sea area is revealed by the neighboring eco-bio-geographically rich influences on this region, and, as a most important large wetlands on the planet, important populations of threatened or rare fish species contribute to the high value of this region in terms of fish diversity too.

Climate change with the qualitative and quantitative dynamics of fish resources over time can be seen as humanity's current unintended planetary experiments (Bănăduc et al., 2020; Helfman, 2007; Ramanathan, 1988). Hydrologic processes that regulate the fish habitats characteristics and quality, generally govern ecosystems features (Laske, 2017), and these are altered by human-influenced modifications, of which climate is a major global force (Zhang et al., 2016). Therefore, the modified ecological features impact the ecological drivers and thus influence fish diversity (Koenigstein et al., 2016). However, a limitation of fish reaction research in relation to a modified climate is that quite infrequently the researchers consider ecosystem complexes such as rivers-deltas-coastal sea areas as threatened and at risk due to possible sea-level rise, subsidence, and sediment starvation, scenario in which many deltas around the world can reasonably be expected to change drastically.

While relatively narrow-scale assessment and monitoring activities are in progress, such as water level forecasts, it is unclear whether we are capable to adapt to this new risk in interconnected regional-global scenarios for the key complex of ecosystems of the planet.

Most of delta areas lie less than five meters above the mean sea level, and the most important 24 deltas and estuaries of the world are sinking, some of them by about 10 cm every year, because of soil compaction, sediment retention upstream behind anthropogenic barriers, and water and mineral overexploitation. Scientific studies reveals that the planet's deltas overexposed to flooding could boom by 50% and 85% have faced extreme overfloodings, inducing submergence shorter or longer than 260,000 km^2; half of the planet's major deltas will gradually become endangered by sea level rise (Brempong et al., 2023; Almar et al., 2021; Nicholls et al., 2021; Becker et al., 2020; Di Paola et al., 2018; Le Conzannet et al., 2015). Can global sea level rise cause the Rhône Delta to be in danger due to salinity intrusion and even to everlastingly be flooded due to the Mediterranean Sea level rises? Are all current populations of fish species under the same threat and risk gradient under these conditions? Can such a delta, with mostly negative relief and carrying less and less sediment to the sea due to human impact, be transformed or even disappear due to seawater intrusion? How different fish species will react to different speed and magnitude scenarios in the sea-level rise? Are the Rhône Delta branches developed enough to escape from being flooded? What will happen to the sensitive fish populations of the Rhône Basin and the Mediterranean Sea if the Rhône Delta is influenced by the negative effects of human actions, or even worse, remodeled, devastated or destroyed? Are humans' awareness and attitudes towards flood threats in the delta good enough or well-defined in the case of this delta? Is the Rhône Delta the Achilles heel of the Rhône Basin and the nearby Mediterranean Sea or a laboratory/training ground for diverse fish species that can adapt over time to the next sea level rise that follows induced modifications, degradation or even partial or total extinction of the Camargue and neighboring areas?

In these mixed complex natural and human induced circumstances, when we have so many multifaceted questions and relatively few potential answers, determination is needed to match aquatic ecosystems and ichthyofauna integrated assessment, monitoring, management, and protection in this region – to "build a boat" of information, data and awareness for the conservation of the most exposed to negative changes fish species and communities by understanding and protecting their under threat ecosystems.

In the milieu of much-needed environmental ethics, and based on the authors' 2023-2025 in situ obtained information and data from local fisherman captures, about ichthyofauna, and on particularly accessible scientific data, this study aims to correlates and reveal the studied region fish species status perspectives in two specific sea-level rise scenarios.

This approach delivers a prospective synthesis of possible influences on fish diversity in the Rhône Delta-Rhône River-Mediterranean Sea coast in ongoing climate change-sea level rise scenario.

The astonishing complexity dynamics of the studied area, the adjacent influential eco-bio-geographic regions, the natural processes, and the effects of human activities make it puzzling to simplify the key elements of the saga, while acknowledging that external factors can play a key role in inducing the probable tendency, intricacy, and rapidity of trends.

RESULTS

Prospective specific ecological effects of the changes of the habitats in the Rhône Delta and/or the potential loss of some fish species: potamodromous (fish born in upstream freshwater habitats, then migrate downstream, still in freshwater, as juveniles to grow into adults before migrating back upstream to spawm), anadromous (fish born in freshwater, then migrate to the sea as juveniles where they grow into adults before migrating back into frashwater to spawn), catadromous (fish born in saltwater, then migrate into freshwater as juveniles where they grow into adults before migrating back into the sea to spawn) and amphidromous (fish born in freshwater/deltas/estuaries, then drift into the sea as larvae before migrating back into freshwater to grow into adults and spawn) guilds.

Some aquatic species only tolerate and perform well in stable environmental salinities, either freshwater or seawater (Remane, 1934). Freshwater-seawater transition habitats usually have high biological productivity due to nutrient input from the riverine overland flow (Whitfield et al., 2012) and high food availability and relatively low interspecific competition may be a strong driving force for physiological and ecological adaptation to tolerate and perform well at intermediate salinity degrees (Brennan et al., 2016). A question raised is whether fish species diversity can be at least partly temporally and spatially greater from both ends of the salinity gradient to intermediate salinities in the mixing zone between freshwater and seawater.

On the other hand, salinity or its dynamic variability or change is one of the key factors that challenge and affect metabolism, foraging, migration, escaping predators in the wild, survival, general behavior, distribution of fish species, etc., as all fish are osmoregular and euryhaline fish maintain osmotic differences between their extracellular fluid and freshwater and seawater (Taugbol et al., 2014). The ability to respond fast to environmental changes is useful in variable environments, making phenotypically plastic organisms better adapted to unstable and unpredictable environments (West-Eberhard, 2005). But last and not least, how can diverse species with different life cycles survive under long-term impacts of the relatively rapidly changing environment?

Euryhaline fish species harbor specific mechanisms that control dynamic changes in osmoregulatory strategy from active salt absorption to salt secretion and from water excretion to water retention. These dynamic control mechanisms of the osmoregulatory strategy include the ability to perceive changes in environmental salinity that disturb body water and salt homeostasis (osmosensing), signaling networks that encode information about the direction and magnitude of salinity change, and epithelial transport and permeability effectors. These specific mechanisms of euryhalinity, involving specific functions of ancestral and derived proteins, likely arose through mosaic evolution. For a physiological self-preparation of fish that have to pass through different habitats in terms of salinity, the gradual succession of a mosaic of habitats helps a lot, this gradient disturbance impeding the fish life cycles, number of species, density, species composition, etc. (Feyrer et al., 2015; Kültz, 2915; Whitfield, 2015; Veale et al., 2014).

In this situation the presence, quality, surface, volume, and natural dynamics and stability of such salt to brackish to freshwater habitats gradient may be a necessity to varying degrees for some potamodromous, anadromous, catadromous, and amphidromous fish species.

The speed and extent of sea-level rise is vital in offering the fish species the needed time and space for in-situ adaptation to the new conditions or not. Different populations of fish species may have a temporal positive adaptation trajectory in the expected future period of time or may be adversely impacted by too rapid and high/large sea level rise in the study area.

Which are the fish species that have the potential to use the researched delta area as an adaptation ground, which offers a buffer and transition complex of ecosystems to enhance adaptation and survival to the new expected environmental conditions?

2.1 Potamodromous fish species

Abramis brama (Linnaeus, 1758) (Teleostei, Cypriniformes, Leuciscidae, Leuciscinae), freshwater bream, is a freshwater-brackish benthopelagic potamodromous species (Kottelat and Freyhof, 2007; Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023. It can be found seldom in the Camargue (Roche et al., 2009b). Throughout the life cycle of this species, habitat salinity type preferences and its mobility from one to another varies from fresh to diverse salinities (Asgari et al., 2013; Kafemann et al., 1998). The diminishing/degradation/disappearance of brackish habitats due to potential flooding of the delta by the sea would have a relatively moderate impact on the range of this fish distribution and the ecological status of the populations. Transitional habitats in terms of salinity gradient will also be affected with effects on opportunities for physiological adaptation.

Cyprinus carpio Linnaeus, 1758 (Teleostei, Cypriniformes, Cyprinidae, Cyprininae), Common carp, is a freshwater, brackish, benthopelagic, potamodromous fish, alien in the studied area (Feyrer et al., 2015) listed as Least Concern by IUCN Red List of Threatened Species in 2023. Salinity variability impacts the common carp sperm activity egg fertilization, growth and development (Karimov and Keyser 1998), fingerlings, juveniles and adults can rear in fresh to high salinity waters (Mangat and Hundal, 2014). The sea level rise would moderate affect local brackish populations of the delta by reducing a part of its specific spawning and feeding habitat, in the circumstances in which there are already low occurrences of individuals in the lower Rhône Basin (Cattanéo et al., 2001). The transitory habitats in terms of salinity gradient will also be negatively affected on opportunities for physiological adaptation.

Gobio gobio (Linnaeus, 1758) (Teleostei, Cypriniformes, Gobioninae), Gudgeon, is a species of freshwater, brackish, benthopelagic, potamodromous fish (Baensch et al., 1995) listed as Least Concern by IUCN Red List of Threatened Species in 2023. Its presence is well-known since ancient times (Kottelat and Persat, 2005) in practically all sorts of riverine and lacustrine habitats (Riede, 2004). In the Rhône Delta some authors say that gudgeons were free in a drainage channel in 1990 (Araújo et al., 1999). They prefer freshwater, but are also present in water with low salinity, a so called transition area (Araújo et al., 1999). Sea level rise would disturb local populations in a low to moderate degree by reducing part of its brackish habitats.

Alburnus alburnus (Linnaeus, 1758) (Cypriniformes, Leuciscidae, Leuciscinae), Bleak, is a freshwater, brackish, benthopelagic, potamodromous species (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023. Due to the fact that it is abundant in the Rhône Basin (Carrel and Rivier, 1996), in the event of delta flooding by the Mediterranean Sea, only the local delta populations would be affected low to moderate, due to the possible impact of saline water influence on semen quality and spermatozoa viability (Lahnsteiner et al., 1996), and flooding would not be a problem for this fish as a whole here.

Esox lucius Linnaeus, 1758 (Teleostei, Esociformes, Esocidae), Northern pike, is a freshwater, brackish, pelagic, potamodromous species (Scott and Crossman, 1973), occurs in lakes, pools, and backwaters of lotic systems, enters brackish water (Page and Burr, 1991), native to the Rhône drainage (Denys et al., 2018, 2014). Above a certain level of salinity in brackish habitats fish roes development, fry behavior and growth are characterized by stress (Jørgensen et al., 2010), highlighting the need for fish access to low salty and freshwater habitats at least for sensitive reproduction and early instar periods of life. In the case of flooding of the Rhône from the Mediterranean Sea, only the local delta population would suffer moderate, this not being a problem at the level of regional distribution of this species, a common native fish in the Rhône Basin. Still, the loss of important spawning brackish habitats (Möller et al., 2019) will negatively influence this species in the area. Under physiologically challenging conditions, pikes may respond by moving to more benign or environmentally favorable areas, generally or at least during critical periods as spawning (Jacobsen et al., 2017). However, the potential disappearance of populations exposed to fluctuating selective pressure due to the presence of brackish water loss some adaptive genetic difference and plasticity of salinity tolerance, which does not allow populations to cope with changes in salinity regimes associated with the future effects of climate change (Sunde et al., 2018). This fish shows the local ability to withstand short trips to high salinity waters (Soldo, 2023), but with the loss of some brackish habitats and their change into salty ones, the distances for such trips increase and become hard to cover in marine water for the colonization of new rivers in the area by sea.

Gambusia affinis (Baird and Girard, 1853) (Teleostei, Cypriniformes, Poeciliidae, Poeciliinae, Mosquitofish, is a freshwater, brackish, benthopelagic, potamodromous fish species, considered as an alien species in the studied area and (Pet Resources, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, most abundant in the lower stretches of rivers (Yamamoto and Tagawa, 2000). Adults live in no-flowing to slow-flowing bodies of water; mostly in vegetated ponds and lakes, backwaters, and noiseless pools of rivers, and are commonly found in brackish water (Man and Hodgkiss, 1981) and in freshwater wetlands of the Rhône Delta (Britton and Moser, 1982) as one of the last historically introduced fish. In Rhône Delta flooding seawater habitats, the local delta population would be low to moderate affected by habitat loss, but still, fish from such populations, with such historical salinity contact may have better reproductive persistence (Chervinski, 1983) and/or relocation during expected increased salinity, to the extent that genetic adaptation to salinity tolerance has been documented in poecilids (Shikano et al., 2001, 2000, 1998).

Gambusia holbrooki Girard, 1859 (Teleostei, Cyprinodontiformes, Poeciliidae, Poeciliinae, Eastern mosquitofish, is a freshwater, brackish, benthopelagic, potamodromous species, considered as an alien species in the Rhône Watershed region (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, adult individuals are usually present in non-flowing and also in slow-flowing bodies of water, more common in vegetated ponds and lakes, backwaters and pools of rivers they are also common in brackish ecosystems (Beaudoin et al., 2008) where they were first released in the Camargue region in 1927, since then, they have been flourishing in nearby habitats (Crivelli and Boy, 1987). On the one hand if the Rhône Delta is flooded by the Mediterranean Sea, the main local population of the delta would suffer low to moderately from habitat loss, but on the other hand, such poeciliids populations extended through numerous generations with long time residence in habitats with a significant salinity will have good survival chances in the event of further increased salinity (Meffe and Snelson, 1989), this being strongly positively influenced by historical salinity exposure, genetic adaptation to salinity tolerance which has been observed on poeciliids (Petriki et al., 2014; Carrel G., 2002; Shikano et al., 2000; Shikano and Fujio, 1998).

Gymnocephalus cernua (Linnaeus, 1758) (Teleostei, Perciformes/Percoidei, Percidae, Percinae, Ruffe, is a freshwater, brackish, benthopelagic, potamodromous fish species (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, that is living in general in eutrophic lakes, including coastal ones and tidal zone, lowland and piedmont rivers, as well as still or slow-flowing water with occurrences in standing to slow-flowing water (Kottelat and Freyhof, 2007) and a historical presence in the Rhône Basin (Rösch et al., 1996). The species is adaptable and tolerates a high range of salinity (Venâncio et al., 2019; Scott et al., 2007; Keup and Bayless, 1964). In case of flooding of the Rhône Delta by the Mediterranean Sea, the main local populations of the delta would suffer a low local habitat loss.

Lepomis gibbosus (Linnaeus, 1758) (Teleostei, Centrarchiformes, Centrarchidae, Pumpkinseed, is a freshwater, brackish, benthopelagic, potamodromous fish species, considered as an alien species in the Rhône Watershed area (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, that lives usually in non-flowing vegetated ecosystems and also in flowing waters pools, a fish that was introduced in Europe (Page and Burr, 1991). In the case of the studied flooding of the Rhône Delta by the Mediterranean Sea, the main local population of the delta would suffer moderate/high, despite the fact that this species has some tolerance to low salinity (Penaz et al., 1992), due to the fact that it cannot fully acclimatize its mortality under the impact of salinity which is significant (O'Hara, 1976).

Leucaspius delineatus (Heckel, 1843) (Teleostei, Cypriniformes, Leuciscidae, Leucisninae, Belica, is one of the last fish introduced into the study area, listed as Least Concern by IUCN Red List of Threatened Species in 2023, a freshwater, brackish, pelagic, potamodromous fish (Riede, 2004) that inhabits lowland riverine habitats mainly oxbows and other water bodies connected to rivers during floods; often found in ponds, lowland lakes and small water bodies not connected to rivers (Kottelat and Freyhof, 2007). In the case of the flooding of the Rhône Delta by the Mediterranean Sea, the main local population of the delta would suffer moderate/high, due to its low capacity to tolerate medium-high salinity (Caffrey et al., 2007).

Leuciscus leuciscus (Linnaeus, 1758) (Teleostei, Cypriniformes, Leuciscidae, Leucisninae, Common dace, a freshwater, brackish, benthopelagic, potamodromous fish species (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, inhabits moderate to fast-flowing large streams to large rivers (Kottelat and Freyhof, 2007). Present in former or present Rhône Basin channels (Vostradovsky, 1973), but not only, in the case of flooding of the Rhône Delta by the Mediterranean Sea, the main local population of the delta would suffer moderatelly, due to its ability to osmoregulate in brackish waters (Pont et al., 2018), but not because the saltier waters are closer to the sea (Svirgsden et al., 2018).

Misgurnus fossilis (Linnaeus, 1758) (Teleostei, Cypriniformes, Cobitidae, Weatherfish, a freshwater, brackish, demersal, potamodromous fish species (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, found in the lower reaches of slow-flowing rivers, but can also be found in still pools, ponds, and ditches (Bouvet et al., 1991), it is known to be present in the Rhône Basin (Härmä et al., 2008). In the event of this flooding of the delta by the Mediterranean Sea, the local populations of the delta would suffer moderately.

Phoxinus phoxinus (Linnaeus, 1758) (Teleostei, Cypriniformes, Leuciscidae, Phoxininae, Eurasian minnow, a freshwater, brackish, demersal, gregarious, potamodromous fish (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, found in a wide range of cold and well oxygenated habitats from small to large lowland rivers, and from small upland lakes to large oligotrophic lakes, in Rhône Basin, possibly an introgression zone with *Phoxinus septimaniae* in lower Rhône, from about Lyon southward (Kottelat and Freyhof, 2007). In case of flooding of the delta by the sea, will be no impact, and lower basin populations would not suffer due to this fish' potential for seawater and brackish residence with shorter or longer migrations to freshwater or to areas with low salinity (Aminat et al., 2023).

Rutilus rutilus (Linnaeus, 1758) (Teleostei, Cypriniformes, Leuciscidae, Leuciscinae), Roach, is a freshwater, brackish, benthopelagic, potamodromous fish (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, found in a wide variety of habitats, mainly in lowland areas, most abundant in nutrient-rich lakes and large to small sized rivers and backwaters, also in brackish coastal habitats; both larvae and juveniles live in a wide variety of littoral habitats (Kottelat and Freyhof, 2007). In the Rhône Basin presence situation (Goubier, 1972), in case of flooding of the Rhône Delta by the Mediterranean Sea, populations in the lower basin would suffer a low impact due to the combined tolerance to brackish coastal areas, but they need low salinity springs for reproduction (Poulet et al., 2009).

Sander lucioperca (Linnaeus, 1758) (Teleostei, Perciformes/Percoidei, Percidae, Luciopercinae), Pike-perch, is a freshwater, brackish, pelagic, potamodromous fish, being alien in the Rhône Basin (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, adults inhabit large rivers and euthrophic lakes, brackish coastal lakes, deltas and estuaries, foraging and reproduction inducing movements of hundreds of kilometers from one type of habitats to another in terms of salinity (Kottelat and Freyhof, 2007). In 1948 the pikeperch colonized the Mediterranean Rhône Delta lagoons (Poizat and Corivelli, 1997) expanding its distribution area here due to multiple introductions (Solberg, 2012). The disparition of the delta habitats, where this species first found the necessary conditions to be able to establish its local population, have no impact and cannot affect the Rhône basin status of this fish in the situation of floods in the delta by the sea, due to its capacity to move on long distances from freshwater, brackish to sea water for its active foraging (Coop, 1993a).

Scardinius erythrophthalmus (Linnaeus, 1758) (Teleostei, Cypriniformes, Leuciscidae, Leucisninae), Rudd, is a freshwater, brackish, benthopelagic, potamodromous fish (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, occurs mainly in nutrient-rich, well vegetated lowland aquatic habitats, including in the Rhône Basin (Bounket et al., 2021; Kottelat and Freyhof, 2007). The use of the Rhône Delta by this fish has biological and ecological consequences (Laroche et al., 1999), but will be no impact on the populations in the lower basin from potential sea flooding of the delta's habitats, due to the fact that this fish can regularly perform seawards migrations entering brackish water (Arzu Becer, 2017).

Squalius cephalus (Linnaeus, 1758) (Teleostei, Cypriniformes, Leuciscidae, Leucisninae), Chub, is a freshwater, brackish, benthopelagic, potamodromous fish (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, most abundant in small and large streams with riffles and pools, found along the banks, in lakes, undertaking spawning migration to inflowing streams (Kottelat and Freyhof, 2007). The Rhône Basin offers a variety of habitats for its migration, the distribution and connectivity of these populations (Coop, 1993b, Weatherley 1959) make this species not threatened by the potential scenario of degradation and disappearance of the current delta habitats, the populations in the lower basin would suffer a low impact due to the reduction and/or destruction delta habitats of this fish, due to the relatively high tolerance of this species to changes in salinity (Pagès et al., 2009).

Tinca tinca (Linnaeus, 1758) (Teleostei, Cypriniformes, Tincidae), Tench, is a freshwater, brackish, demersal, potamodromous species (Riede, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, typically found in shallow, densely vegetated lakes, backwaters, pools (Kottelat and Freyhof, 2007). The Rhône River basin offers a variety of microhabitats and habitats required for this species (Tabardel, 1994) in the potential scenario of delta degradation and extinction, the populations in the lower basin populations would suffer a moderate impact from the reduction and/or destruction of this fish delta habitats, due to their unremarkable salinity tolerance, despite the fact that sometimes they lead a normal life in brackish water (Bauchot, 1987).

All potamodromous fish species listed above are already negatively affected by partial fragmentation induced by man-made hydrotechnical structures for land agriculture purposes, and by other human activities impact.

This relative fragmentation of natural water cycles and associated biota mobility will ameliorate in the medium term if the sea rises moderately, bringing back the natural cycles and aquatic species mobility over the present dykes and drainage systems.

If the sea level rises sharply in the short, medium or long term to the expected level of more than five meters above the current sea level, and the current dykes are not raised and properly managed in the future, much of the delta's wetlands are at risk; the extinction trend will increase or the habitats characteristic of this area may even disappear if they do not have the time and space necessary to retreat upstream, this last hypothesis being questionable.

In both upper possible scenarios, negative pressures on local and regional potamodromous species are expected to varying degrees to continue, increase or start for these species, relative to their biological and ecological characteristics and potential spatial and temporal conditions to adapt to climate and ecosystems changes. For some species, few local positive effects can also remain or appear at the local level.

On the whole, potamodromous fish species will be more affected compared for example to amphidromous fish species but less than the catadromous fish species, as is revealed below.

2.2 Anadromous fish species

Acipenser sturio Linnaeus, 1758 (Chondrostei, Acipenseriformes, Acipenseridae, Acipenserinae), Common sturgeon, is a marine, freshwater, brackish, demersal, migratory anadromous fish species, it is Critically Endangered in the IUCN Red List, with a historical well known presence in the lower Rhône-Camargue-Mediterranean coasts areas too until the 70's, considered with good chances to be reintroduced here again (Billard, 1997; Rochard et al., 1997; Rochard and Elie, 1994), they live most of their life in the sea but enter lotic ecosystems for reproduction (Brosse et al., 2009; Billard and Lecointre, 2001; Williot et al., 1997). At sea, it occurs in coastal, brackish, and freshwaters, inhabiting coastal areas and large rivers (Kottelat and Freyhof, 2007) listed as Critically Endangered by IUCN Red List of Threatened Species in 2023, which includes the importance of the brackish areas. In the studied area, the potential rise of the sea level would highly affect the brackish habitats, from this perspective, due to the diminishing/disappearance of some of these habitats the individuals of this species may be affected. Especially the juveniles found both in deltas and the sea adapt slowly to salt water (Acolas et al., 2017) and usually spend several years in brackish areas before moving to the sea (Maitland and Hatton, 2003). Finally, we believe that the sustainable reintroduction of this fish species here (Whitehead, 1985) depend significantly on the presence of brackish delta habitats in good ecological balance, where juveniles prefer freshwater/saline transition waters (Léger, 1945).

Alosa alosa (Linnaeus, 1758) (Teleostei, Clupeiformes, Alosidae), Allis shad, is a marine, freshwater, brackish, pelagic-neritic, migratory anadromous fish species, listed as Critically Endangered by IUCN Red List of Threatened Species in 2023, which in brackish water near deltas and estuaries, adults prey mainly on aquatic invertebrates and may add small schooling fish while at sea (Costa-Dias et al., 2009; Bardonnet and Jatteau, 2008). This fish species was stocked in the Rhône River in the middle of the 19th century, since then this species has been declining (Lochet et al., 2009; Le Corre et al. 2000) in the studied area the potential sea level rise would highly affect it from this perspective, due to the diminishing/disappearance of the brackish ecosystems which allow the fish to adapt progressively from the marine to freshwater environments, especially for the larvae which need a transition zone from salty to freshwater, the direct seawater exposure inducing high mortality in young larvae whatever the ontogenetic stage (Le Corre et al. 2005). During their migration period, this species individuals also need to stay in the brackish habitats for the needed period before their exit to the sea, this brackish phase being a bottleneck for this species (Banister et al., 1986).

Alosa fallax (Lacepède, 1803) (Teleostei, Clupeiformes, Alosidae), Twaite shad, is a marine, freshwater, brackish, pelagic-neritic, migratory anadromous fish species, listed as Least Concern by IUCN Red List of Threatened Species in 2023, and is present in the lower Rhône River (Aprahamian et al., 2003; Béchu et al. 1995), adults individuals from the sea water begin to congregate near the mouths of deltas and estuaries in the spring season, after that ascend the river above as long as they are not totally blocked by local hydroelectric constructions and dams without appropriate bypasses in the brackish zone, and return to the sea after spawning (Bardonnet and Jatteau, 2008; Kottelat and Freyhof, 2007). In the studied Rhône Basin region, the potential rise of the sea level would highly affect it from this specific perspective, due to the fragmentation/diminishing/disappearance of the brackish ecosystems that allow this fish species individuals to progressively adapt from the marine to the freshwater environment and to remain in the brackish area during the migration period for the necessary period of time before their exit to the sea, this brackish phase being a bottleneck for this species (Banister, 1986).

Gasterosteus aculeatus Linnaeus, 1758 (Teleostei, Perciformes/Gasterosteoidei, Gasterosteidae) is a marine, freshwater, brackish, benthopelagic, anadromous fish species (Reide, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023. Adult individuals occur in freshwaters, estuaries, deltas, and also in marine coastal zones (Coop, 1993a). Anadromous, but also non-anadromous populations of this fish species appear in brackish or fresh water bodies, seldom in the marine coastal water, in freshwaters they are present in streams, rivers, and lakes (Coop, 1993b). The existence of this species in the Rhône Basin has been known since the last glacial maximum where there is a refuge area. The osmoregulatory characteristics of both marine and freshwater populations have not been environmentally channeled, but are able to react plastically to sudden salinity so the Mediterranean water level rise effects will be non-existent on the distribution and fish abundance in the surveyed area.

Perca fluviatilis Linnaeus, 1758 (Teleostei, Perciformes/Percoidei, Percidae, Percinae) is a freshwater, brackish, demersal, anadromous species (Reide, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023. It inhabits, as most clumped fish in the Rhône Basin (Christensen et al., 2019) a wide range of habitats like lagoons, lakes to streams (Kottelat and Freyhof, 2007). Will be no sea-level rise effects over delta's populations, which can have both low salinity tolerance and high salinity tolerance (Christensen et al., 2019).

Petromyzon marinus Linnaeus, 1758 (Petromyzonti, Petromyzontiformes, Petromyzontidae, Petromyzontinae) is a marine, freshwater, brackish, demersal fish species, some populations are permanent freshwater residents while others are anadromous, listed as Least Concern by IUCN Red List of Threatened Species in 2023, occupying a wide range of habitats (Renaud, 2011). Mature adults ascend rivers during spring and also in early summer (Muus, 1999). In the Rhône Basin, including the coastal zones, it is present but considered vulnerable, mainly due to fragmentation of the critical habitats (Banabera et al., 2020). The molecular and physiological limits of this fish species influence, under the condition of the disappearance of brackish water under the near sea level rise, the potential return to seawater for lampreys in search of alternative freshwater systems in which to spawn (Ferreira-Martins et al., 2016). A transition period in a transitional salinity zone is needed for this fish species osmoregulatory physiology dynamic (Barany et al., 2020). The degradation and loss of brackish habitats under all these conditions can high negatively affect this fish being detrimental in the sea-level rise scenario.

Pungitius pungitius (Linnaeus, 1758) (Teleostei, Perciformes/Gasterosteoidei, Gasterosteidae) Ninespine stickleback is a marine, freshwater, brackish, benthopelagic, anadromous fish species (Reide, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, living in low depth lakes, ponds and pools of slow-moving lotic ecosystems, now and then in open water, sea water populations are found near sea coast and travel into freshwater for spawning (Denys et al., 2017; Arai et al., 2010); there seems to be seasonal presence and activities from inshore to shallow water bodies in spring to spawn, and in autumn, offshore to deep water, or even in low salinity parts of the sea, in terms of young and adults after spawning process (Nelson, 1968) in the Rhône Basin, including near coastal areas (Benjamin, 1978). Changes in delta habitats of the Mediterranean sea-level rise scenario can moderately affect local populations due to the fact that in stable brackish conditions permanently resident populations can find good ecological conditions and thrive (Kangur et al., 2003), due to the reduced ability of this species to use freshwater habitats in the conditions of the decreasing of salty habitats accessibility in comparison to other species of this order for example (Page and Burr, 2011), due to the fact that the replacement of individuals from freshwater to seawater induce physiological stress and cellular changes and degradation (Rochard and Elie, 1994).

Salmo salar Linnaeus, 1758 (Teleostei, Salmoniformes, Salmonidae, Salmoninae) Atlantic salmon is a marine, freshwater, brackish, benthopelagic, anadromous, listed as Near Threatened by IUCN Red List of Threatened Species in 2023, amphihaline species spending most of its life in freshwater (Roule, 1920), juveniles remain in freshwater for one to six years, then migrate to coastal marine waters where they remain for one to four years before returning to freshwater for spawning (Parry, 1960). Even if extremely rare in the Rhône Basin (Bagliniere et al., 2002), the disappearance of the transition in terms of salinity of the brackish delta habitats can be detrimental for the gradual attraction, due to gradual environmental elements, of such species specimens in the upper freshwater. These detrimental effects are expected to be low in general due to the ability of this species to survive transfers to waters with different salt content (Parry, 1960) but especially high here due to its scarce presence in the studied area.

All the counted anadromous fish are by now influenced by the fragmentation made by anthropogenic technical structures for the expansion of agricultural land, and by other antropogenic impact types.

This fragmentation in terms of natural hydrographical cycles and the freedom of movement of related aquatic organisms will improve in the medium term if the level of the Mediterranean Sea rises moderately, reestablishing the normal water cycles and the agility of fish to overcome the existing technical works.

If the Mediterranean Sea level rises to more than five meters above the actual sea level, and the existent dykes are not elevated more than in the present and used properly in terms of water dynamic in the future, the threat of diminishing or even disappearing for the majority of delta's habitats will become a reality if they do not have enough space and time to gradually relocate upstream.

In both of the described potential scenarios, significant impacts on anadromous fish are also predictable, at different levels, from small to high, from one species to another, relative to their biological and ecological features and the spatial and temporal situations possible to adapt to climate and ecosystem changes. Some local positive effects can also remain or appear at local level.

In general the anadromous species will be more affected compared for example to amphidromous species, as is revealed below.

2.3 Catadromous fish species

Anguilla anguilla (Linnaeus, 1758) (Teleostei, Anguilliformes, Anguillidae), European eel, is a marine, freshwater, brackish, demersal, migratory catadromous fish species, listed as Critically Endangered by IUCN Red List of Threatened Species in 2023, it is present in lower Rhône-Camargue-Mediterranean coastal area too (Kottelat and Freyhof, 2007; Deelder et al., 1984), they enter brackish freshwater from the sea and colonize upstream freshwater lakes and rivers (Edeline et al., 2005), some individuals can remain in low and coastal waters to grow there into adults (Crivelli 1998). In the researched area, the potential high rise in sea level would affect it from this perspective, due to the fragmentation/diminishing/disappearance of brackish habitats which allow the fish to progressively adapt from marine to freshwater environments. More than this *Anguilla anguilla* population in the Camargue lagoonal system is divided into two subunits living in two distinct biotopes, freshwater, and brackish water (Acou and Lefebre, 2002). Further reduction of brackish habitats reduces the volume of eel rearing habitats, diminishing freshwater habitats that replenish with adult individuals the production of adults in more human affected freshwater habitats (Durif et al., 2023). Due to the fact that coastal eels tend to grow faster than freshwater eels (Edeline et al., 2005), the reduction or disappearance of habitats in this area moderately affects the different growth rates between different populations and the chances of survival of this species local individuals and populations.

Chelon ramada (Risso, 1827) (Teleostei, Mugiliformes, Mugilidae), Thinlip grey mullet, is a marine, freshwater, brackish, pelagic-neritic, catadromous fish species, listed as Near Threatened by IUCN Red List of Threatened Species in 2023, it is also present in the coastal area of the Mediterranean Basin (Kottelat and Freyhof, 2007), adult individuals are pelagic occurring near the shore, entering near lagoons, deltas and lower reaches, juvenile individuals colonize the littoral zone, estuaries and also deltas (Guillard and Colon, 2000), including the Rhône and Petit-Rhône basins areas (Quingnard and Authem, 1981). This fish species can stay for several months in fresh and brackish water (Lassere and Gallis, 1975) using local resources opportunities. In the researched area the potential sea level rise would moderately affect it from this perspective, due to the fragmentation/diminishing/disappearance of the brackish ecosystems which allow these fish to progressively adapt from the marine to the freshwater environments and to use much more diverse habitat resources. Further reduction of brackish habitats reduces volume of living and breeding habitats of this fish species.

Chelon auratus (Risso, 1810) (Teleostei, Mugiliformes, Mugilidae), Golden grey mullet, is a marine, freshwater, brackish, pelagic-neritic, catadromous fish species, listed as Near Threatened by IUCN Red List of Threatened Species in 2023, which also lives in the Mediterranean Sea basin coasts (Habib and Thiemann, 2021; Reide, 2004), adult individuals are generally neritic in schools, rarely entering lagoons, deltas, estuaries, and also freshwater (Thomson, 1990). Juvenile individuals move to lagoons in coastal areas, deltas, and estuaries in winter and spring seasons (Kottelat and Freyhof, 2007). Reproduction takes place in seawater habitats (Breder and Rosen, 1966). Potential sea-level rise would moderately affect this fish species, due to the reduction/disappearance of brackish ecosystems which allow fish to adapt gradually from marine to freshwater habitats and use more diverse habitat resources. Further possible reduction of brackish habitats diminishes the volume of this fish living habitats.

Mugil cephalus Linnaeus, 1758 (Teleostei, Mugiliformes, Mugilidae), Flathead grey mullet, is a marine, freshwater, brackish, benthopelagic, catadromous fish species (Reide, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, it is also present in the Rhône Basin, at least until the first major locks from the Rhône River (Albaret, 2003). Adults are found in coastal waters (Cardona, 2000) often entering estuaries, deltas, and rivers (De Silva and Perera, 1976), sometimes up-river, lagoons, and hypersaline environments (Barman et al., 2005). In the researched area, the potential sea level rise would moderately affect it from this perspective, due to the fragmentation/diminishing/disappearance of brackish ecosystems that allow the fish to progressively adapt from the marine to freshwater environments. Also, better growth, food intake and food conversion efficiency, intestinal enzyme activity of young, but not only individuals in decreased salinity habitats is diminished (Barman et al., 2005; De Silva and Perera, 1976) due to these potential brackish habitats reduction and loss.

Platichthys flesus (Linnaeus, 1758) (Teleostei, Pleuronectiformes, Pleuronectidae), European flounder, is a marine, freshwater, brackish, demersal, catadromous fish (Reide, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023, it is a current presence in the coastal area of the Rhône Bassin (Pomport-Castillon et al., 1997). It is migratory, most of the year can be found in low coastal areas (Bos, 1999), larvae and small juveniles, use selective tidal transportation to move upstream on lotic systems using salinity concentration gradient as a trigger (O'Neill et al., 2011), adult individuals appear in not deep water, in salt and brackish water, frequently entering freshwaters (Kottelat and Freyhof, 2007). In the researched area the potential sea level rise would moderately affect it from this perspective, due to the fragmentation/diminishing/disappearance of the brackish habitats which allow the fish to progressively adapt from the marine to the freshwater environments; habitats that offer supplementary feeding areas and habitats with low predator/competition risks.

All these catadromous fish are impacted by the human-made disruption of salt, brackish and freshwater habitats caused by anthropogenic hydrotechnical constructions to obtain new permanent terrestrial agricultural areas, and other human impact effects on the studied area.

This ruptures have negatively influenced natural water cycles and some of the connected catadromous fish. If the Camargue area near sea rises from a low to moderate level, it will improve water transport based on natural cycles and the mobility of aquatic species over the current dikes and drainage systems.

If the sea level rises a lot in the relatively long term (beyond the expected five meters higher than the actual sea level, and the dykes are not raised accordingly, the risk of a big part of the delta wetlands diminishing or even disappearing will activate if they do not have enough time and space to move upstream the Rhône River, this last hypothesis remaining questionable.

In all these probable scenarios harmful forces are also estimated on catadromous fish, to varying degrees, from small to high, from one species to another, in connection to their habitat needs and the possibilities of acclimatization to the new environmental conditions. Some local positive effects can also remain or appear at local level. Catadromous species will be more affected compared for example to amphidromous species, which are expected to have a greater potential to adapt to these changes, as is revealed below.

2.4 Amphidromous fish species

Atherina boyeri Risso, 1810 (Teleostei, Atheriniformes, Atherinidae, Atherininae), Big-scale sand smelt, is a marine, freshwater, brackish, demersal, amphidromous fish species, listed as Least Concern by IUCN Red List of Threatened Species in 2023, it is present and migrating particularly to spawn among the different habitats of the lower Rhône-Camargue-Mediterranean coastal area too (Kottelat and Freyhof, 2007; Focant et al., 1999). Being extremely euryhaline, inhabiting coastal, estuarine, and inland freshwaters (Boudinar et al., 2015), exhibiting similar growth performance in the marine, brackish and fresh water (Gençoğlu et al., 2020) and even moving daily from one type of habitat to another (Bardin and Pont, 2002) the loss of brackish delta habitats due to the sea level rise will induce a low impact on this species populations from the spatial scale respect.

Ameiurus melas (Rafinesque, 1820) (Teleostei, Siluriformes, Ictaluridae), Black bullhead, is a freshwater, demersal, amphidromous species, considered as an alien species in the studied area (Reide, 2004) listed as Least Concern by IUCN Red List of Threatened Species in 2023. It inhabits pools, backwaters, sluggish current sectors, impoundments, oxbows, and ponds (Kottelat and Freyhof, 2007). Due to the continuous growth of its populations in the Rhône area (Coop et al., 2016), if brackish water is a viable alternative for this species habitats (Bordignon et al., 2024), in the event of flooding of the Rhône Delta by the Mediterranean Sea, local delta populations would be affected, but flooding would have a low impact for this species as a whole in this basin.

Syngnathus abaster Risso, 1827 (Teleostei, Sygnathiformes, Sygnathidae), Blackstriped pipefish, is a marine, freshwater, brackish, amphidromous species (Reide, 2004), listed as Least Concern by IUCN Red List of Threatened Species in 2023, it is present in the Rhône Basin (***). Given the ability of this species to endure a large variation in water salinity, this fish can now be encountered in a wide variety of aquatic environments, not only marine and brackish but also in purely freshwater habitats (Monteiro and Vieira, 2017). In the event of flooding of the Rhône Delta by nearby sea waters, only local delta populations would be affected and flooding would have a low impact for this fish as a whole in this basin.

All the identified amphidromous fish species are obstructed by the anthropogenic technical structures that have generated through their presence and management the partial breakdown between the neighboring aquatic ecosystems (salt, brackish, freshwater), structures built for the acquisition of new agricultural land at the expense of wetlands.

This human-induced fragmentation has prejudiced the natural water cycle and some of the dependent amphidromous fish species. If the studied area near the Mediterranean Sea raise a little but enough to cross the actual dykes, it will allow the natural reconnection among different types of habitats, and the fish motion among them will be reestablished as well.

If the salt water level rises significantly above the expected five meters higher than in the present, and the dykes are not raised, the threat to a large portion of the habitats specific to the delta will be diminished or even lost, if they do not have enough time and space to retreat upstream of the Rhône River.

In all these possibilities, some low destructive effects on amphidromous fish are predicted, but it is important to highlight that this group of fish will be much less affected than the other three groups of fish studied here in this regard, also local positive effects can remain or appear at local level.

CONCLUSIONS

All the studied fish species of the Rhône Delta area and the upstream and downstream sectors are more or less impacted by the partial spatio-temporal fragmentation induced by the significant hydrotechnical works carried out for the acquisition of terrestrial agricultural land, due to the reduced surfaces and volumes of their habitats.

This relative fragmentation in terms of natural water circulation and the associated accessibility of biota to a wide range of ecosystems, will improve in general in the medium term if the sea rises moderately and the present dykes fail to stop seawater from coming in either and partially or completely, temporarily or permanently flood the Rhône Delta. In this case, the characteristic wetlands of the delta will once again thrive, as well as the associated ichthyodiversity too. We will see if the economic value of the potential flooded agricultural land will be enough to determine the authorities to raise the dykes higher and higher, exceeding two meters.

If the sea level rises sharply in the long term to the expected level of more than five meters above the current sea level, and the present two meters high dykes are not raised and properly managed in terms of water dynamic in the future to protect the brackish habitats, the risk of the extinction trend of much of the delta's wetlands will grow or habitats characteristic of this area may even disappear if they are not given the time and space to retreat upstream. Negative pressures on local and regional fish species are expected to continue as well, to varying degrees, from low to high, from one species to another, inside different guilds, in relation to their biological and ecological characteristics and spatio-temporal potential conditions to adapt to climate and ecosystems changes. Namely, potamodromous, anadromous, and catadromous species will be more affected compared to amphidromous species, which are expected to have a greater potential to adapt to these challenging changes.

Among the studied species, the followings are considered as alien in the studied area: *Cyprinus carpio*, *Gambusia affinis*, *Gambusia holbrooki*, *Ameiurus melas*, *Lepomis gibosus* and *Sander lucioperca*. All those species add a supplementary threats and risks to the local and regional ichthyodiversity (Teletchea and Beisel, 2017; Vilizzi, 2012).

Finally the synergic effects of the anthropogenic historic land changes and various other human impacts over posed with the sea level rise, create an extremely complex situation, which hardly offer any realistic on the ground sustainable management direction to be followed, only sectorial improvements based on in depth knowhow use for a proper in situ adapted fish ecosystems management will be possible on short to average term.

ACKNOWLEDGEMENTS

The authors thank Marie Coubard and Menjhi De Creny for their contributions to this research, and Ecotur Sibiu Association for its financial support of the fieldwork. The co-author George Secăreanu was supported by the Romanian Ministry of Research, Inovation and Digitalization, PNRR i8 760054 – JUST4MPA project.

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