Trajectory of a coastal social-ecological system: analyzing co-evolution and regime shifts in the Thau lagoon (Mediterranean Sea, France), 1970–2018

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Abstract

As coastal social-ecological systems (SES) are used for many different purposes and subject to different stressors, they are also among the most vulnerable and change the most rapidly. To achieve resilience, coastal areas require adaptive management based on integrated interdisciplinary approaches, requiring a deep understanding of SES dynamics, i.e., the ecological and social changes that comprise synchronicities and regime shifts.

For the purpose of analyzing co-evolution and regime shifts, we propose an original and operational methodology combining: (i) a chronosystemic timeline approach and (ii) time series analyses based on indicators from the "Drivers-Pressures-State-Impacts-Responses" framework (14 indicators including population growth, eutrophication status, ecosystem services, management actions and climate change indicators). The methodology was tested on a SES located on the French Mediterranean coast, the Thau lagoon, whose trajectory we studied over a 5-decade period (1970-2018).

Our results show that the dynamics of co-evolution and regime shifts of the SES were driven by a succession of interactions between sanitary or ecological crises and management adaptations. During the study period, this typical Mediterranean coastal SES appears to have evolved toward the multiplication of uses, improvement of water quality and more integrative management. Our methodology also highlighted three contrasting periods characterized by stable emerging properties and identified several cause-and-effect relationships, which is rare in historical analyses of SES. These cause-and-effect relationships concern major sanitary and ecological crises that have led to a reorganization of governance mechanisms and to technical remediation actions.

Our approach based on long-term trajectories will help identify the conditions required for increasing the resilience of coastal SES and the best management objectives to face new challenges related to global climate change.

Keywords: social-ecological system (SES); resilience; regime shift; timelines; trajectories; coastal lagoon.

1. INTRODUCTION

Coastal ecosystems are known to provide many ecosystem services that contribute to human wellbeing (Newton et al. 2014). As they are used for multiple purposes and subject to many different stresses, they are also among the most vulnerable (Halpern et al. 2008). It is therefore increasingly acknowledged that to achieve resilience, coastal zones require adaptive management and development policies based on interdisciplinary and integrated approaches (Lloyd et al. 2013). Stemming from ecology, resilience theory has become a powerful transdisciplinary tool to understand the dynamics and trajectories of social-ecological systems (Gunderson and Holling 2002). The idea of explicitly coupling the dynamics of ecological and social systems as a whole was extensively developed for the first time by Berkes and Folke (1998). These authors used the term social-ecological system (SES) to stress that the delineation between social and ecological systems is artificial and arbitrary: basically, the SES perspective analyzes how ecological and social processes interact at different spatial and time scales, and to consider this complex dynamic system as capable of self-organization and perpetual adaptations (Folke 2006). In practice, dealing with the diversity of processes involved in SES dynamics has given rise to numerous conceptual and methodological frameworks requiring interdisciplinary approaches.

Many frameworks have been proposed to analyze a whole complex SES, which often overlap or refer to each other (Binder et al. 2013). Some are purely conceptual, such as the theory of adaptive cycles and its extension to panarchy proposed by Gunderson and Holling (2002). Panarchy analyzes how SES evolve and re-organize at different spatial and temporal scales: a panarchy is defined as a set of nested adaptive cycles organized into a hierarchy, which connects adaptive cycles at small scales to adaptive cycles at large scales (Gunderson and Holling 2002). Other approaches appear to be more appropriate to understand the dynamics of a local SES while encompassing the wide range of the issues and processes at stake in coastal zones, such as the approaches developed in the three frameworks below.

First, the framework developed by Ostrom (2009), based on an institutional analysis, is the one that presents the most thorough analysis of the social components of an SES. Secondly, more and more frameworks include ecosystem services (ES) as a boundary object between disciplines (Steger et al. 2018). Considering both the potential of ecosystems to maintain useful ecological functions and the benefits people derive from it, the ES framework is able to describe the complexity of ecosystem-society interactions in an understandable and comprehensive way (Pendleton et al. 2015). Finally, many scientists involved in the management of coastal zones use the Drivers-Pressures-State-Impacts-Responses (DPSIR) analytical framework because it can be an efficient tool to simultaneously organize sophisticated empirical scientific research and transdisciplinary knowledge at an appropriate level to build knowledge on coastal SES (Lewison et al. 2016; Newton et al. 2014). The European Environment Agency (EEA 2003) defines each category of the DPSIR framework, allowing to analyze the causality of interactions. The causal links start with Driving forces, continue through Pressures to the State of the environment and Impacts on ecosystem functions and Human welfare, while Responses may apply to all the other four categories. DPSIR focuses on the factors of change (drivers and pressures) that people are capable of managing.

However, these frameworks also have certain shortcomings that need to be overcome. The DPSIR framework is structured around an adaptive management feedback loop designed to address a particular issue, and fails to account for certain dimensions of the SES that are not considered *per se*, such as ecological functions, ecosystem services or institutions. For these reasons, the DPSIR approach should be combined with the ecosystem services and the institutional analysis approaches to be sure to take all the ecological, social and governance issues raised by the SES dynamics into consideration. Ecological and social dynamics are at the core of SES research (Holland 1992; Costanza et al. 1993; Levin 1998; Gunderson & Holling 2002). However, few SES conceptual frameworks have produced an empirical methodology capable of systematically analyzing changes over time and of providing a comprehensive view of the SES trajectory (Binder et al. 2013). Most applications of the SES approach to case studies end with narratives that identify the conditions required to achieve resilience (see for instance Lloyd et al. 2013), but fail to provide clear evidence of changes through quantitative assessments, especially as regards institutions and governance. Several authors recently highlighted the need to use historical or dynamic approaches to study changes in ecosystem services, but few applications are available to date (Lavorel et al. 2015; Renard et al. 2015; Tomscha et al. 2016).

In this article, we hypothesize that long-term trajectories of coastal SES, which are exposed to high anthropogenic pressure and environmental changes and are therefore marked by synchronicities between ecological and social evolution, can be split into contrasted periods separated by regime shifts involving both ecological and social dynamics. Indeed, most current SES approaches consider that ecological and social changes are made of synchronicities and regime shifts (Norgaard 1995). However, although regime shifts in ecological sciences are based on well-documented theories (Scheffer and Carpenter 2003) and have been widely studied (Möllemann et al. 2011; Tomczak et al. 2022), their operational definition at the scale of SES is still the subject of debate (Biggs et al., 2018). We use the definition of SES regime shift proposed by Biggs et al. (2018): "large systemic changes that are policy relevant, in that they affect ecosystem services, and where there are established or at least proposed changes in feedbacks that make the systemic changes difficult to reverse". To test our hypothesis, we developed and applied an operational methodology to understand the trajectory of a local SES and to highlight synchronicities and regime shifts. We argue that an efficient methodology should combine qualitatively and quantitatively oriented approaches to account for the key processes involved in SES dynamics.

Several recent operational methods proposed for resilience assessment recommend building the first stages of the study of an SES based on timelines and historical profiling and on interviews with key stakeholders (Resilience Alliance 2020; Enfors-Kautsky et al. 2021; Biggs et al. 2021). The qualitative part of the methodology proposed in the present paper is adapted from the "chronosystemic timeline" approach (Bergeret et al. 2015; Spiegelberger et al. 2018), which consists in an interdisciplinary and holistic analysis of the trajectory of local territories based on literature searches and interviews with stakeholders. The quantitative part of the assessment used time-series analyses based on DPSIR indicators, including ES assessments, as proposed by Santos-Martín et al. (2019) to scrutinize long-term social-ecological dynamics at national scale. We applied our methodology to the Thau lagoon, an SES located on the French Mediterranean coast, and focused our analysis on the adaptation of local societies to changes in the state of the Thau lagoon (South of France) over a 5-decade period (1970-2018).

2. METHODS

The original approach we used to design our analytical framework and for the organization and classification of the information available on the SES led us to distinguish several steps corresponding to the qualitative (steps 2a-3a) and quantitative (steps 2b-3b) approaches (Fig. 1). The two approaches were combined by matching variables (steps 2a and 2b) and looking for regime shifts (steps 3a and 3b), to provide a synthesis of contrasting periods (step 4).

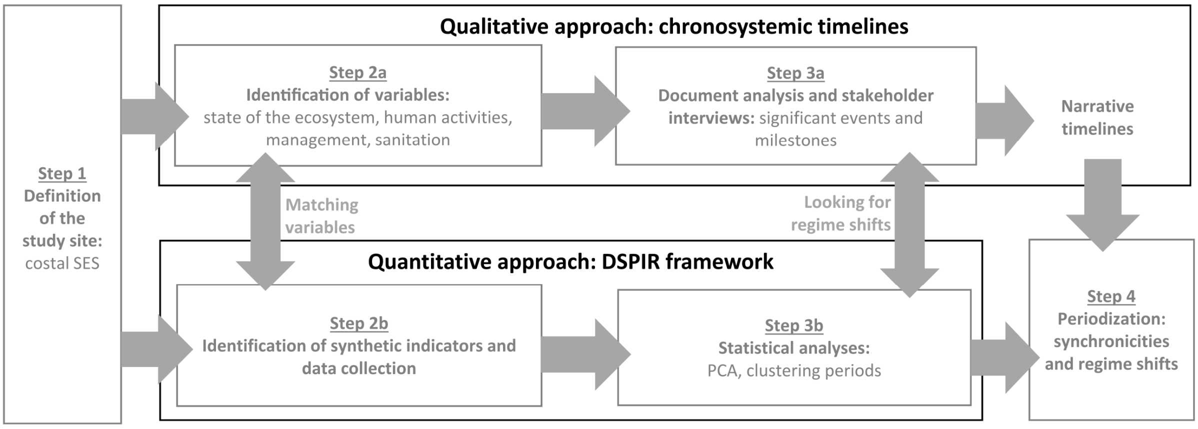

Fig. 1 Methodological process developed to analyze the long-term trajectory of a coastal social-ecological system (SES), combining a chronosystemic timeline approach (steps 2a-3a) and a Drivers-Pressures-State-Impacts-Responses (DPSIR) approach (steps 2b-3b). The two approaches were combined to analyze synchronicities and regime shifts (step 4)

2.1. Step 1 - Study site: Thau lagoon

Thau lagoon is a euhaline coastal lagoon, the largest and deepest in the Gulf of Lions (appendix, Fig. 4). Our study focused on the water body of the Thau lagoon, which covers about 6,790 ha (Fiandrino et al. 2017).

The population of the watershed is 103,500 inhabitants, half of whom live in the municipality of Sète (INSEE, 2016). Thau lagoon is the scene of traditional fishing and shellfish farming. The shellfish species reared today are *Mytilus galloprovincialis* (*M. galloprovincialis*) mussels but mainly the Pacific oyster *Crassostrea gigas* (*C. gigas*), whose production is estimated at about 10% of the total oyster production in France (Gangnery et al. 2003).

2.2. Qualitative approach: chronosystemic timelines

The full implementation of the "chronosystemic timeline" approach presupposes the formation of a multidisciplinary team of researchers (Bergeret et al. 2015; Spiegelberger et al. 2018). This work was conducted by a multidisciplinary team of researchers (one ecologist, three social scientists) as recommended for the methodology, but due to the limited number of researchers, we applied a simplified version (Fig. 1, steps 2a-3a).

2.2.2. Step 2a - Identification of processes and components

Because we focused on the adaptation of local societies to changes in the state of the Thau lagoon, we depicted the trajectory of our coastal SES through four main processes: the state of the ecosystem, human activities, management of the SES and sanitation. Each of these processes is depicted in a thematic narrative timeline (i.e. descriptive chronology) including components of an economic, political, environmental or social nature, with a particular attention paid to institutions and their changes. The following components were considered:

- **state of the ecosystem:** anoxic crises, appearance of invasive macroalgae, sanitary crises or ban on the sale of shellfish due to microbiological contamination or toxic phytoplankton, chemical or ecological problems that impact shellfish;
- **human activities:** fishing, shellfish farming, recreational and spa activities, tourism;
- **management of the SES:** European and national regulations and funds, regional water management schemes, creation of local structures, a local charter and decree, management tools and contracts for the use of the SES;
- **sanitation:** chemical wastewater treatment plant or lagooning treatment, changes in the treatment system: transformation into lagooning/chemical process, connection to the sanitation network, hydraulic, rehabilitation or resizing works.

2.2.3. Step 3a - Analysis of documents and identification of milestones

Several documents and data sources were used to inform the components and to identify significant events to be reported in the first version of the timelines:

- gray literature on ecology, shellfish farming and management of coastal SES over the period 1970-2018, representing 418 digitized files;
- search for scientific gray literature and publications in Web of Science databases;
- documents in the departmental archives and on regional and local websites;
- phone and email surveys of associations and administrative services in 2019 and 2020 to assess the importance of some tourist and recreational activities.

Data were mainly qualitative but quantitative data were also used to inform some components (see appendix, Table 2 for the list of indicators and the data sources).

To validate and possibly clarify the interpretations resulting from our document analysis, we interviewed nine organizations representative of the range of local institutions, involved in water management and use and identified as key-actors by previous studies on the Thau lagoon (Bouleau et al. 2009; La Jeunesse et al. 2015) (appendix, Table 3). One person per organization was selected for the interviews, according to its seniority in the territory. Only for the Syndicate of the Thau Lagoon (SMBT), two people were interviewed to represent the broad spectrum of activities carried out by this management structure. In that case, quantitative data were averaged and qualitative information were merged.

In a semi-structured interview lasting 90 minutes and transcribed, the stakeholders were asked about their perception of changes in the SES between 1970 and 2018 concerning environmental and socioeconomic problems, human activities and SES management (appendix, Table 4). They were given two blank chronological timelines and asked to position the 'major events' of the SES trajectory in relation to (1) the ecological and sanitary state of the ecosystem, (2) uses and management of the SES. The 'major events' were defined as events that marked the evolution of the characteristics and management policies of the lagoon (environmental and/or socio-economic issues). We listed the major events mentioned by stakeholders in the timelines and also during interviews (questions 2, 7 and 8 in appendix, Table 4). A second version of the four narrative timelines was then produced, highlighting the 'milestones' corresponding to the major events cited by more than five stakeholders among the nine interviewed, representing 55.5% of the stakeholders interviewed.

2.3. Quantitative approach: DPSIR framework

We adapted the methodology proposed by Santos-Martín et al. (2019) to analyze time series of the coastal SES based on DPSIR indicators. From a SES perspective, we expanded the scope of DPSIR indicators to include environmental drivers of change (Fig. 1, steps 2b-3b).

2.3.1. Step 2b - Synthetic indicators

To summarize the SES dynamics according to the DPSIR approach, we selected a set of synthetic indicators using the standard evaluation criteria recommended by Tam et al. (2017). Availability and reliability of data was evaluated according to the following criteria: 1) data available for a large part of the study period (1970-2018); 2) data of medium reliability (qualitative data supported by several sources or quantitative data with relatively high uncertainty) or high reliability (quantitative data delimited in space and time). This resulted in the selection of 14 indicators (appendix, Table 2). We selected population growth as the driving force (D) linked to human activities and as for a coastal SES. As climate change cannot be considered as a result of local pressures, rainfall and temperature were included as environmental drivers of change. As waste waters are known to be the most impactful anthropogenic pressure for marine waters (Pedreschi et al. 2019) and especially Mediterranean lagoons (Souchu et al. 2010; Derolez et al. 2019), the proportion of households not connected to the sanitation system was the variable chosen to illustrate the anthropic pressure (P) caused by urban nutrient inputs. Then, two environmental variables illustrating the eutrophication status of the ecosystem and used for Water Framework Directive diagnoses (MTES 2018) were selected as state indicators (S) and corresponding to regulation ecosystem services. Five variables illustrating ecosystem services, corresponding to provisioning and cultural services, were selected as impact indicators (I). The selection of the ES was drawn up in a multidisciplinary manner by scientists specialized in the study area, based on the Common International Classification of Ecosystem Services (Haines-Young and Potschin 2018). Finally, three variables illustrating management actions were selected as response indicators (R). The eight variables including missing values (NA) (appendix, Table 2) were interpolated using the algorithm of Stineman (*imputeTS* package in R).

2.3.2. Step 3b - PCA analysis and clustering

Data from 1970 to 2018 on the 12 environmental and social variables selected using the DPSIR approach were analyzed through an explanatory Principal Component Analysis (PCA) (*ade4* package in R). The two environmental drivers of change were considered as illustrative variables and not included in the construction of the PCA space. K-means cluster analysis was then applied to identify years with similar patterns of environmental and social variables (*vegan* package in R). The optimal number of clusters was estimated based on the simple structure index (SSI) (Dolnicar et al. 1999).

2.4. Step 4 - Periodization: synchronicities and regime shifts

Synchronicities were characterized with the help of PCA analyses showing correlations between DPSIR indicators. We considered that the periods were separated by a regime shift, using the definition given by Biggs et al. (2018).

To highlight contrasting periods and regime shifts, we compared the results of the two approaches: (i) milestones identified using the chronosystemic timelines approach and (ii) groups of years with similar patterns identified by the DPSIR approach. A regime shift separating contrasting periods corresponds to phases of rupture: (i) highlighted by clustering and identified as a milestone by the stakeholders; and (ii) that led to the reorganization of actor strategies in a context of regulatory renewal and governance mechanisms. Emergent properties of the SES at each period were also identified by both PCA and the narrative timelines. These results were used to build a synthetic timeline to describe the contrasted periods identified along the SES trajectory.

3. RESULTS

The analysis of the synchronicity of factors makes it possible to identify trajectories and to distinguish different contrasting periods in terms of modes of organization on a local scale, and on a wider scale in terms of societal and institutional developments. Several timelines specific to each field were therefore produced (Section 3.1) and then combined to characterize the global trends and the factors of change characteristic of the different periods (Section 3.2).

3.1. CHRONOSYSTEMIC TIMELINE APPROACH USED TO ANALYZE THE TRAJECTORY OF COASTAL SES

The trends and milestones found with document analysis and mentioned by stakeholders on the first two processes - (i) the sanitary status of the waters, the shellfish, and the ecological and chemical status of the lagoon; (ii) and human activities - evidenced a succession of environmental crises and a strong vocation for fishing and shellfish farming for the Thau lagoon during the period 1970-2018 (see the timelines in appendix, Fig. 5 and 6).

The milestones identified by stakeholders concerning the management measures and the wastewater treatment system (timelines in appendix, Fig. 7 and 8) show a change from: i) sectoral management, hierarchical organization and sanitation works (1970s-1980s), to ii) a structuring of watershed management (1990s) and then to iii) integrated management (from the 2000s).

3.2. SYNCHRONICITIES AND REGIME SHIFTS IN THE COASTAL SES TRAJECTORY

3.2.2. DPSIR approach

PCA was performed on 12 active environmental and social variables selected for the DPSIR approach, with two illustrative variables corresponding to environmental drivers of change (changes observed between 1970 and 2018 in each variable are available in appendix, Fig. 9). The first two axes of the PCA explained 87.8% of total variability (axis 1 explaining 75.0% and axis 2 explaining 12.8%; the correlation circle of the PCA is available in appendix, Fig. 10). The first axis (horizontal) revealed a clear temporal structure, contrasting the earliest and the most recent years (respectively on the left and right in Fig. 2).

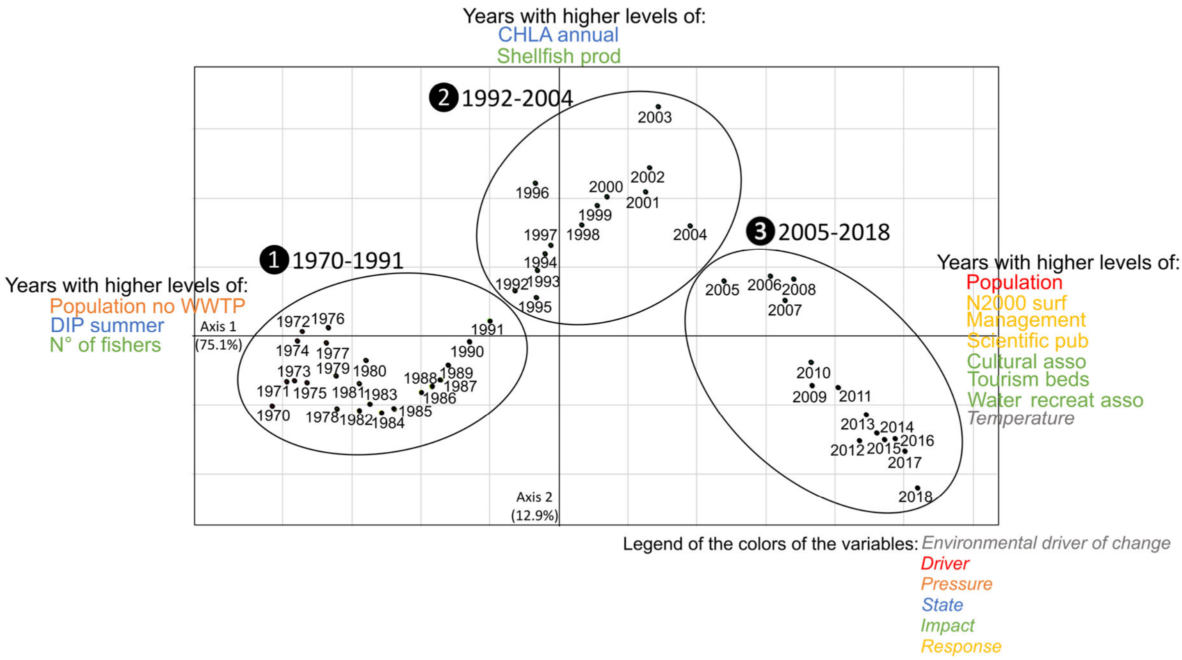

Fig. 2 Results of PCA of environmental and social variables from 1970 to 2018. Years on the plane defined by the first and second axes and ellipses representing the 3 groups of years identified by cluster analysis. The variables are positioned on the plane according to their correlations with axes 1 and 2 (correlation circle is available in appendix, Fig. 10; meaning of the acronyms available in appendix, Table 2), and colored according to their DPSIR category. The first and second axes account for 87.8% of total variability

This axis, driven by many variables, illustrates the synchronicity of several processes in the SES trajectory. This axis is negatively correlated mainly with the number of fishers, and to a lesser extent with the population not connected to the wastewater treatment plant and the Dissolved Inorganic Phosphorus (DIP) levels in water (on the left in Fig. 2). The first axis is positively correlated mainly with the number of tourist beds, water recreational and cultural associations, of management structures and tools and with population (on the right in Fig. 2). The first axis is correlated to a lesser extent with the number of scientific publications, the surface area of the lagoon protected by Natura 2000 and with temperature. The second axis (vertical) is mainly defined by shellfish production (at the top in Fig. 2). Chlorophyll *a* concentration is correlated with both axis 1 and 2, but to a lesser extent.

Among the three clusters identified by the simple structure index index in the PCA, the first cluster, located on the left in Fig. 2, groups the first 22 years of the study period (1970 to 1991). This first cluster is associated with the variables negatively correlated with the first axis. On the opposite side, the third cluster groups the last 14 years of the study period (2005 to 2018) and is associated with the variables positively correlated with the first axis (on the right in Fig. 2). In the middle of Fig. 2, the second cluster isolates the period 1992 to 2004, among which the years 2001 to 2003 were characterized by high levels of shellfish production.

3.2.3. Periodization: synchronicities and regime shifts

Among the events listed in the four narrative timelines, nine were identified as milestones by the majority of stakeholders (more than 5 of 9, Table 1). Five milestones concerned the ecosystem status of the lagoon, two milestones referred to shellfish farming and two milestones concerned lagoon management. The events related to sanitation works were not identified as milestones by the stakeholders even though they contributed to significant changes in water quality.

Table 1 Summary of the approaches used to identify the regime shifts: i) milestones mentioned by the majority of stakeholders through the chronosystemic timeline approach (left column), ii) years identified by cluster analysis in the DPSIR approach (right column). Rows shaded in grey represent the regime shifts considered to separate the 3 contrasting periods. *The colors represent different components: blue: ecological and sanitary status, orange: shellfish farming, green: management tools

Chronosystemic timeline approach Milestones mentioned by the majority of stakeholders*	**DPSIR approach** Years identified with the cluster analysis
1970-1972: reorganization of shellfish farming area	
1989: « *Salmonella* crisis »	**1991-1992**
1995: Sea Development Plan (French acronym 'SMVM')	
2003: anoxic crisis	
2004: sanitary downgrading	**2004-2005**
2005: creation of the Syndicate of the Thau Lagoon (SMBT)	
2006: anoxic crisis	
2008: Oyster spat mortalities (OsHV-1)	
2018: "Green water crisis"	

Among these milestones, two periods of environmental crises can be considered as regime shifts because (i) they led to reorganization of actor strategies in a context of regulatory renewal and governance mechanisms; (ii) they were identified by the clustering analysis applied in the DPSIR approach (Table 1). The first regime shift occurred in 1989 with the "*Salmonella* crisis", which caused an economic crisis and led to the involvement of all the local actors in the problem of the quality of the water in the lagoon, and to the first Management Contract in 1990. The sequence of these events constitutes a first cause-and-effect relationship identified with our analyses. The DPSIR approach also identified a shift between clusters of years in this period, with clusters 1 and 2 separating in 1991-1992. The second regime shift occurred in 2004 with sanitary downgrading of the lagoon that took place between two major anoxic crises, one in summer 2003 and the other in summer 2006. These environmental crises occurred in a context of changes in regulations related to water management (Water Framework Directive in 2000) and transformation of the local institutional organization that favored the creation of the Syndicate of the Thau Lagoon in 2005, a major actor in the management of Thau SES. The creation of this syndicate, dedicated mainly to the protection of water quality, following the ecological crises of 2003 and 2006 constitutes the second cause-and-effect relationship highlighted by our analyses. The year 2008, which the stakeholders identified as a milestone because of the oyster spat mortalities, was not identified by PCA clustering. However, as this event in 2008 did not lead to reorganization of actor strategies or governance, we did not consider it as a regime shift.

The two regime shifts identified with our combined approach distinguished three contrasting periods in the trajectory of Thau SES: period 1 (1970-1989), period 2 (1990-2004) and period 3 (2005-2018). The emerging properties of these periods are highlighted by the two axes of the PCA and can be interpreted as follows (i) axis 1 discriminates periods 1 and 3 (from left to right), as a gradient of oligotrophication, change of uses (from the domination of traditional uses to recreational and diversified uses), development of management tools, demographic growth and climate warming; ii) axis 2 discriminates period 2 as a gradient of shellfish production. Fig. 3 is a synthetic timeline of Thau SES that summarizes the regime shifts, the periods and their emergent properties.

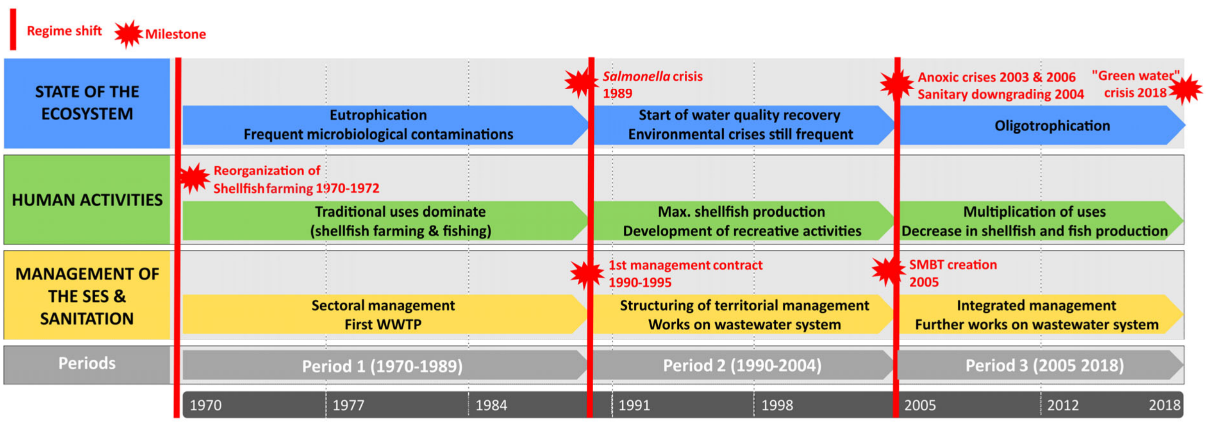

Fig. 3 Synthetic timeline of trajectory of Thau SES from 1970 to 2018, showing the regime shifts that separate 3 contrasting periods with their emergent properties concerning the state of the ecosystem, human activities, management of the SES, sanitation and environmental drivers of change (climate). Milestones identified by the stakeholders are shown in red

The main characteristics of the three periods are listed below:

- Period 1 (1970-1989)

The beginning of this period was marked by the reorganization of shellfish farming that allocated more space to shellfish farming encroaching on areas traditionally dedicated to fishing. Both this event and the parallel disappearance of the Portuguese oyster can be considered as a regime shift in the trajectory of the SES. During this period, the lagoon was the scene of few recreational activities apart from recreational fishing, hydrotherapy, swimming and boating. Management of these activities was essentially sectoral, with considerable intervention by the State as regulator. This period was marked by the installation of the first wastewater treatment plants in the lagoon watershed. The status of the lagoon was seriously damaged by excessive inputs of nutrients - causing a eutrophic state and recurring anoxic crises - and by regular microbiological contamination leading to measures banning the sale of shellfish.

- Period 2 (1990-2004)

The "*Salmonella* crisis" in 1989 triggered the establishment of partnership management by the stakeholders in the territory and corresponded to the start of a series of Management Contracts for the Thau lagoon. The work to improve the sanitation system resulting from these contracts improved the status of the lagoon in terms of eutrophication and reduced the intensity of anoxic episodes. However, anoxic crises continued and microbiological contamination of shellfish still frequently occurred. The Sea Development Plan (1995) reaffirmed the priority given to traditional activities such as shellfish farming and fishing in the lagoon. This period also saw the development of tourism centered on the lagoon and the emergence of new recreational and leisure uses.

- Period 3 (2005-2018)

The beginning of the third period was marked by the sanitary downgrading of the lagoon to category B, meaning the shellfish had to be purified before being sold. The creation of Syndicate of the Thau Lagoon in 2005 marked the establishment of an integrated management policy, implemented in collaboration with professional actors, municipalities and State services. The Syndicate of the Thau Lagoon pursued a dual objective of reconciling uses and preserving the good status of the lagoon. The period that then began was characterized by the diversification of uses of the lagoon and significant development of tourism and new recreational activities. This period was also marked by weakening of shellfish farming activity from 2008 (mortality of OsHV spat) and a decline in fishing. Despite the ongoing oligotrophication of the lagoon, anoxic crises occurred during summer heatwaves (2003, 2006, 2018), and the "Green water crisis" in 2018, a sign of the growing pressure of global warming on the Thau lagoon. This unprecedented dystrophic crisis can be seen as a new regime shift in the trajectory of Thau SES.

4. DISCUSSION

4.1. Summary of the coastal SES trajectory

The methodology we used to analyze the long-term trajectory of a coastal SES enabled us to show a succession of sanitary or ecological crises and management adaptations. Similar successions of crises leading to adaptations of local management methods have been highlighted in other estuarine systems in Europe and in Pacific regions (Daniell et al. 2020). Examples of coastal SES regime shifts in the literature are generally associated with degradations (de Jonge et al. 2002; Biggs et al. 2021), but few examples are available to illustrate the recovery or coastal lagoon ecosystems (Derolez et al. 2019), and even less at the SES scale (De Wit et al. 2020; Erostate et al. 2022). Our dynamic study over a 5-decade period showed that the SES evolved towards the improvement of water quality, multiplication of uses and more integrative management. Our results revealed a shift in a system originally dedicated to food production towards a system with diversified uses, with a particular focus on the development of tourism and recreational activities. This trend reflects the growing attraction of the coast for leisure activities (Corlay 1995). The three contrasting periods we identified in this study of the trajectory of the coastal SES are almost identical (within one or two years) to those identified in a study based only on the ecological changes (Derolez et al. 2020). This study showed successive periods in ecosystem functioning during the oligotrophication process: a eutrophic period (1970-1992), a transition phase (1993-2003) and a regime shift (2003-2006) followed by a period towards oligotrophy (2006-2018). The similarity of the periods could be explained by the low inertia of estuaries and coastal lagoons in terms of ecological functioning in response to reduced nutrient loads following remediation measures (Boynton et al. 2013; Lie et al. 2021). In parallel, the social system is very responsive to water and shellfish quality issues, which play a major role in mobilizing local actors when they are threatened (Barone 2016). However, the management measures we identified in our study were driven by more general issues, given that the Thau basin was selected as a national pilot site for the implementation of the Integrated Coastal Zone Management (GESAMP 1996). Likewise, the changes in management methods should be considered in the broader context of decentralization in France in the 1980s, and their promotion by European Union recommendations and French laws in the 1990s designed to promote sustainable development (French Law 1999; Parliamentary Assembly 1999). The principles of « New public management » were reinforced in France in the 2000s, and decentralization was reinforced to the benefit of local authorities.

Despite improvements in water quality and the development of an integrated management policy in the most recent period, several problems still threaten the stability of the SES. The recent ecological crises associated with the increasing pressure of global warming (Lagarde et al. 2021) greatly weakened shellfish farmers and point to a new regime shift in the trajectory of the SES. Shellfish diseases continue to affect production (Pernet et al. 2018) and fishing is also declining. Finally, the average age of today's fishers and shellfish farmers is going up, so these traditional uses do not suggest stability or future growth. However, for those involved in water policy, the strict water quality standards required by the traditional fishing and shellfish farming activities, who readily present themselves as "sentinels of the coastal environment", can be considered as a driving force for the territory towards exemplarity and innovation in scientific activities and environmental management (Barone 2016; Chesbrough 2003; Daudin et al. 2021).

4.2. Perspectives for the dynamic analysis of the SES

The original and operational methodology used to depict the trajectory of a coastal SES proposed in this paper, which combines qualitative and quantitative information, proved to be particularly appropriate to reveal the dynamics of coevolution of the social and ecological components of a complex coastal system along with regime shifts. As recommended by Bergeret et al. (2015) and Spiegelberger et al. (2018), the trajectory of a SES must be studied using a holistic approach, calling on interdisciplinary expertise and using timelines as boundary objects between the natural sciences and social sciences. This holistic approach is in accordance with the theories developed by researchers studying complex systems (Holland

1992; Levin 1998). Moreover, our study enabled the identification of regime shifts, in accordance with the concepts developed by several authors in the system analysis perspective (Scheffer and Carpenter 2003; Biggs et al. 2018) and illustrated in several terrestrial or aquatic SES (Kermagoret et al. 2019; Lavorel et al. 2015). Other recent studies analyzed the long-term dynamics of SES from the same theoretical perspective, to name a few examples: a study of the management of the Everglades wetlands (Florida, USA) (Gunderson et al. 2002), the trajectory of Lake Taihu (China) (Lin et al. 2019) or of a Corsican lagoon (Erostate et al. 2022).

The holistic and combined approach we developed allowed us to identify several cause-effect relationships and stable emerging properties characterizing contrasted periods, but needs to be completed by more detailed analyses of causal links and to better account for the complexity of systems (Costanza et al. 1993). For example, more precise characterization of the ecological and social determinants of the stability or instability of the SES is required to fully understand its dynamics. To this end, our study could be supplemented by a study of historical changes in ecosystem services (ES) as recommended by several authors (Renard et al. 2015; Tomscha et al. 2016). Other authors have analyzed the past trajectory of a mountain SES through changes in nature's contributions to people and resulting adaptations (Bruley et al. 2021). A dynamic approach is crucial to explore the threshold effects and possible irreversibilities and to identify the synergies and antagonisms between ES that require trade-offs or compromises (Renard et al. 2015; Tomscha et al. 2016). In addition, the distinction between demands, flows and potentials of ES is particularly useful to assess the sustainability of uses and thus to support environmental management (Burkhard et al. 2014; Villamagna et al. 2013).

Our study of historical trajectories will also be useful to identify the conditions that trigger crises or favor the ability of SES to adapt in the long term. In the context of global change and faced with the multiplicity of uses and the complexity of the issues, stakeholders need more knowledge and management scenarios to increase resilience and guarantee the sustainability of SES activities (Yorque et al. 2002; van Staveren and van Tatenhove 2016). Such models have already been applied to Thau lagoon to test the influence of different nutrient inputs and shellfish stock scenarios on oyster production, carrying capacity, and Water Framework Directive ecological status (Pete et al. 2020). However, the lack of reliable data on fish and shellfish production is an obstacle to the calibration of such models and the necessary management tools need to be co-developed by scientists and stakeholders (Byron et al. 2011). More knowledge on how local users, inhabitants, managers perceive ecosystem and how it is changing is needed to better define restoration goals and to account for the notion of the "desired state" of the environment, whose meaning may differ among local actors and is sometimes far removed from ecological standards (de Wit et al. 2020; Baker and Eckerberg 2016). Some authors designed a participatory diagnosis approach for fisheries and demonstrated its potential to guide contextually informed improvements to management in practice, including transitions to contemporary forms of governance (Eriksson et al. 2016). Finally, the results we obtained using the empirical analysis of the long-term trajectory of a coastal SES highlighted the key role of episodic disturbances in triggering reorganization of governance. These results should now be reanalyzed using the concept of ecological resilience to provide the critical insights needed to identify the role of social dynamics during alternating periods of stability and instability in SES. Such an approach could help identify the structures and processes best suited to shift governance towards sufficiently flexible forms to meet the challenge of mitigating the impacts of global climate change (Chaffin and Gunderson 2016).

5. CONCLUSION

We propose an innovative analytical framework to study the long-term trajectory of coastal social-ecological systems. Our methodology, which combines qualitative and quantitative information, was applied to the Thau lagoon case study and revealed co-evolution and regime shifts caused by a succession of sanitary or ecological crises and highlighted the key role of episodic disturbances in triggering reorganization of governance. The contrasting periods shown in the 5-decade trajectory of the SES were almost identical to those based on ecological changes alone. This confirmed the importance of water quality and of the traditional uses of shellfish farming as well as their role in mobilizing local actors when threatened.

Our method provides the first clues to emergent properties that may favor resilience at the coastal SES scale and guide future management options to protect ecosystem functions and services in times of global changes. The analysis of past changes makes it possible to characterize the processes at the origin of the observed adaptations. These result from interactions between spontaneous responses, both ecological and socio-economic, and the responses of regulatory systems, which are the responsibility of local governance, but also of multi-level decisions due to the interweaving of governance systems. The synchronicities observed lead us to advocate the reactivity of regulatory systems, but also the evolution of paradigms according to the periods. Moreover, this type of analytical framework, conducted in collaboration with the stakeholders, illustrates the interest of close collaboration between scientists and managers to better understand the complexity of interactions. The aim is to better understand the interactions between the various components, but also between cyclical and structural determinants. This understanding of past trajectories facilitates the analysis of the conditions of adaptation of the SES and thus its long-term resilience, which must be dynamic and adaptive (Sgrò et al. 2010; Davoudi et al. 2012).

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Supplementary materials

Table 2 List of the 12 variables (and 2 environmental drivers of change) selected to analyze the SES trajectory according to the DPSIR approach. The process addressed, using the chronosystemic timeline approach, is listed in the second column: state of the ecosystem, human activities, management of the SES, sanitation. The category and number of ecosystem services according to CICES typology are given for impact indicators. The period covered by the data is given in column 5. Column 6 lists the data sources and the variables for which interpolation was applied to replace the missing data (*). The last column indicates the level of data reliability

Category in the DPSIR approach	Process addressed using the chronosystemic timeline approach	Service category (CICES Class)	Indicator (unit) *"Name on the PCA"*	Data availability period	Data sources[1] (details on the data) The symbol (*) indicates that interpolation was used to replace NA	Data reliability: (1) low, (2) moderate, (3) high
Driver	Environmental driver of change	/	Annual cumulative rainfall (mm) *"Rainfall"*	1970-2018	Sète Météo-France weather station (n°34301002)	3
	Environmental driver of change	/	Annual mean air temperature (°C) *"Temperature"*	1970-2018	Sète Météo-France weather station (n°34301002)	3
	Human activities	/	Watershed population (inhabitants) *"Population"*	1975-2018	(*) La Jeunesse 2001; INSEE 2006-2015, 2018 (14 cities in the watershed: Balaruc-les-Bains, Balaruc-le-Vieux, Bouzigues, Gigean, Loupian, Marseillan, Mèze, Montagnac, Montbazin, Pinet, Pomerols, Poussan, Sète, Villeveyrac)	3
Pressure	Sanitation	/	Watershed population not connected to the sanitation system and discharging into the lagoon *"Population_no_WWTP"*	1975-2015	(*) La Jeunesse (2001); INSEE (2006-2015, 2018); Couton et al (2007) (14 cities in the watershed)	3
State	State of the ecosystem	Regulation (2.2.5.2)	DIP concentration in water (summer median, µM) "DIP_summer"	1972-2018	(*) Souchu et al (1998); Derolez et al (2020a)	3
	State of the ecosystem	Regulation (2.2.4.2)	Chlorophyll *a* concentration in water (annual median, µg L^{-1}) *"CHLA_annual"*	1976-2017	(*) Vaulot and Frisoni (1986); Péna (1989); Collos et al (2009); Derolez et al (2020a)	2
Impact	Human activities	Provisioning (1.1.4.1)	Total shellfish production (t.y-1) *"Shellfish_prod"*	1970-2018	(*) Affaires Maritimes de Sète (1970-1989); Comps (2000); DML (2011-2019)	3
	Human activities	Provisioning (1.1.6.1)	Number of active fishers *"N° Fishers"*	1973-2018	(*) Mazouni et al (1999); Cejpa (1985); Les Ecologistes de l'Euzière (1988); Affaires Maritimes de Sète (2004, 2005); Cépralmar (2006); SMBT (2010, 2014); Chaboud et al (2015); SIH (2018, 2019).	2
	Human activities	Cultural (3.1.1.1)	Number of associations linked to water recreational activities (sailing, diving, kitesurf, water skiing, rowing) *"Water_recreat_asso"*	1970-2018	Survey on the web (French Yellow Pages) and phone or e-mail contacts by N. Lautrédou-Audouy (associations with headquarters located in the Thau watershed)	2
	Human activities	Cultural (3.1.1.2)	Number of tourist beds *"Tourist_beds"*	1975-2016	(*) La Jeunesse (2001); SMBT (2010); Pagès (2003); Rey-Valette (2006); data SMBT 2016 (comm. pers. L.Cesmat) (14 cities of the watershed)	2
	Human activities	Cultural (3.1.2.3)	Number of associations for the protection and enhancement of cultural and linguistic heritage *"Cultural_asso"*	1970-2018	(*) Répertoire National des Associations de l'Hérault (1970-2006, 2018): Search of city websites (data available only for Sète and Balaruc-les-Bains)	2
Response	Management of the SES	/	Number of publications citing the Thau lagoon *"Scientific_pub"*	1975-2018	Search of Web of Science (search terms = "Thau lagoon" or "étang de Thau")	3
	Management of the SES	/	Part of the lagoon protected as a Natural Area of Ecological Floristic and Fauna Interest under Natura 2000 (ha) *"N2000_surf"*	1970-2018	SMBT 2010	3
	Management of the SES	/	Number of management tools & structures *"Management"*	1970-2018	Gray literature[1]	3

(1) Data sources for step 2b (gray and local literature):

Affaires Maritimes de Sète (1970 to 2005) Statistiques des Affaires Maritimes. Monographies conchylicoles

Andral B, Sargian P (2010) Directive Cadre Eau. District “Rhône et Côtiers Méditerranéens”. Contrôles de surveillance/opérationnel

Bec B, Derolez V, Soudant D, Cesmat L, Pete R et al (2018) Projet CAPATHAU : Capacité Trophique de la lagune de Thau. Evolution temporelle de l’état écologique de la lagune de Thau et des performances des coquillages en élevage au regard de la réduction des apports issus du bassin versant et des changements météo

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Cépralmar (2006) Prud’homies du Languedoc-Roussillon. Données de suivi de la pêche aux petits métiers

Cesmat L (2018) Note d’identification des diverses crises et évaluation de la vulnérabilité de l’activité conchylicole sur la lagune de Thau

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Couton P, Marty D, Lequette C, Serais O, Derolez V et al (2007) Inventaire et hiérarchisation des sources de pollution microbiologique du bassin de Thau - OMEGA Thau étape 1

DML (Délégation à la Mer et au Littoral, Direction Départementale des Territoires et de la Mer 34) (2011 to 2019) Bilan de la production conchylicole dans le département de l’Hérault

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Table 3 Type of stakeholders interviewed during the study and date of the interviews

Stakeholder category	Name of the organization	Date of the interviews
Local management organization	Syndicate of the Thau Lagoon (French acronym 'SMBT')	June 21 2019
State representatives	Delegation for the Sea and Coast (French acronym 'DML')	June 19 2019
	Rhône-Mediterranean-Corsica Water Agency (French acronym 'AERMC')	June 27 2019
Representative of the Region for shellfish and fishing	Center for the Promotion of Lagoon and Maritime Activities (French acronym 'Cépralmar')	August 2 2019 and March 24 2020
Research institute	French Research Institute for the Exploitation of the Sea (French acronym 'Ifremer')	February 7 2019
Environmentalist association	Center for the Promotion of Environmental Initiatives (French acronym 'CPIE')	June 28 2019 and April 2020
Representative of shellfish and fisheries	Regional Mediterranean Shellfish Committee (French acronym 'CRCM')	April 4 2019
	Mèze 'Prud'homie'	October 7 2019
	Regional Committee for Maritime Fisheries in the Mediterranean (French acronym 'CRPMEM')	July 22 2019

Table 4 Interview guide for stakeholders

I. Environmental and socio-economic problems related to the Thau lagoon	II. Uses and benefits of the Thau lagoon	III. Management of the lagoon
1. What does the Thau lagoon represent for your structure? Or how would you define the Thau lagoon?	4. Can you tell us how the weight of the different activities and uses linked to the lagoon has evolved from 1970 to today? (diversity of uses: shellfish farming, fishing, tourism, thermalism, recreational activities, etc.)	8. How has the management of the lagoon evolved in terms of objectives and actors involved? What have been the main milestones in this area? Who are these new actors? When did they appear? And why?
2. What are the major events that have marked the evolution of the lagoon's characteristics and management policies (environmental and/or socio-economic problems)? *A timeline is presented to be completed with these events. Additional questions will be asked when the actor establishes the timeline in order to know the causes and consequences of these events.*	5. How do you rate the level of ecosystem services provided by the lagoon from 1970 to today? *To do this, we present a list of services in a table and propose to give a score to each service on a scale of 1 to 5 over 3 different time periods from 1970 to today.*	9. What are your organization's commitments to lagoon management? Are these commitments the same since the beginning or have they evolved or changed? What are the strategic choices in managing the lagoon to meet user needs? From 1970 to the present?
3. In your opinion, what are the threats to the lagoon today?	6. Has the lagoon always had the same expectations of the services it provides? If so, what are the new forms of demand from 1970 to the present?	10. Are there conflicts between the user community and/or between the lagoon management community? If so, over what periods from 1970 to the present? What do they consist of? And how are they managed?
	7. In your opinion, what are the contributions of the lagoon to the territory? Are they the same (from 1970 to today)? Or has the relationship between these contributions changed over this period?	11. How do you see the future of the lagoon? Will the lagoon be able to ensure the sustainability of its uses?

Fig. 4 Geographical location of the Thau lagoon. Shellfish aquaculture concessions are located in three rearing areas: Bouzigues, Mèze and Marseillan. The main exchanges of sea water take place via the Sète Canals

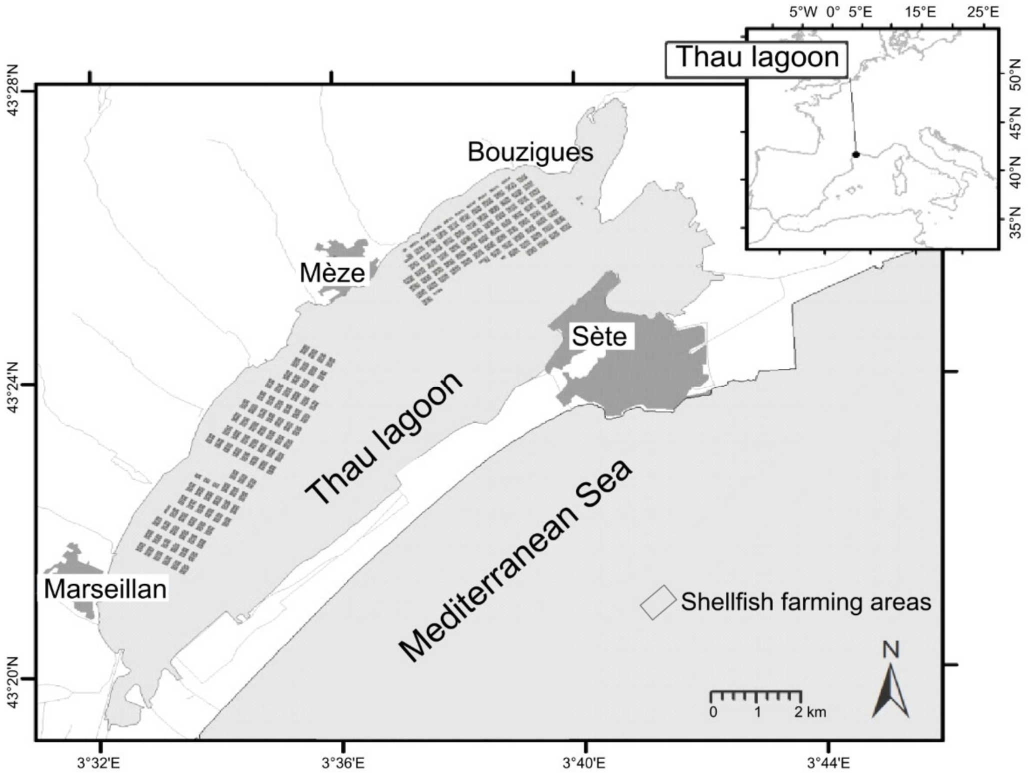

Fig. 5 Timeline of the main events concerning the ecological, chemical and sanitary status of the Thau lagoon (1970-2018)

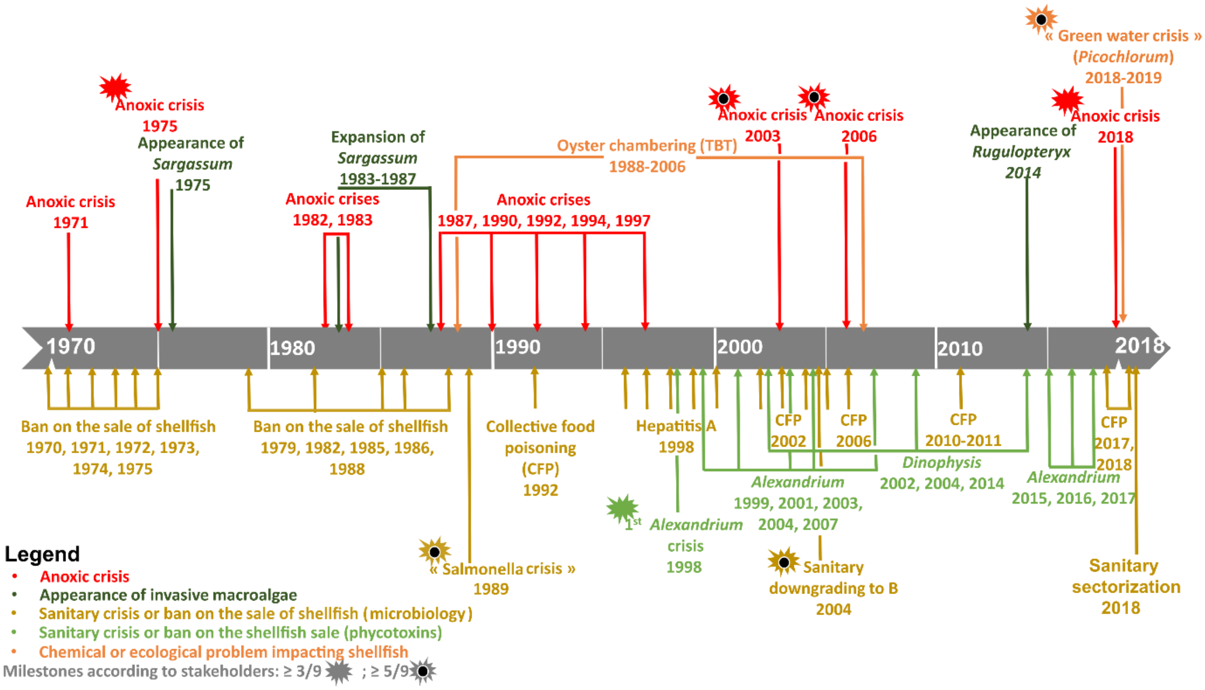

Fig. 6 Timeline of the main events concerning human activities centered on the Thau lagoon (1970-2018)

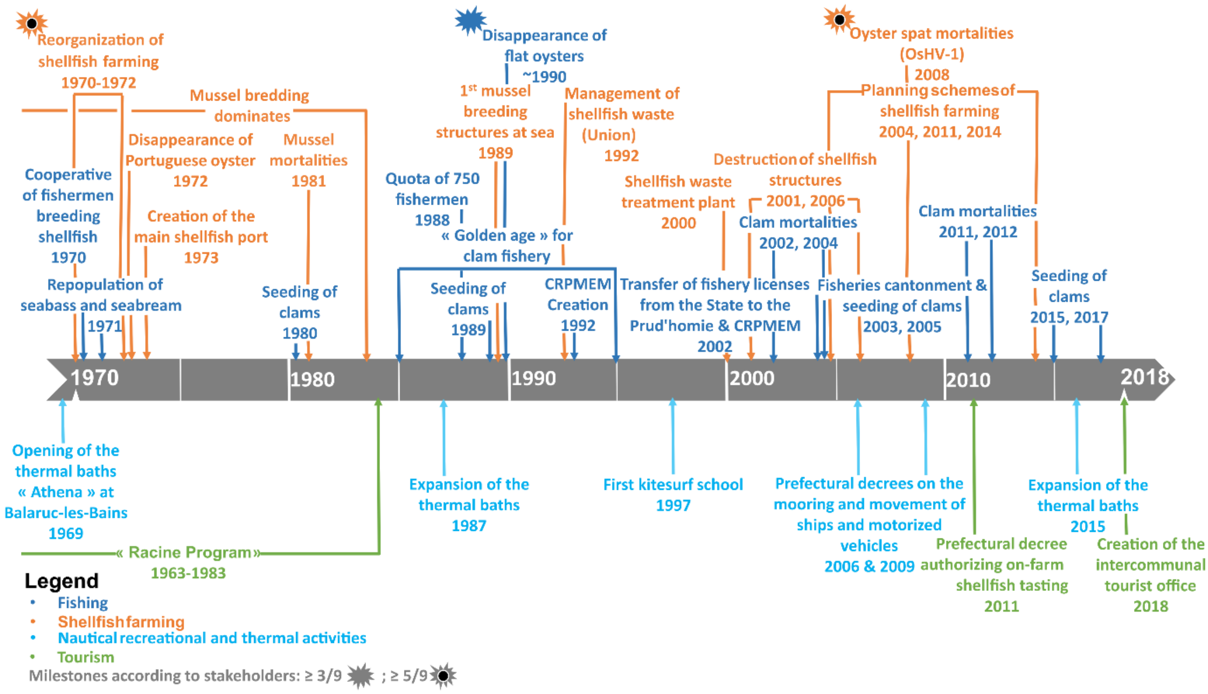

Fig. 7 Timeline of the main events concerning the management of the Thau lagoon (1970-2018)

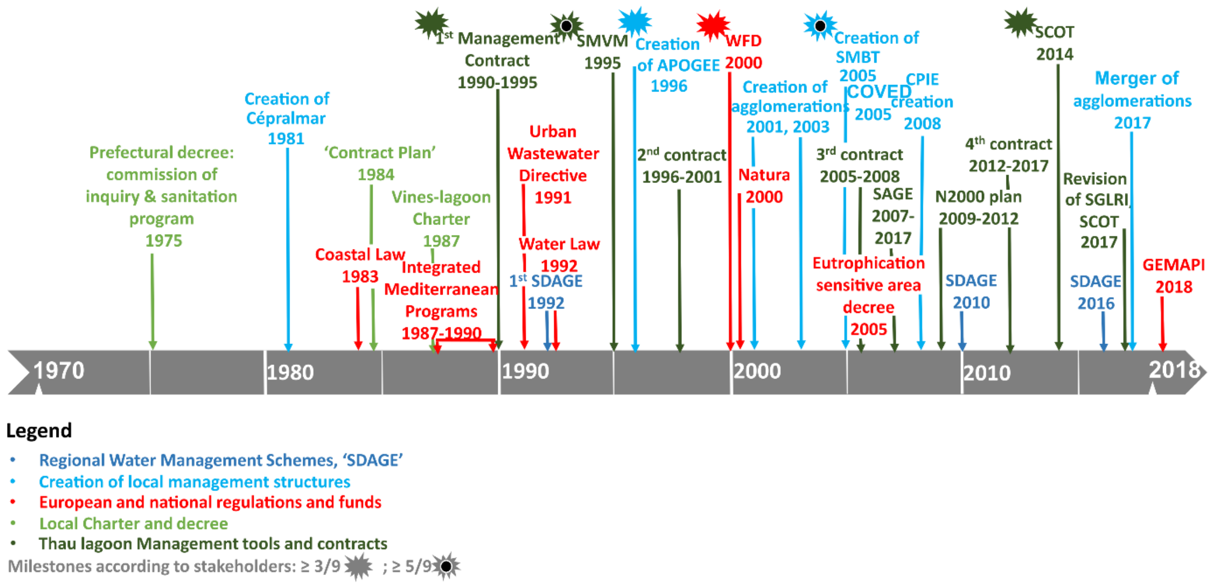

Fig. 8 Timeline of the main events concerning the installation of wastewater treatment plants and the main works on the wastewater treatment system of the Thau lagoon from 1970 to 2018 (La Jeunesse 2001; pers. comm. L. Cesmat, R. Pete/SMBT, A. Barrera/AERMC)

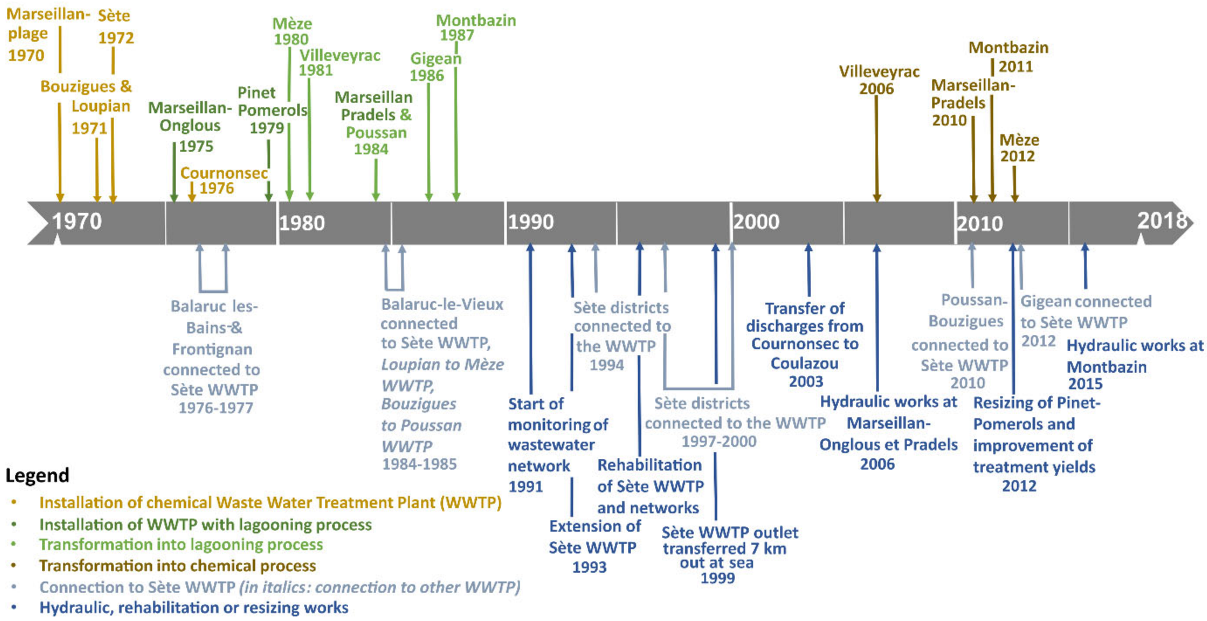

Fig. 9 Changes observed between 1970 and 2018 in the 12 variables selected by the PCA in the DPISR approach and environmental drivers of change (in parentheses, code of the variables according to Table A1). Drivers: 1) Population of the watershed ("Population"); Pressures: 2) Population not connected to WWTP ("Population no WWTP"); State: 3) DIP concentration in water ("DIP summer") and 4) Chlorophyll *a* concentration in water ("CHLA annual"); Impacts: 5) Shellfish production ("Shellfish prod"), 6) Number of fishers ("N° fishers"), 7) Number of tourist beds ("Tourist beds"), 8) Number of cultural associations ("Cultural assoc"), 9) Number of water recreational associations ("Water recreat asso"); Responses: 10) Surface area protected by Natura 2000 ("N2000 surf"), 11) Cumulative number of scientific publications ("Scientific pub"), 12) Number of management tools and structures ("Management"); Environmental drivers of change: 13) Annual mean temperature ("Temperature") and 14) Annual cumulative rainfall ("Rainfall"). Interpolated data are in grey

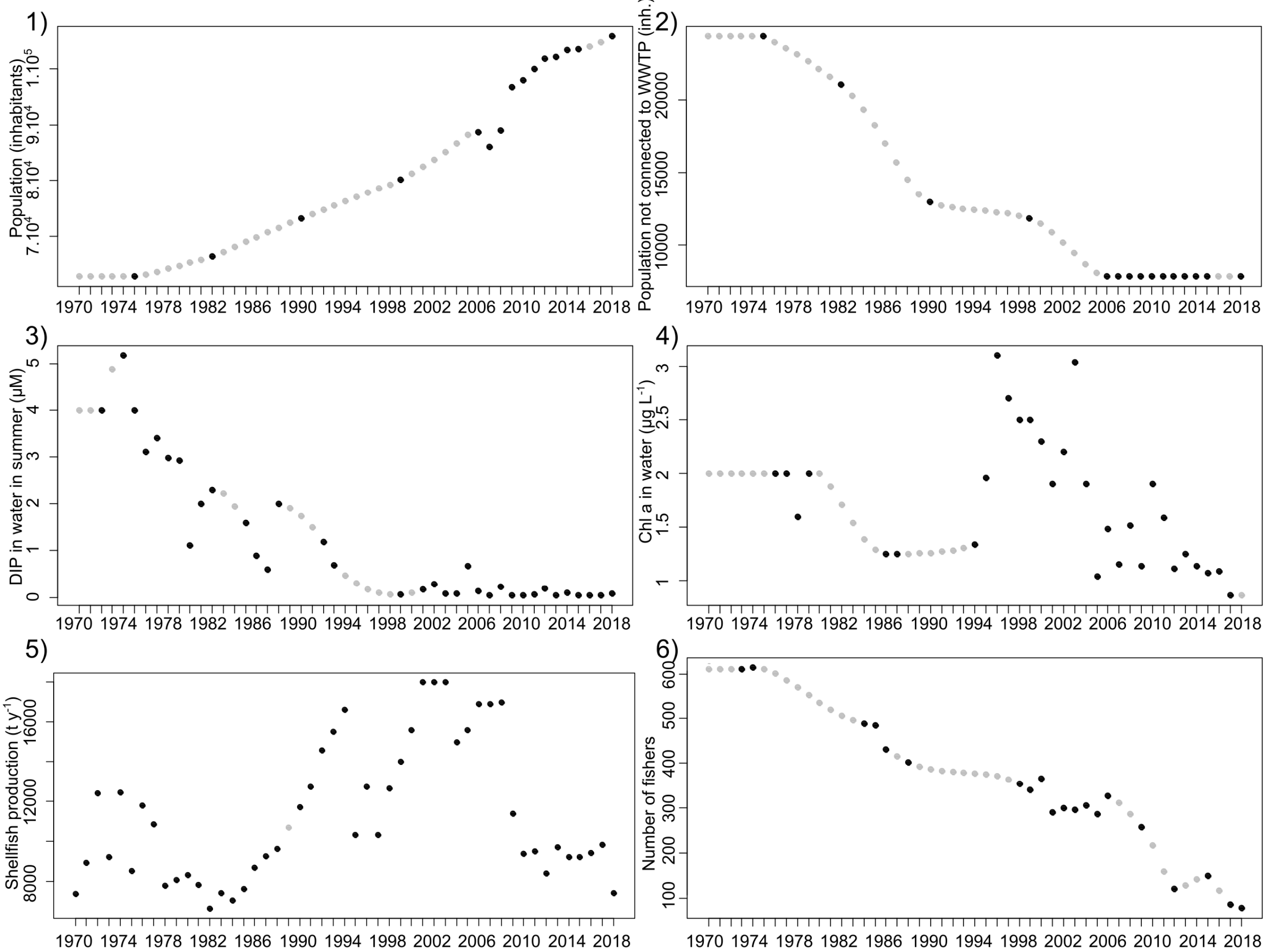

Fig. 9 (continued)

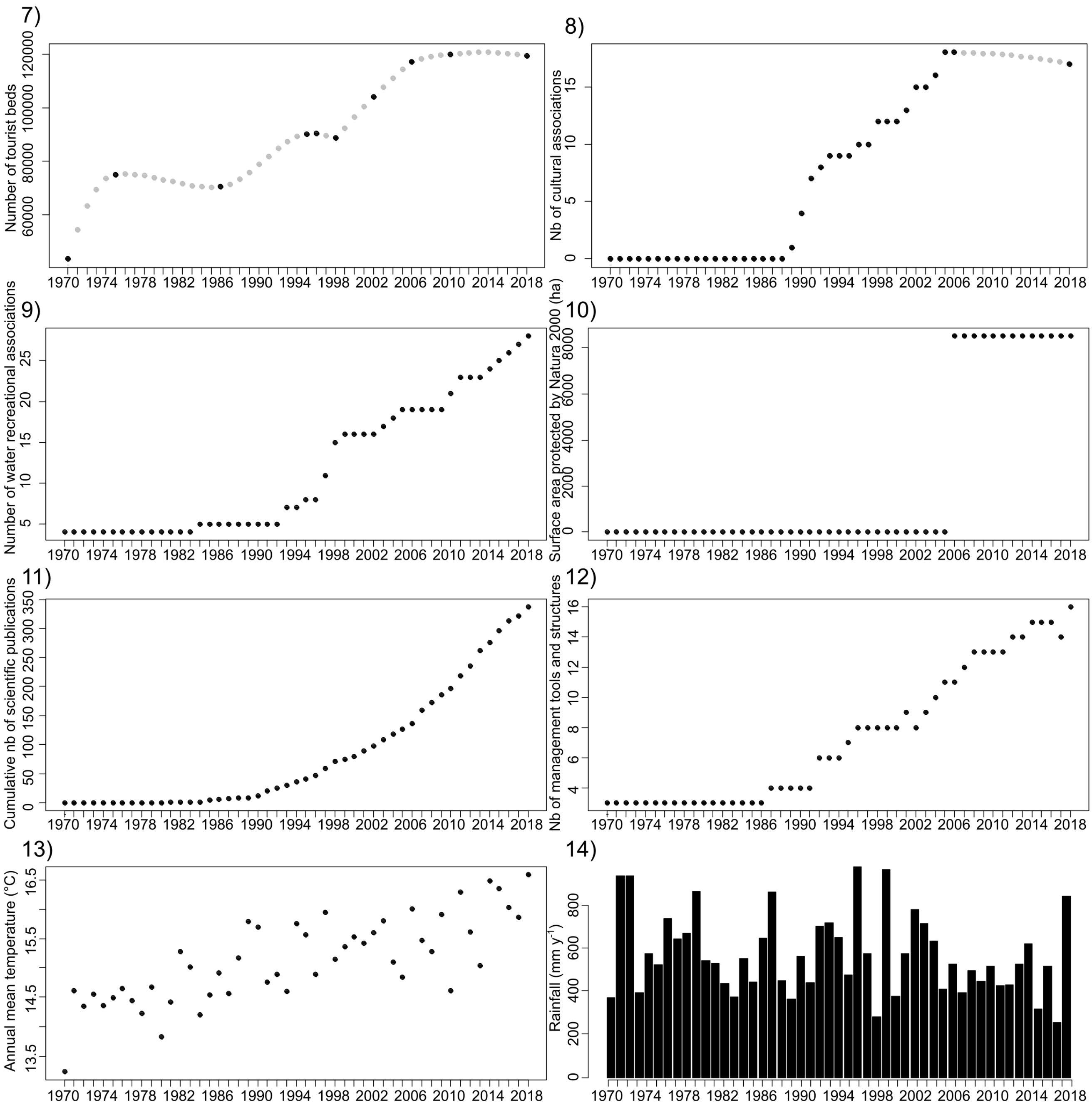

Fig. 10 Results of PCA of environmental and social variables from 1970 to 2018. First and second axes showing the 12 active variables colored according to their DPSIR category (+2 illustrative variables in grey). The first and second axes account for 87.8% of total variability