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Participatory modelling for sustainable development: Connecting coastal and rural social-ecological systems

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ABSTRACT

Integrated planning and informed decision-making require an understanding of the interactions between coastal and rural social-ecological systems and quantification of the impacts of adaptive management across sectors. The Mar Menor lagoon (SE-Spain) provides an example of how a lack of integrated planning can lead to environmental and socio-economic crises. Here we present a systems approach using participatory modelling to identify optimal solutions for the sustainable development of this social-ecological system. Through a participatory process, we co-developed causal loop diagrams that formed the starting point of a System Dynamics model. Model development and its application helped facilitating knowledge exchange between stakeholders, identify challenges and opportunities for sustainable development, and evaluate the socio-economic and environmental impacts of different management and policy solutions. Model results were evaluated using multi-criteria analysis demonstrating its potential application as a decision support system to identify an optimal set of solutions.

1. Introduction

The sustainable development of coastal areas is often strongly affected by inland rural activities and vice versa. Coastal areas, for example, suffer pressures from the intensification of agriculture and industry affecting water quality and quantity (Malone and Newton, 2020), whereas many rural areas face decreasing population and lack of socio-economic development with people moving to the coastal areas (Martínez-Sastre et al., 2017; van Leeuwen et al., 2019). Many coastal areas encounter similar challenges concerning governance to protect environmental, economic and social objectives.

Informed decision-making and the identification of pathways towards more sustainable development of coastal and rural areas requires integrated planning based on an understanding of the interactions between coastal and rural social-ecological systems (SES)s and the quantification of impacts of potential solutions on all sectors involved. However, the lack of coordination between the management of inland and coastal areas, and insufficient exchange of data and knowledge frequently impede the transition towards sustainable development building on coastal-rural synergies (Martínez-López et al., 2019a).

In addition to coordination between public administrations, wider stakeholder participation with representatives from all relevant sectors is crucial to identify optimal solutions for the sustainable development of these complex SES. While diverse priorities between stakeholders can be an obstacle to environmental management, well-designed participatory approaches can reduce conflict, build trust, and facilitate learning among stakeholders, who are then more likely to support sustainable development goals and implement decisions (de Vente et al., 2016; Reed, 2008).

A participatory systems approach can help to create a more in-depth common understanding of positive and negative feedback mechanisms between sectors, based on which collective action to restore a SES can be initiated. However, this is a very challenging task, as it often touches upon resource conflicts or different value systems (Martínez-López et al., 2019a; Voinov et al., 2016). Therefore, participatory processes that aim to co-develop holistic solutions for sustainable development, need a careful design based on the definition of objectives and facilitation with special attention to managing conflict, power dynamics and expectations (e.g. de Vente et al., 2016; Reed, 2008).

The Mar Menor coastal lagoon (SE Spain) provides a typical example

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of how insufficient integrated planning can lead to environmental and social degradation (Álvarez-Rogel et al., 2020). The sudden ecological collapse of the lagoon is negatively affecting the attractiveness for tourism and real estate prices (Lamas Rodríguez et al., 2023). Intensive irrigated agriculture is identified as the main driver causing pressure on water resources and strong eutrophication of surface and groundwater, further aggravated by insufficient urban wastewater treatment and contaminated sediments from historic mining activities (García-Pintado et al., 2007; Martínez-Fernández et al., 2014). The environmental and socioeconomic consequences have strongly revived the need to move towards sustainable models of agriculture and tourism (Guaita-García et al., 2020, 2022).

The identification of solutions and trade-offs to this environmental and socio-economic crisis requires careful assessment of system interactions. System Dynamics modelling is often used to simulate the behaviour of such complex SES. In a System Dynamics model, feedback loops, time delays, and nonlinear relationships are considered to identify the causes of system behaviour and to help decision-makers understand the potential consequences of their actions (Meadows, 2008; Sterman, 2002). Involving stakeholders in model development through participatory modelling can help obtain a comprehensive understanding of systems functioning and of crucial interactions between systems components (Martínez-López et al., 2019b; Voinov et al., 2016).

The idea of participatory modelling is that stakeholders are involved in the design, development, and credibility of a model, rather than simply being presented with a completed model. Participatory modelling based on System Dynamics can be instrumental to create a common system understanding, incorporate stakeholders' local knowledge, ensure that models are accurate, relevant, and widely accepted by stakeholders, thereby increasing their potential to support decision-making (Kenny et al., 2022; Voinov and Bousquet, 2010).

The objective of this paper is to use a participatory modelling approach to develop a System Dynamics (SD) model of the SES of the Mar Menor and surrounding Campo de Cartagena and demonstrate how the model can be used to support informed decision-making by evaluating the environmental, social, and economic impacts of different policy solutions for sustainable development of the coastal and rural environment.

2. Methods

2.1. Study area

The Mar Menor coastal lagoon (135 km^2) forms part of a Specially Protected Area of Mediterranean Importance (SPAMI) located in the Region of Murcia (SE Spain) and is characterised by a very high biodiversity with singular species of birds, fishes and bivalves (Martínez-Fernández et al., 2014). The catchment draining into the Mar Menor, known as 'Campo de Cartagena', covers an area of 1255 km^2 with predominantly gentle slopes, and a semi-arid climate with an average annual precipitation of 300 mm, and potential annual evapotranspiration of 1275 mm (Jiménez-Martínez et al., 2016). The area is characterised by multiple environmental, social-cultural and economic interests, often competing for scarce resources, with water being the most important. This situation is expected to become more challenging under future climate conditions when less water is projected to be available (Pellicer-Martínez and Martínez-Paz, 2018).

Land use is dominated by intensive irrigated agriculture with horticulture, tree crops and greenhouses, while the coastline is occupied by villages and tourist accommodations representing one of the hotspots for coastal tourism in the region (Fig. 1). Coastal tourism has developed strongly since the 1960s, concentrated in summer months, whereas tourism in the rural inland is limited to several golf resorts.

The opening of the Tagus-Segura water transfer in the 1980s led to an uncontrolled expansion of irrigated croplands in an area traditionally dominated by rainfed agriculture (Conesa and Jiménez-Cárceles, 2007). Nowadays, agriculture provides labour and income to the region but also constitutes a source of nutrients, sediments and contaminants into the Mar Menor coastal lagoon and associated wetlands (Martínez-López et al., 2014a). The resulting eutrophication has had a devastating impact on the ecology of the lagoon, as evidenced by the proliferation of jellyfish since the 2000s, a major phytoplankton bloom in 2016, and the sudden massive anoxia event in 2019 (Bernardeau-Esteller et al., 2023). The latter was triggered by an extreme rainfall event causing extensive flooding and yielding large amounts of sediments and nutrients to the lagoon (Álvarez-Rogel et al., 2020). This ecological collapse has had severe implications for tourism, fisheries and property prices, resulting in significant social unrest and protests (Guaita-García et al., 2020).

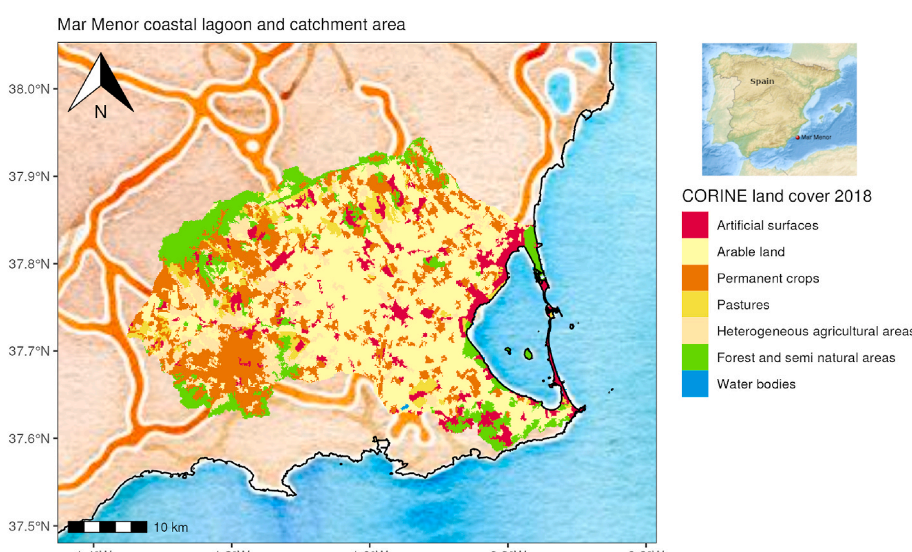

Fig. 1. Location of the Mar Menor coastal lagoon and its Campo de Cartagena catchment area (SE Spain). Land cover classes are adapted from CORINE 2018. Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under CC BY SA. Coloured linear features represent main roads.

2.2. Participatory modelling for better-informed decisions and policy support

To co-develop a System Dynamics model and apply this model to evaluate the environmental, social, and economic impacts of different policy solutions, we initiated a participatory process with stakeholder representatives from different sectors. This process consisted of 6 sectoral workshops, 2 multi-sectoral workshops, expert interviews, and 2 online questionnaires (Fig. 2). We started with sectoral workshops to optimise the conditions for stakeholders to express their views, avoid unnecessary conflicting discussions and reduce power imbalances before bringing representatives from different sectors together in multi-sectoral workshops.

During each of the six half-day sectoral workshops, participants developed mental maps representing the main interactions within the SES of the Mar Menor-Campo de Cartagena, following the methodology described in Tiller et al. (2021). The 6 sectoral workshops were held in November 2018 with representatives from (i) agriculture; (ii) tourism; (iii) fishery and salt pans; (iv) public administrations; (v) local populations, and (vi) researchers & NGOs. To obtain optimal representation of all sectors, we used a snowball sampling method (Biernacki and Waldorf, 1981) to invite a total of 240 stakeholders from the different sectors to the first sectoral workshops, as further explained in Tiller et al. (2021). Through the workshops, we identified the most relevant land-sea interactions, positive and negative externalities, as well as drivers and barriers to collaboration between sectors. Following the sectoral workshops, the six mental maps were merged into a combined Causal Loop Diagram (CLD) representing all interactions and issues raised. The merging process consisted of harmonisation and renaming of variables representing the same concept so that they would be comparable between mental maps and making sure they could eventually be measured in qualitative or quantitative terms. In this process, we made sure to respect the structure and interactions between variables identified by the participants following the good practices proposed by Olazabal et al. (2018).

The merged CLD was presented and discussed with representatives from all six sectors during the first Multi-Sectoral Workshop (MSW), when participants evaluated the represented system interactions, added variables or interactions and further defined ideas regarding policy and management solutions. Following the first MSW, the research team started the System Dynamics (SD) model development using the merged final CLD as the starting point. During this model design phase, in addition to an extensive review of scientific and grey literature and public datasets for model design and parameterization, seventeen expert interviews were conducted via online meetings and e-mail exchanges. In these interviews, experts commented on the model structure, available data, and the design and parametrization of the policy and management solutions within the SD model. Few observed data series were available for direct comparison with simulation runs and hence model testing was mainly based on checking with stakeholders and experts opinion in a process of confidence building. Different methods are available to support confidence building like co-design, testing of the model dynamics in response to changes in the model structure, parameter settings and exogeneous model input, and testing of the policy implications of the model and confrontation of stakeholders and experts (Qudrat-Ullah and Seong, 2010; Senge and Forrester, 1980).

Therefore, after this intensive model-building phase, a pilot version of the SD model was presented to representatives of all sectors in a second MSW (online due to the covid-19 pandemic). This workshop was used for another round of feedback on the model structure, confidence building, and further defining the policy and management solutions to be evaluated with the SD model. During the workshop, participants filled in an online questionnaire regarding the model structure to identify possible missing interactions and come up with a time sequence for implementation of the proposed solutions (Annex I). After the received stakeholder inputs were implemented, the final model outcomes were presented in a stakeholder roundtable discussion. During this roundtable, the impacts of the implementation of the selected policy and management solutions on Key Performance Indicators (KPI)Adams, 2006) were presented and discussed with representatives from all sectors.

2.3. Modelling and evaluation of the impacts of management and policy solutions on Key Performance Indicators for policy support

The System Dynamics (SD) model was built using VenSim

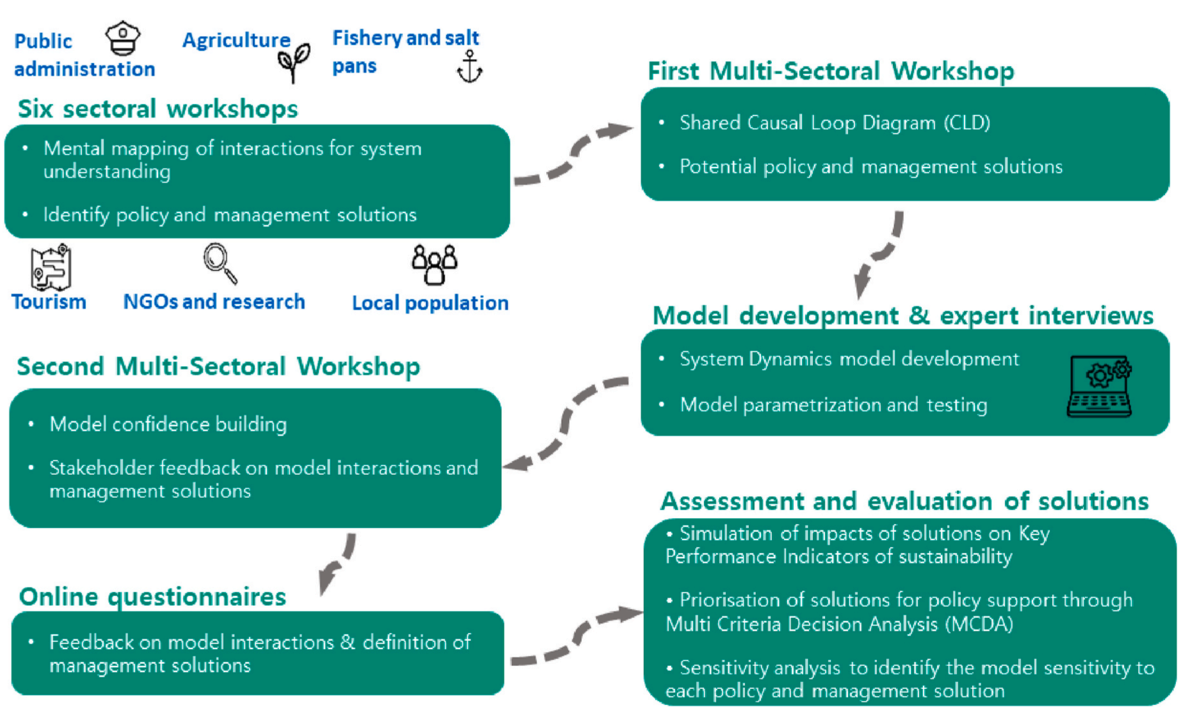

Fig. 2. Overview of the main steps in the participatory modelling process.

(VENTANA SYSTEMS, 2018) and included the interactions between all relevant variables and sectors in the SES of the Mar Menor-Campo de Cartagena, identified during the stakeholder workshops. The simulation period covered 1961 to 2070 in a yearly time step. Model equations and data sources used for calibration were compiled based on an extensive review of scientific and grey literature and information obtained during workshops and expert interviews.

Besides improving the understanding of the interactions within the SES, the model was specifically developed to assess the impacts of management and policy solutions that were identified by stakeholders and to identify the optimal and minimal combination of solutions required for sustainable development. Therefore, the model was iteratively tested by performing numerous model runs using R (Duggan, 2018), based on all possible combinations of the solutions proposed by stakeholders. To this end, KPIs related to social, economic and environmental output variables were selected. The values of these variables in the year 2070 based on all model runs were used in a multiple-criteria decision analysis (MCDA) using the TOPSIS method (Meyer et al., 2021). To identify optimal solutions, normalised values of the KPIs for all combinations of policy solutions (from zero to one) representing worst and best scenario values were assessed and ranked based on the TOPSIS score. To exclude combinations of solutions that reached high overall TOPSIS scores but showed very low performance on one or more individual KPIs, only those combinations of solutions were considered that reached a threshold of at least 0.5 for all KPIs in order to look for a sustainable development for all sectors involved.

To identify the model sensitivity to each of the potential management and policy solutions, a sensitivity analysis was conducted by iteratively running the model using a range of values for the same input variable representing a management solution, and comparing the effect on KPIs (Martinez-Moyano and Richardson, 2013). The following formula (equation (1)) was used to calculate the sensitivity of each KPI (Y) to each of the management and policy solutions (X):

$$\text{Sensitivity}\,(X,Y) = \text{ABS}(Y(X_{\text{best scenario}}) - Y(X_{\text{worst scenario}}))\,/\,(Y_{max} - Y_{min}) \quad (1)$$

Computing the absolute value of the numerator ensures that all results are positive thereby facilitating comparison of sensitivity. The Y_{max} and Y_{min} values for each KPI were obtained from the full set of individual policy solutions tested in the sensitivity analysis (including the implementation of the full set of solutions). For some policy solutions, the best or worst case referred to implementing or not implementing the solution, in some other solutions that required numerical values to indicate the level of implementation, we assumed the most reasonable “best” and “worst” values based on a 50% positive or negative increase with respect to the reference value used, as agreed with stakeholders.

3. Results

3.1. Participatory model development and confidence building

An interactive version of the combined Causal Loop Diagram that was obtained by merging the six individual mental maps developed during the sectoral workshops is presented in Annex II, and the number of participants attending the different workshops and expert interviews is provided in Annex III. Representation of stakeholders was overall balanced between sectors, with the exception of fishery and salt pans who were underrepresented. The main land-sea system interactions identified during the sectoral workshops and reflected in the CLD were: (a) habitat degradation and biodiversity loss in the lagoon and associated wetlands around the Mar Menor due to eutrophication and contamination, caused by nutrients and sediments from agriculture, urban areas and pig manure, heavy metals from the old mining areas and wastewater inputs; (b) decrease in recreational opportunities for tourists and for local populations living around the Mar Menor due to poor water quality; and (c) unsustainable use of low-quality groundwater resources due to an excessive growth of agricultural areas that exacerbates the export of nutrients to the Mar Menor lagoon from brine wastes generated by the desalinisation of groundwater.

In the first MSW in April 2019, we confirmed whether all relevant variables were correctly represented in this combined system map, and demonstrated how this CLD could be used to provide a first qualitative assessment of the impacts of management and policy solutions on multiple sectors. Together with the increased insight into system interactions, this helped participants to further define combinations of solutions in different sectors to support sustainable development.

The main topics discussed in the sectoral and first multi-sectoral workshops dealt with social and ecological aspects, such as social well being, ecotourism, sustainable intensification of agriculture, social cohesion, tourism seasonality, soil erosion, governance, climate change mitigation and adaptation and lagoon water quality,. Moreover, the main ideas regarding solutions building on synergies referred to the implementation of Sustainable Land Management practices or nature-based solutions in croplands (e.g. vegetation buffers around cropland areas, conservation agriculture and crop diversification); the promotion of more sustainable coastal and rural tourism, including agrotourism, and the promotion of small-scale solar energy facilities as an additional source of income.

During the expert interviews, pilot versions of the System Dynamics (SD) model and preliminary results were shown to different domain experts to get a first round of feedback and contribute to model confidence building. The topics covered in the expert interviews concerned the agricultural water and nutrient balances, sustainable land management practices, development of the agricultural, tourism and photovoltaic energy sectors, the coastal-rural recreation potential, and the social awareness and governance submodels. These interviews helped to obtain reference data for input variables, add or further define relevant management and policy solutions, and identify their expected impacts and Key Performance Indicators. Moreover, additional variables were identified that could be affected by changes in international policy and market developments (e.g. changes in price of electricity or agricultural commodities, or tourism growth) or by climate change.

During the second MSW in December 2020, participants provided some minor suggestions and confirmed their agreement with the general model structure, the submodels and the interactions represented in the model. Participants also provided detailed input regarding the timing (i.e. short, medium, long-term implementation), and expected impact of the management and policy solutions included in the model. This entire process resulted in the identification of 14 stakeholder-defined management and policy solutions to enhance sustainable development, which were included in the model structure (section 3.2) and evaluated through a model optimization procedure (section 3.3). In addition, model variables were identified that can be used for further scenarios analysis (e.g. changing commodity prices, climate change, population growth), but this is not further elaborated in this study. Throughout the process, stakeholders also provided 59 proposals of practical measures that could contribute to the 14 management and policy solutions (Boix-Fayos et al., 2023). For example, practical measures that could help make tourism more sustainable by reducing environmental impacts and pressure in summer months like promotion of agrotourism or the restoration of cultural heritage and wetlands with visitor centres. These proposals were too detailed to be included in the SD model, but were documented and shared with stakeholders.

3.2. Model structure

Given the complexity of the merged CLD, direct conversion into one corresponding System Dynamics (SD) model was infeasible. Therefore we identified partial problem domains based on main categories identified by stakeholders and started SD model development per domain. After identification of common variables between each domain we connected them in one SD model. This is reflected in the final structure of the SD model (Fig. 3) consisting of 7 submodels describing the SES of the Mar Menor and Campo de Cartagena: (a) agricultural water balance; (b) agricultural nutrients balance; (c) sectoral development and economic profit; (d) Mar Menor degradation; (e) coastal-rural recreation potential; (f) social awareness and governance; (g) sustainable land management practices.

The SD model reflects the interactions between the different topics and sectors. The main economic sectors (agriculture, tourism, and photovoltaic energy) contribute to the total economic profit and jobs in the study area. The Mar Menor ecological status is influenced by agricultural development via water and nutrient input and the implementation of Sustainable Land Management (SLM) practices and nature-based solutions. On the other hand, the ecological status of the lagoon affects coastal and rural tourism development and social awareness and governance, which in turn could lead to the adoption of SLM practices and regulate the development of the agricultural sector. Besides, there is a potential synergy between the agricultural and tourism sectors via promoting agritourism.

The following subsections summarise each submodel of Fig. 3. A detailed description of the model structure can be found in Annex IV, together with all model equations (Annex V). The Vensim model file can be found online under an open-source license (Martínez-López et al., 2022).

3.2.1. Agricultural water balance

Agricultural water use in the Segura catchment (Mar Menor catchment is a sub-basin of the Segura catchment) represents around 85% of the total water consumption (Martinez-Fernandez et al., 2014; Martínez et al., 2007). Hence the available water for irrigation largely determines the potential expansion of irrigated crops (Eekhout et al., 2024). Stakeholders emphasised that the agricultural water balance was central to account for the sustainability of the system in terms of water use and the potential growth of agriculture (Alcon et al., 2022). Given the structural water scarcity in the region, the high amount of groundwater extraction and the opening of the Tagus-Segura water transfer in 1979 were mentioned as the main drivers of the expansion of irrigated agricultural areas (Morote et al., 2017).

Fig. A1 in annex VI shows a simplified diagram of this submodel. The total agricultural water demand is driven by the expansion of irrigated land and is calculated by multiplying the agricultural water demand per hectare by the irrigated land area (in hectares). The available surface water for agriculture is the sum of several sources (e.g. water transfer, treated urban wastewater, seawater desalination). The water gap is the amount not met by the available surface water and is used to compute the number of groundwater wells needed to extract the required volume of water, using an average volume of water extracted per well. The agricultural pressure on water resources is a function of the available surface water for agriculture and the total agricultural water demand, indicating the extent to which groundwater is needed to cover the existing water demand in relative terms.

This submodel includes some variables that directly relate to potential management actions and technical solutions, suggested by stakeholders during the co-design process, such as the increase in seawater desalination, the allowed number of groundwater wells, and the decrease in agricultural water demand per hectare by adapting to less water-demanding crops or minimising water loss by evaporation. Based on the multi-sectoral workshops and expert interviews, the "number of groundwater wells" variable was easier to grasp and use by stakeholders than the total "volume of pumped water" for management purposes.

In the last few years, an increase in groundwater levels has been observed in the Campo de Cartagena, which has been attributed to a persistent surplus of water used for irrigation draining into the aquifers (Alcolea et al., 2019; Jiménez-Martínez et al., 2016). This groundwater also contains a high amount of nitrates and therefore, one of the proposed measures to avoid nutrients entering the Mar Menor lagoon directly from the aquifer is to extract a certain amount of groundwater annually and reuse it for irrigation purposes. This proposed solution is part of what is known as the 'zero discharge' plan (i.e. "*Vertido Cero*").

3.2.2. Agricultural nutrients balance

There is scientific consensus that the most important source of nutrient inputs leading to the eutrophication and ecological degradation of the Mar Menor lagoon is caused by the ground- and surface water pollution from fertilisers used in irrigated agricultural areas in the Campo de Cartagena (Álvarez-Rogel et al., 2020). The submodel describing the role of agricultural nutrient inputs focuses on the quantification of the nutrient's export from irrigated agricultural areas to the Mar Menor lagoon based on the amount of fertiliser excess. It includes some management and policy solutions related to potential end-of-pipe solutions, such as the 'Vertido Cero Plan' (see section 3.2.1), suggested by stakeholders during the co-design process.

There are three main flows of agricultural nutrient inputs to the Mar Menor lagoon (Fig. A2 in annex VI), i.e. nutrients contained in (1) surface runoff, (2) groundwater, and (3) brine wastes. The latter result from polluted water being pumped from the aquifer and then treated to remove excessive salts and nutrients before its use for irrigation. This submodel is primarily driven by the fertiliser excess use per hectare and

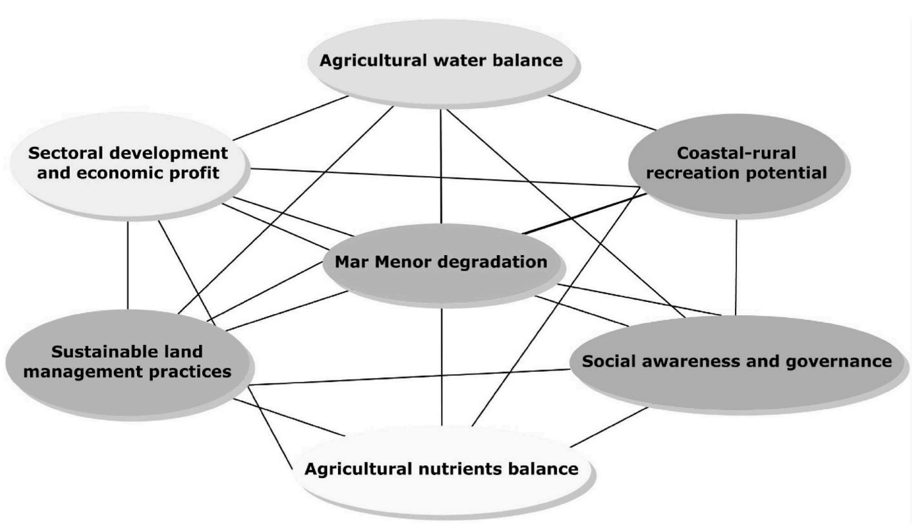

Fig. 3. Schematic overview of the SD submodels and their connections.

by agricultural expansion. There are two management and policy solutions considered: (a) the *Vertido Cero Plan*, explained in the previous subsection and (b) the surface water pumping from the 'Albujón' ephemeral river, which is the main watercourse entering the Mar Menor lagoon and draining the Campo de Cartagena.

3.2.3. Sectoral development and economic profit

The discussions during the workshops pointed out that most of the gross economic profit in the study area depends on the development of the agricultural and tourist sectors. However, it was also suggested that promoting different economic sectors, including the renewable energy sector, could increase total economic profit, help create new jobs, and support sustainable development.

This submodel aimed to simulate the development of the three main economic sectors mentioned during the workshops, i.e. agriculture, tourism and solar photovoltaic facilities. The model includes the development of each sector together with the number of jobs created and its gross economic profit. While these 2 indicators obviously represent a simplification of economic impacts, they were considered to be sufficiently indicative of expected trends to support decision making. The next subsections present the development of each sector individually.

3.2.3.1. Agricultural development. Concerning agricultural development (Fig. A3 in annex VI), the change in irrigated land area is a function of the existing irrigated land areas and the potential agricultural development, which is driven by (a) the historical observed growth rate of agriculture (Caballero Pedraza et al., 2015; Carreño et al., 2015; Martínez-López et al., 2014b), and (b) the potential growth of agriculture based on water availability, which is a function of the agricultural pressure on water resources (see section 3.2.1). The agricultural pressure on water resources does not account for groundwater that could be used to decrease water scarcity because the main driver of the agricultural expansion is the Tagus-Segura water transfer. Groundwater can be used for irrigation but first requires desalination, thereby producing brine waste. The model can limit the total amount of irrigated land areas to the maximum area with legal access to irrigation water sources through the variable 'control of irrigated land areas'.

The number of employees in agriculture is based on the extent of irrigated land areas and the average number of jobs generated by irrigated agriculture per hectare. Additionally, the yearly gross economic benefit of irrigated agricultural production is a function of gross agricultural revenue per hectare and the extent of irrigated land areas.

3.2.3.2. Tourism development. Tourism's yearly gross economic benefit depends on the expected number of tourists, the daily average expenditure per tourist and the average number of overnight stays per tourist per year (Fig. A4 in annex VI). The expected number of tourists increases as a function of the potential tourist growth, which primarily depends on the observed growth rate of tourism over the past years, the initial number of tourists and the current expected number of tourists. The expected number of tourists also decreases according to the Mar Menor degradation status and the associated rate of tourism loss influenced by the degradation of the Mar Menor. The number of employees in tourism is calculated based on the expected number of tourists and the number of jobs created per tourist. The model also calculates the yearly gross economic benefit of tourism based on the expected number of tourists, their average daily expenditure and the average number of overnight stays per tourist per year (Arroyo Mompeán, 2018).

3.2.3.3. Development of photovoltaic energy facilities. The potential photovoltaic energy (PV) installed refers to the total power capacity of solar photovoltaic energy installed in megawatts (MW) and is a function of the estimated initial capacity installed in the Campo de Cartagena and the potential PV installation (Fig. A5 in annex VI). The potential PV installation depends on the observed PV growth rate (MW) and the promotion of PV facilities. The number of jobs in PV facilities depends on the potential PV installed and the average number of jobs generated by PV facilities per MW installed. Finally, the yearly gross economic benefit of PV energy production is a function of the potential PV installed, the electricity price and the average number of hours per day of PV electricity production (APPA, 2018).

3.2.4. Mar Menor lagoon degradation

Fig. A6 (annex VI) shows the main drivers of the degradation of the Mar Menor lagoon based on the feedback received during the stakeholder workshops. No specific mechanisms were described during the workshops to explain the ecological processes within the lagoon leading to its collapse in 2016. However, previous research has identified eutrophication episodes caused by long-term agricultural export of fertilisers as the main driver of environmental degradation (Álvarez-Rogel et al., 2020; Bernardeau-Esteller et al., 2023; Comité de Asesoramiento Científico del Mar Menor, 2017; Ruiz-Fernández et al., 2020).

This submodel quantifies the degradation of the Mar Menor lagoon in relative terms linked to the long-term non-point-source inputs of nutrients observed and modelled in the agricultural nutrients balance sector and from other point sources like urban wastewater. The Mar Menor degradation goes from 0 to 1, from undegraded to degraded status, and is calculated using an exponential function based on the agricultural nutrients contained in the lagoon plus the relative contribution of other sources of pollution (Fig. A6 in Annex IV and Annex V). The agricultural nutrients in the lagoon are accumulated over time and are calculated as the difference between the agricultural nutrients input and the amount of nutrients that can be metabolised by the native lagoon ecosystem. Other point sources of pollution are measured in relative terms, from 0 to 1 and are assumed to be constant with a default value of 1 unless a scenario of pollution reduction is activated. Based on stakeholders' and experts' opinions, the model does not account for a potential increase in point source pollution, which is considered very unlikely.

3.2.5. Coastal-rural recreation potential

Given the already high pressure from tourism in summer months, stakeholders stressed the importance of decreasing tourism seasonality and increasing inland and coastal recreation potential through promotion of ecotourism activities to promote the local economy, making the region economically less dependent on intensive agriculture (Velasco et al., 2018). In this submodel, we assess the observed influence of the degradation of the Mar Menor on the coastal recreation potential, and the effect of increasing the rural and coastal recreation potential on tourist growth through the promotion of ecotourism activities in coastal and rural areas.

As previously mentioned (section 3.2.3.2), the potential tourism growth variable (Fig. A7 in annex VI) depends on the observed yearly growth rate of tourism but also on the coastal-rural recreation potential. The promotion of rural and coastal ecotourism variables represent management and policy solutions, going from 0 to 1 and defaulting to 0, reflecting the relative increase in the number of rural and coastal ecotourism activities and ultimately affecting the coastal or rural recreation potential. The coastal recreation potential is a function of the Mar Menor degradation, whereas the rural recreation potential is also a function of the coastal recreation potential, highlighting an important synergy between tourism in coastal and rural areas. Based on stakeholders and expert opinion, the rural recreation potential can be promoted primarily by attracting tourists from the coastal area.

3.2.6. Social awareness and governance

Stakeholders and previous studies highlighted environmental education, social awareness, territorial bonding and participatory governance as crucial components to overcome the ecological crisis (Visseren-Hamakers et al., 2021). Given the importance that stakeholders attributed specifically to territorial bonding and environmental education, this submodel includes the effect of environmental education on society and ultimately on participatory governance, linked to the regulation and development of the agricultural sector. Territorial bonding is a variable between 0 and 1 that refers to stakeholders' awareness and values related to emotional and ethnographic heritage and environmental status that can be affected by education (e.g. Boix--Fayos et al., 2023).The potential agricultural development variable (Fig. A8 in annex VI and section 3.2.3.1) can be negatively affected by the social pressure on public administrations, which is a function of the Mar Menor lagoon degradation and territorial bonding. Environmental education is a variable between 0 and 1, with higher values representing the implementation of more environmental education activities that is expected to slowly increase territorial bonding.

3.2.7. Sustainable land management practices

Sustainable land management (SLM) practices in agriculture, such as a decrease in the use of fertilisers, or their retention through buffer strips, cover crops, crop diversification, or other nature based solutions, can have beneficial effects on agricultural production and the environment (Pärn et al., 2012). In this submodel, we have quantified the benefits of implementing two SLM practices in our case study, i.e. the decrease in the application of fertilisers and the implementation of nutrient, soil and water retention measures (e.g. vegetation buffers around agricultural fields and cover crops).

The agricultural nutrient inputs to the Mar Menor via surface and groundwater are influenced by the average excess of fertiliser use (see section 3.2.2), which can be mitigated by the percentage of reduction in fertiliser excess (Fig. A9 in annex VI). This solution decreases the export of nutrients to the lagoon via surface and groundwater. On the other hand, concerning nutrients export via surface water, the implementation of nutrients, soil and water (NSW) retention measures is included as a solution, ranging from 0 to 1 (from no retention measures to a complete implementation), weighted by the effectiveness in nutrients reduction of NSW retention measures (Rey Benayas et al., 2017).

3.3. Optimization of management and policy solutions and sensitivity analysis

All model variables were fully documented in VenSim and a dashboard was included that allows users with limited knowledge of System Dynamics modelling to evaluate the impacts of different combinations of management and policy solutions on a range of environmental, social and economic KPIs. The list of 14 management and policy solutions identified by stakeholders during the workshops, questionnaires, and expert interviews, which are implemented in the model, can be found in Table 1, together with a more detailed explanation in Annex VII.

In case of limited resources available for the implementation of all 14 management and policy solutions, the model allows prioritising a subset of solutions through an optimization procedure. To identify the optimal combination of solutions, the following five Key Performance Indicators (KPIs), representing main social, economic, and environmental impacts, were selected together with stakeholders during the second MSW: (a) agricultural pressure on water resources, (b) agricultural nutrients in the Mar Menor lagoon, (c) coastal-rural recreation potential, (c) territorial bonding, and (d) the total number of jobs.

All possible combinations of the 14 solutions were automatically tested through 16,383 model runs. Then, based on a multi-criteria decision analysis we minimised the value of the first two KPIs (a and b) and maximised the value of the other three KPIs (c-d), together represented by the TOPSIS score between 0 and 1. This multi-criteria evaluation, and a subsequent application of the 0.5 threshold criterion explained in section 2.3, allowed us to find optimal combinations of management solutions. This optimization showed that at least 6 solutions were needed to assure sustainable development in economic, environmental and social terms, whereas, the maximum TOPSIS score was achieved when 5 additional solutions were included (Table 1 and Fig. 4).

Table 1
Set of 14 policy and management solutions identified by stakeholders and grouped based on their contribution to the achievement of best model results, according to the TOPSIS analysis.

Minimum set of solutions required for sustainable development	Additional solutions required for optimal sustainable development	Complementary solutions for additional benefits
Promotion of rural ecotourism activities	Denitrification of brine waste from groundwater treated for irrigation	Implementation of nutrient soil and water retention measures
Promotion of coastal ecotourism activities	Decrease in agricultural water demand per hectare	More restricted number of groundwater wells
Reduction in fertiliser use	Groundwater pumping and treatment	Surface water pumping and treatment from the Albujón ephemeral river
Control of the extension of irrigated areas	Increase in seawater desalination amount	
Promotion of small (<10 Megawatt) (agro) photovoltaic facilities	Control of other point sources of pollution to the lagoon	
Promotion of environmental education		

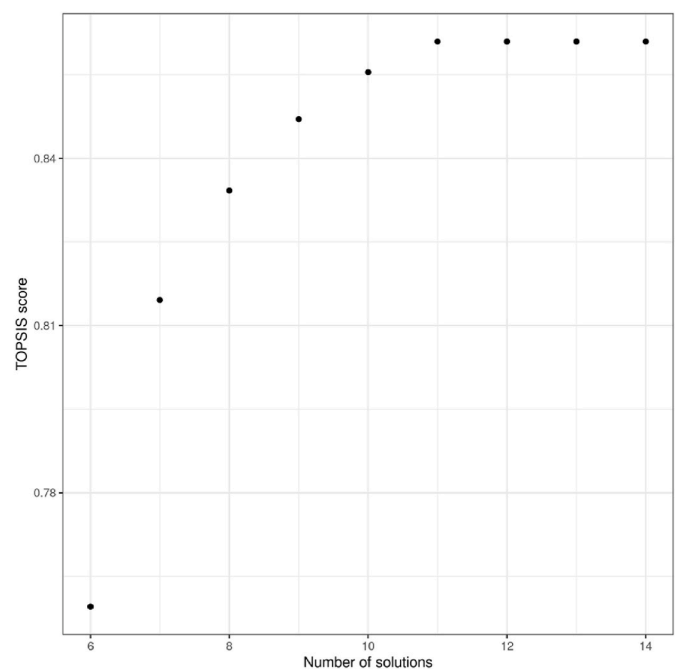

Fig. 4. TOPSIS scores for the optimal sets of management solutions based on the KPIs optimization procedure.

The TOPSIS score did not increase when including the complementary set of management and policy solutions (Fig. 4) and thus, the set of 11 solutions could be considered as optimal.

Fig. 5 shows the expected trend for the 5 KPIs, with and without the implementation of all 14 solutions. These graphs clearly show the positive impact of the 14 solutions. Although the total number of jobs shows an important initial decline, in the medium-long term this KPI is also expected to exceed the value when no solutions are implemented (BAU). Annex VIII shows how different sets of 6–14 management solutions affect each of the five KPIs in 2070, illustrating how particularly the agricultural pressure on water resources, agricultural nutrients in the lagoon, and to a lesser extent also the total number of jobs benefit from the 5 additional solutions for optimal sustainable development.

The results of the sensitivity analysis provided further insight into

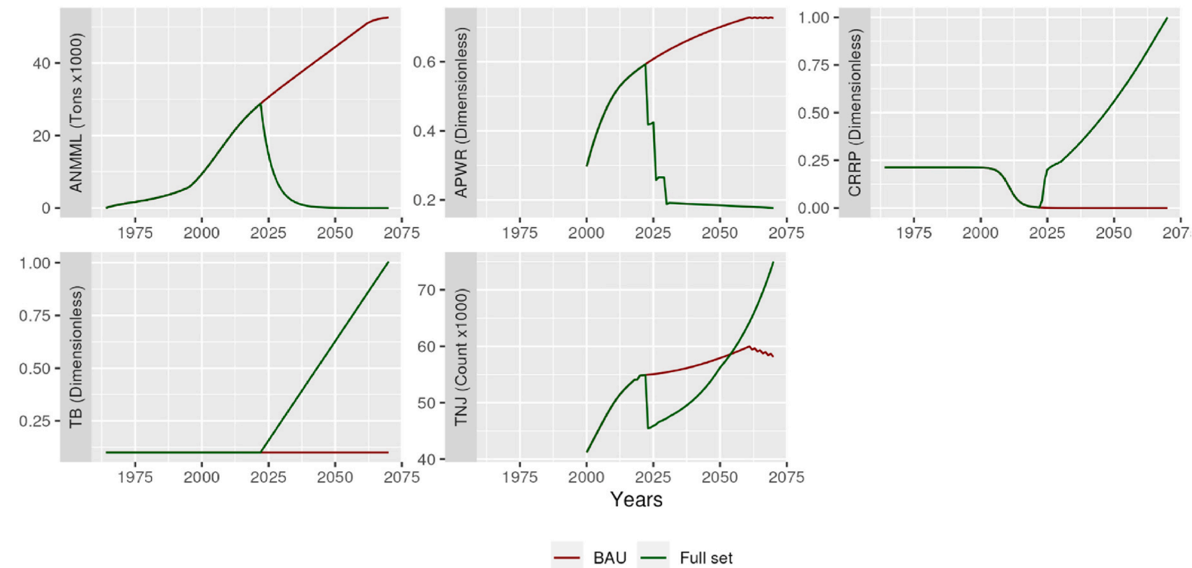

Fig. 5. Model results showing the development of the five KPIs with implementation of the full set of management and policy solutions (Full set) and under a Business as usual scenario (BAU) with no implementation of solutions (see annex VII for more details). Agricultural nutrients in the MM lagoon (ANMML); Agricultural pressure on water resources (APWR); Coastal-rural recreation potential (CRRP); Territorial bonding (TB); Total number of jobs (TNJ).

the relevance of each of the management and policy solutions. Fig. 6 shows the relative impact of each individual solution on selected KPIs (see section 2.3). The effect on territorial bonding was not included in the sensitivity analysis since this KPI was only dependent on a single management solution. Results showed that control of irrigated areas and the allowed number of wells were the solutions with the most impact on the 4 KPIs represented in Fig. 6. Agricultural nutrients in the Mar Menor was the most strongly affected KPI, followed by the total number of jobs, while the agricultural pressure on water resources and the coastal-rural recreation potential were only sensitive to a limited number of solutions.

4. Discussion

4.1. Participatory modelling for sustainable development

Participatory modelling of SES is about integrating scientific model building in a social process that engages scientists, decision-makers, and other stakeholders to achieve shared problem understanding and help identify policy solutions that provide long-term improvements for society (Hamilton et al., 2022). While traditional modelling approaches aim to assess the impacts of environmental change, scenarios, or

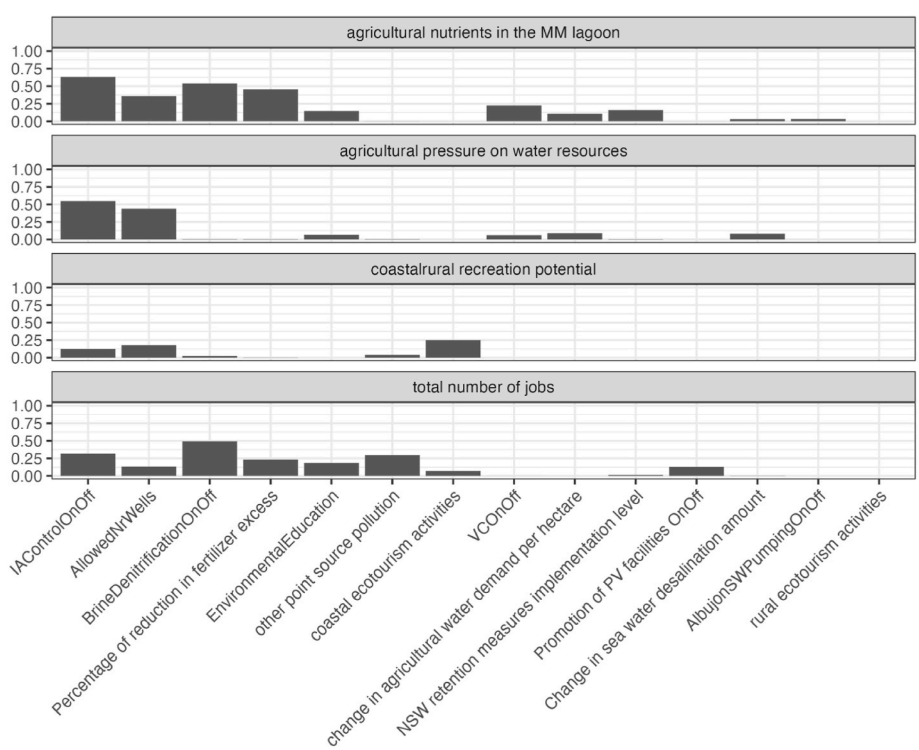

Fig. 6. Sensitivity analysis of management solutions for selected KPIs. Sensitivity values range from zero (low sensitivity) to one (high sensitivity), as explained in section 2.3.

enhance scientific process understanding, participatory modelling aims to go beyond this by sharing stakeholders' knowledge in a learning process and by building public interest in adaptive management (Hamilton et al., 2019; Kenny et al., 2022; Voinov and Bousquet, 2010). The participatory modelling process presented here contributed to enhanced understanding and knowledge exchange amongst a wide range of stakeholders on how different socio-economic sectors and the environment can be affected by adaptive management of the studied SES. Moreover, while not presented here, the SD model allows for evaluation of the robustness of suggested solutions under changing socioeconomic, political, and environmental conditions as part of scenario studies. For example, the combined impacts of management and policy solutions under scenarios with changing prices of agricultural inputs, electricity prices, international tourism, environmental legislation, or climate change can be evaluated. Through these insights, the participatory modelling process and the resulting System Dynamics model provide an important step forward to support integrated management of the Mar Menor and Campo de Cartagena.

In order to make models more useful for environmental decision-making, Schuwirth et al. (2019) emphasised the need for alignment of the model to the management decisions through transdisciplinary collaboration between modellers and stakeholders and through transparent communication on model structure, assumptions and limitations. In this sense, the participatory modelling approach in our study proved a powerful tool for the identification of challenges and opportunities for sustainable development and to facilitate knowledge exchange and trust building between stakeholders with opposing interests, like representatives from the agriculture and tourism sectors. The iterative co-design process resulted in a SD model representing those aspects considered most important by stakeholder representatives. Correct representation of current available knowledge on systems interactions and confidence building was achieved through representation of all relevant stakeholders, transparent stepwise problem analysis, identification of causes and effects, discussion of potential solutions, and interpretation of the simulated model outcomes. Much effort was put into model testing and realistic parameterization using data analysis, literature review, expert interviews and where possible contrasting outcomes with historic observed data (e.g. observed growth rate of tourists and the surface of irrigated areas). The stakeholders' confidence in the model structure and the management and policy solutions included in the model was confirmed during the multi-sectoral workshops and questionnaires. This exemplifies how embedding model development in a participatory process can make the outcomes relevant to support informed decision-making.

The design of any participatory process strongly affects its outcomes (e.g. de Vente et al., 2016; Reed, 2008), and it is often difficult to identify which methods and tools are most appropriate for a particular participatory modelling project (Voinov et al., 2018). Here, we aimed to illustrate how a combination of different methods in an iterative process of participatory model development can support scientific discovery, social learning, and better-informed decision-making. In order to develop a model that is useful (i.e. addressing the needs of the end-users), reliable and feasible (i.e. within the practical constraints of the project) (Hamilton et al., 2022), we used a range of co-design methods, each with a different function and complexity. Following the typology proposed by Voinov et al. (2018), we started with qualitative modelling using mental mapping and Causal Loop Diagrams for conceptualization, then we used interviews and surveys for the fact-finding needed to design and parametrize the SD model and its application for quantitative assessments. Finally, we used multi-criteria analysis and sensitivity analysis for decision support regarding management and policy solutions. Our experience shows that the combination of these methods resulted in a comprehensive representation of the system needed to evaluate the impacts of alternative management and policy solutions in collaboration with stakeholders from all sectors of the Mar Menor and Campo de Cartagena.

Power imbalances, conflicts, opposing interests, or different value systems can impede effective collaboration between stakeholders (Boix-Fayos et al., 2023; Voinov et al., 2016). The sequential co-design process followed in this study was designed to create trust and mutual understanding among stakeholders regarding sectoral interests and the potential impacts of stakeholder-defined solutions. In this case, through sectoral and multi-sectoral workshops to reduce power imbalances and conflict, stakeholders reached an agreement on the model structure and main system interactions, resulting in one SD model that was used to assess the impacts of different combinations of management and policy solutions. In the case of continued disagreement or insufficient data for model parameterization, another option could be to develop different models and compare outcomes to represent uncertainty. Altogether, this illustrates how participatory modelling can be effective to facilitate co-production of knowledge, create trust, and support integrated management of SES based on the best available data and knowledge, e.g. (Guittard et al., 2024), thereby advancing in the grand challenges in SES modelling identified by Elsawah et al. (2020).

4.2. Increased systems understanding

Increased shared understanding of the SES of the Mar Menor and Campo de Cartagena is one of the main outcomes of the participatory modelling process. Detailed analysis of the SD model structure reveals several important feedback loops driving the system's behaviour. For example, the Mar Menor degradation is mainly caused by nutrient input from agriculture that indirectly affects tourism growth via coastal recreation potential. This affects social pressure on public administrations, which negatively affects the potential growth rate of irrigated agriculture. Besides, the expansion of irrigated land areas increases water demand and agricultural pressures on water resources, which in turn decreases the potential growth of agriculture based on water availability. The increase in agricultural water demand also increases the groundwater needed, thereby producing brine wastes and more nutrient inputs to the lagoon leading to further degradation of the lagoon. The social pressure on public administrations and its implications for agricultural and tourism growth potential are central to the effectiveness of this feedback loop.

The system's interactions represented in the model clearly illustrate how a transition to more sustainable agriculture through reduced fertiliser use and implementation of water and nutrient retention measures has environmental, social and economic benefits. More sustainable agriculture will enhance the ecological status of the lagoon and support the development of sustainable rural and coastal tourism activities. The model quantifies the benefit of diversification of economic activities through the development of rural and coastal ecotourism and solar photovoltaic energy production facilities, resulting in the creation of jobs and increased gross economic benefit. Another important system interaction represented in the model is how a transition to a more environmentally aware society through environmental education will also lead to more integrated sustainable management based on participatory governance and more effective environmental control and regulation. Together, this will contribute to a more balanced development considering environmental, social and economic interests.

4.3. Decision support for informed decision making and prioritisation of solutions

One of the main intended applications of the System Dynamics model is facilitation of informed decision making based on integrated evaluations of impacts on environmental, social and economic KPIs. By considering a range of KPIs representing impacts in different sectors, model outcomes are useful to identify benefits and tradeoffs, assess feasibility of solutions and identify where additional support is required for implementation. For example, the model quantifies how the export of nutrients from intensive irrigated agricultural areas causes degradation of the Mar Menor lagoon, affecting tourism and local populations, whereas a combination of solutions is capable of mitigating these impacts, supporting sustainable socioeconomic and environmental development. Some of these solutions concerning changes in agricultural management and policy solutions were proposed in previous studies (Boix-Fayos and de Vente, 2023; Guaita-García et al., 2022; Perni and Martínez-Paz, 2013) or have been included in the latest framework of priority actions for restoration of the Mar Menor promoted by the national government (MITERD, 2022), but their socioeconomíc and environmental impacts were not yet quantified. The model outcomes also illustrate that implementation of the 14 stakeholder defined solutions has an immediate positive impact on most KPIs. Only the total number of jobs shows an important initial decline, and only exceeds the number of jobs under a business as usual scenario at medium-long term. This highlights the need to find additional policy solutions to overcome this first phase of the transition to sustainable development.

Combining the SD model in a multi-criteria optimization analysis provides a strong decision support tool since it allows evaluation of what happens if policymakers have to choose between the 14 solutions when resources for implementation are limited. The multicriteria optimization analysis shows that a balanced sustainable development of the Mar Menor and Campo de Cartagena requires at least six solutions that support a transition towards more sustainable models of tourism and agriculture and to more integrated management. For optimal results, five additional solutions related to sustainable agriculture and integrated management are required. While the remaining three complementary solutions might not be crucial for sustainable development when the other eleven solutions are implemented, some of these complementary solutions, like the allowed number of groundwater wells for irrigation, can have a significant impact on multiple KPIs. The sensitivity analysis further highlighted that most solutions in one way or another affect the amount of agricultural nutrients in the Mar Menor or the total number of jobs, which is indicative of the stakeholders' main environmental and socio-economic concerns.

4.4. Recommendations for further development

During the modelling process several aspects were identified that could not be modelled in full detail due to lack of data or insufficient knowledge of system processes and interactions. One of the main challenges was to accurately simulate the aquatic ecological processes leading to the degradation of the lagoon. Monitoring data clearly illustrate how the lagoon went through a process of progressive eutrophication, evidenced by bioindicators, jellyfish proliferation, a major phytoplankton bloom in 2016, and an episode of anoxia leading to a sudden mass starvation of sea life in 2019 (Bernardeau-Esteller et al., 2023). The complexity of ecological processes involved made it unfeasible to include them all in the SD model. Therefore, we decided to simplify the model equations related to the degradation of the lagoon and link it directly with the nutrient input to the lagoon. Nevertheless, a more accurate representation of the nutrient load and possible risks for the occurrence of episodes of anoxia could possibly be implemented by integration with an ecological process-based model in combination with remote sensing based monitoring of water quality and the role of wetland restoration (Caballero et al., 2022; Martínez-López et al., 2014a, 2014c, 2015). Lack of data has also affected some other important system components. For example, while the model does have the possibility to account for retention of water and nutrients through Sustainable Land Management in agriculture, it does not account for nutrient retention by wetlands around the lagoon, the effect of extreme rainfall, or the contribution of livestock on nutrient inputs. This means that actual nutrient inputs are most likely underestimated. However, as more empirical data become available these aspects can be added to the model.

Another aspect for improvement relates to providing spatially explicit outcomes to identify the optimal locations for the implementation of solutions. Integration of the SD model with spatial process-based simulation models represents a relevant but challenging next step to support integrated spatial land use planning and optimization. Furthermore, a full quantitative economic analysis, including costs and benefits of solutions as a function of implementation rate would enhance the economic evaluation. It is however important to maintain a balance between model complexity, accuracy, transparency, and its application potential to support better informed decision making for adaptive management.

Finally, making predictions over a long period using deterministic models poses some challenges regarding unexpected behaviour of some variables over time due to emergent and non-linear responses and changes in behaviour. Hence, further model development should include representation of adaptive responses through more feedback loops, such as changing people's values or ecosystem behaviour. For example, the combined positive outcomes of the different management solutions might also have a positive effect on the territorial bonding. As a first step in that direction, results of the SD model application to assess the robustness of the proposed management and policy solutions under global change scenarios following different pathways of international socioeconomic, political and environmental development will be developed in a future study.

5. Conclusions

The participatory modelling process presented here demonstrates how the sustainable development of the social-ecosystem (SES) of the Mar Menor and Campo de Cartagena requires a systemic transition towards more sustainable models of agriculture and tourism in rural and coastal areas and more integrated management based on participatory governance, incentives, environmental education, as well as control and compliance of regulation. Stakeholder representatives participated in the co-development of potential management and policy solutions and provided crucial input regarding systems interactions that formed the basis of a Systems Dynamics (SD) model of the SES of the Mar Menor and Campo de Cartagena. The co-design process contributed to constructive collaboration, increased trust and understanding between stakeholders. The SD model builds on the best available knowledge from stakeholders and domain experts and facilitates informed decision-making based on integrated evaluations considering environmental, social and economic Key Performance Indicators. Model simulations can help quantify the impacts of action versus inaction, whereas the multicriteria optimization and the sensitivity analysis help prioritise solutions that facilitate a gradual transition and promote sustainability across sectors. The main strength and application of the SD model is to identify the tendencies of expected impacts on multiple sectors following management decisions, rather than quantification of the absolute values of single variables. While further model development and integration with process-based and spatially distributed ecological models and monitoring can provide additional insights, we conclude that participatory modelling using System Dynamics provides an important tool to support the transition towards sustainable development of complex SES like the Mar Menor and Campo de Cartagena.

Software and data availability

- Name of the software: A System Dynamics model of the Mar Menor - Campo de Cartagena socio-ecosystem
- Developer: Javier Martínez-López
- Contact information: javier.martinez@ugr.es
- Year first available: 2022
- Program language: Vensim
- Cost: Free
- Software and data availability: https://doi.org/10.5281/zenodo.7142764 (model input data are embedded in the Vensim model file)
- Program size: 83.5 kB

CRediT authorship contribution statement

Javier Martínez-López: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Juan Albaladejo:** Conceptualization, Validation, Writing – original draft. **Joris de Vente:** Conceptualization, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Model input data are embedded in the Vensim model file (https://zenodo.org/records/7142764)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2024.106061.

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