SMARTLAGOON

DELIVERABLE 5.5

Report on the outcomes of the long-term scenarios of socio-environmental dynamics

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017861.

Innovative modelling approaches for predicting Socio-environMentAl evolution in highly anthRopized coasTal LAGOONs

Deliverable 5.5

Deliverable No.:	5.5
Project Acronym:	SMARTLAGOON
Full Title:	Innovative modelling approaches for predicting Socio-environMental evolution in highly anthRopized coastal LAGOONs
Grant Agreement No.:	101017861
Workpackage/Measure No.:	WP5
Workpackage/ Measure Title:	Digital twin development
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Date:	31/08/2024
Status:	
Dissemination level:	Public

HISTORY OF CHANGES

Date	Content	Author(s)

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Abstract

This document presents the outcomes of the SMARTLAGOON project, with focus on simulated impacts of long-term socio-environmental dynamics in the Mar Menor lagoon and its catchment area. Utilizing advanced and holistic modeling techniques, including the coupling of GOTM-WET and SWAT+ models, the project evaluates a range of scenarios over decades, focusing on the impacts of Best Management Practices (BMPs) and flood mitigation measures. These scenarios are designed to assess how various interventions can potentially influence the frequency of flooding in the catchment and the occurrence of phytoplankton blooms and hypoxia in the lagoon, which is critical for maintaining livelihoods as well as the ecological balance of this sensitive environment.

The study also incorporates climate change projections, allowing for a comprehensive analysis on how climate change may also contribute to shaping the future of Mar Menor. By linking modeling efforts from climate change and BMPs, which focuses on evaluating changes in water quality, the project aims to provide comprehensive insights that reflect the range of anticipated impacts of human anthropization and climate change on the lagoon's hydrology and nutrient dynamics. The results can offer insights relevant for choosing effective management strategies for enhancing the resilience of the Mar Menor lagoon. This document underscores the importance of integrating innovative modeling approaches with real-world data to inform sustainable management practices and policy decisions aimed at protecting coastal lagoon ecosystems in the face of ongoing environmental changes.

We found that regardless of whether future climate scenarios are considered, implementing all BMPs scenarios together creates a synergistic effect, leading to significant reductions in nutrient inputs to the Mar Menor—up to 55% for nitrates and up to 65% for phosphorus. However, due to the generally low slopes in the study area, the effectiveness of BMPs in reducing sediment inputs to the Mar Menor is moderate.

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Introduction

1.1. Motivation

This document is the fifth deliverable of the Work-Package 5 (WP5) of the SMARTLAGOON project, led by the UCAM. The focus of this Work-Package is to develop the digital twin of the Campo de Cartagena – Mar Menor system. While the digital twin focus on short-term forecasting, the modelling tools used may also be used for experimenting with long-term scenarios. The latter is the core focus of the present report, in which we have employed the models developed in the previous work packages to simulate long-term scenarios, aiming to predict the impacts of best management practices (BMPs) and flood mitigation measures on the hydrology and state of the lagoon.

The motivation of the document, as outlined in the report, includes the following key points:

- **Addressing Environmental Challenges**: The document aims to tackle the pressing environmental issues faced by coastal lagoons, particularly those that are highly anthropized. This includes understanding the impacts of human activities and climate change on these sensitive ecosystems.
- **Improving Management Practices**: By developing innovative modeling approaches, the project seeks to provide tools and insights that can help in the effective management of coastal lagoons. This is particularly important for choosing and implementing BMPs that can mitigate negative environmental impacts.
- **Enhancing Predictive Capabilities**: The motivation also lies in enhancing the predictive capabilities regarding socio-environmental dynamics. This involves simulating various scenarios to better understand potential future changes and their implications for lagoon health and sustainability.
- **Collaboration and Knowledge Sharing**: The document emphasizes the importance of collaboration among various organizations and stakeholders involved in the project, fostering a shared understanding and approach to managing coastal lagoon ecosystems.

Overall, the motivation is rooted in the need for sustainable management and conservation of coastal lagoons in the face of ongoing environmental changes and anthropogenic pressures.

1.2. Goals

The goals of the document, as outlined in the report, include the following:

- **Development of a Digital Twin**: One of the primary goals is to create a digital twin that can accurately simulate the socio-environmental dynamics of coastal lagoons. This involves integrating various data sources and modeling techniques to enhance predictive capabilities. In case of this report, we apply the models of the digital twin for long-term scenarios.
- **Evaluation of Best Management Practices (BMPs)**: The document aims to assess the effectiveness of different BMP scenarios in reducing sediments and nutrients entering the Mar

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Menor lagoon, and how this may translate into changes in the dynamics of hypoxia formation. This evaluation is crucial for identifying strategies that can improve water quality and ecosystem health.

- **Long-term Scenario Analysis**: Besides the short-term forecasting focus of the digital twin, the project also seeks to analyze long-term scenarios to understand the potential impacts of climate change and human activities on coastal lagoon ecosystems. This includes simulating various environmental conditions and their effects on lagoon dynamics.
- **Model Calibration and Validation**: Another goal is to improve the calibration and validation of the SWAT+ and GOTM-WET models, ensuring that these models can accurately represents the processes and variables relevant to the lagoon's environmental conditions.
- **Knowledge Dissemination**: The document aims to disseminate key findings in relation to longer-term scenarios and insights from the project to stakeholders, policymakers, and the scientific community, promoting informed decision-making regarding the management of coastal lagoons.

These goals collectively aim to enhance the understanding, management, and sustainability of coastal lagoon ecosystems in the context of environmental changes and anthropogenic pressures.

1.3. Innovations and relevance of results

The results of this study are interesting for several reasons:

- **Innovative Modeling Techniques**: The study introduces advanced modeling approaches, such as the GOTM-WET model and its integration with the SWAT+ catchment model – for the first time producing a holistic catchment-lagoon modelling system that is able to simulate both hydrology and water quality aspects. These innovations provide valuable tools for simulating complex environmental processes in coastal lagoons, which can enhance predictive accuracy and inform management strategies.
- **Impacts of Climate Change**: The findings highlight the projected impacts of climate change on the Mar Menor lagoon, including rising temperatures, altered precipitation patterns, and increased nutrient inputs. Understanding these dynamics is crucial for developing effective adaptation and mitigation strategies to protect vulnerable ecosystems.
- **Best Management Practices (BMPs)**: The evaluation of BMP scenarios demonstrates practical solutions for reducing sediments and nutrients entering the lagoon. The results can guide agricultural practices and land management strategies, promoting sustainable agriculture while protecting water quality and ecosystem health.
- **Ecosystem Resilience**: The study provides insights into the resilience of the Mar Menor lagoon to extreme weather events and environmental changes. This information is vital for stakeholders and policymakers aiming to enhance the lagoon's resilience and sustainability.
- **Socio-Environmental Dynamics**: By analyzing long-term scenarios of socio-environmental dynamics, the study contributes to a deeper understanding of the interactions between

human activities and natural processes. This knowledge is essential for informed decision-making and effective management of coastal lagoons.

Overall, the results of this study are significant for advancing scientific knowledge, informing policy, and promoting sustainable management practices in coastal lagoon ecosystems.

SWAT Model Updates

As mentioned in Deliverable 3.1, the Soil and Water Assessment Tool Plus (SWAT+) is an advanced and restructured version of the original SWAT model, developed by the USDA Agricultural Research Service and Texas A&M University (Arnold et al., 1998; Bieger et al., 2017). SWAT+ enhances the spatial representation of watershed interactions by modularizing various components such as hydrological response units (HRUs), aquifers, and channels, allowing for more flexible and detailed simulations of hydrological processes (Arnold et al., 2018). This model operates on a semi-distributed, continuous-time framework, capturing the dynamics of water, sediment, and nutrient fluxes within a watershed. SWAT+ retains the core functionalities of SWAT, such as using HRUs to simulate land use, soil, and slope interactions, but offers enhanced configurational flexibility and accuracy, particularly in aquifer simulations and stream connectivity (Bieger et al., 2019). This model is pivotal for assessing the long-term impacts of land management practices, climate change, and water resource management at various scales, making it an invaluable tool for hydrological research and environmental planning (Jimenez-Navarro et al., 2021).

At this stage of the project, the SWAT+ model of the Mar Menor has been improved compared to its previous version (Deliverable 3.1). Among these improvements and adjustments, it is worth highlighting the use of the latest available code versions of the SWAT+ model to date (rev 60.5.7), the implementation of a new soil map (DSOLmap, López-Ballesteros et al., 2023a) developed by the authors as input data of SWAT+, the simulation and assessment of agricultural practices applied in the Campo de Cartagena, and the enhancement of the model calibration and validation procedure. This new calibration and validation procedure includes extending the period to 2022, incorporating GLEAM satellite soil moisture data, and applying a multi-objective function in the calibration and validation done through SWATplus-CUP. All of these improvements will be detailed further in the following sections.

2.1 Spatial and climatic data

As can be observed in Table 1, the input data used by the new version of the SWAT+ model of the Mar Menor are equivalent to previous versions, except for the inclusion of a higher spatial resolution soil map (DSOLmap, López-Ballesteros et al., 2023a). DSOLMap is a new global digital soil property map at a 250 m spatial resolution with a detailed six-horizons soil profile, tailored for direct use with the SWAT+ model. This allows the model to have greater discretization regarding soil types,

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consequently providing a more reliable representation of the spatial heterogeneity in hydrological processes within the Mar Menor watershed.

Table 1. SWAT+ input data for the Mar Menor.

Data	Description	Source
DEM	25 m x 25 m resolution map	Spanish National Geographic Institute (IGN)
Land use map	Vector database (1:50,000)	Crop and Land Use Map 2000-2010
Soil map	250 m x 250 m resolution map	Digital Soil Open Land Map (DSOLMap)
Climate data (2000-2022)	Daily meteorological stations called CA21, CA42, CA52, CA91, MU31, MU62, and TP42.	Murcian Institute of Agrarian and Food Research and Development (IMIDA)

2.2 Agricultural data

In agricultural areas, such as the Mar Menor watershed, a realistic representation of agricultural management practices is essential for achieving accurate simulations of water quantity and quality (Samimi et al., 2020). Therefore, the main agricultural management practices for the agricultural land use of the Campo de Cartagena were also incorporated into the SWAT+ model. The irrigated land use in the study area primarily consisted of horticultural crops, citrus trees, and greenhouses. For horticultural crops, a standard annual three-crop rotation (broccoli, cantaloupe, and lettuce) was implemented (Table 2). Fertilization rates for each crop were obtained from official government documentation (BORM, 2012a, 2012b, 2012c; BOE, 2004). Additionally, irrigation volumes for the irrigated agricultural area were extracted from the Hydrological Plan of the Segura River Watershed.

Table 2. Standard crop rotation schedule of the Campo de Cartagena.

Year	Date	Operation	Application Rate	Crop
1	January 1st	Planting begin		Broccoli
1	January 1st	Irrigation	~45 mm/month	Broccoli
1	January 1st	Fertilization[1]	245 KgN/ha/year 100 KgP/ha/year	Broccoli
1	January 30th	Harvest and kill		Broccoli
1	May 1st	Planting begin		Cantaloupe
1	May 1st	Irrigation	~48 mm/month	Cantaloupe
1	May 1st	Fertilization[1]	225 KgN/ha/year 105 KgP/ha/year	Cantaloupe
1	August 31th	Harvest and kill		Cantaloupe
1	September 1st	Planting begin		Lettuce
1	September 1st	Irrigation	~31 mm/month	Lettuce
1	September 1st	Fertilization[1]	100 KgN/ha/year 58 KgP/ha/year	Lettuce
1	December 31th	Harvest and kill		Lettuce

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The implementation of agricultural practices carried out in the Campo de Cartagena allows the SWAT+ model to more accurately represent the current situation of the study area. This better representation of agricultural practices is due to the powerful agricultural module incorporated into the SWAT+ model, which allows for the simulation of both the amount of irrigation and the fertilizers applied to the different crops as well as the simulation and testing of multiple best management practices (BMPs). The evaluation of BMPs effectiveness for reducing sediments and nutrients entering the Mar Menor is one of the main objectives of this deliverable, as detailed in the following sections.

2.3 Calibration data

As with the previous version of the Mar Menor SWAT+ model (Deliverable 3.1), this latest version also utilized satellite data from Global Land Evaporation Amsterdam Model (GLEAM; Miralles et al., 2011). However, for this latest model, soil moisture data from surface and root-zone have also been included for the calibration and validation of the model. This has allowed for a reduction in model uncertainty by calibrating and validating the model against a key hydrological element within the hydrological cycle in semi-arid areas such as the Mar Menor watershed. Moreover, the latest available version of GLEAM to date has been used (version 3.7b). GLEAM v3.7b is a global dataset generated by a combination of remote sensing observations from multiple satellites, meticulously validated with eddy-covariance towers and in-situ sensors (Martens et al., 2017). The version 3.7b encompasses a data period from 2003 to 2022 at a spatial resolution of a 0.25° regular grid.

2.4 SWAT+ Model setup

In the latest and improved version of the SWAT+ model for the Campo de Cartagena, the long-term release of QGIS version 3.34 was utilized in combination with the QSWAT+ version 2.4 plugin to delineate the watershed and sub-basins, generate the existing stream network, and including the Mar Menor coastal lagoon as a lake object. As a result, the initial step delineated 144 sub-basins, 340 channels, and 1 reservoir or lake (lagoon). In the second step, 13,889 HRUs were created by combining land uses, soil types, and slope classes (<2%, 2%–8%, and >8%). To reduce the computational time required by SWAT+, a minimum area threshold of 100 ha was implemented for HRUs. This resulted in the creation of 750 HRUs. Subsequently, all files generated in the previous steps were imported into the SWAT+ Editor version 2.3.3 software, where climatic data were incorporated and the Penman-Monteith method was selected for calculating potential evapotranspiration (PET).

2.5 Sensitivity analysis, calibration and validation

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The total simulation period used in this version of the SWAT+ model of the Mar Menor spans from 2000 to 2022, which includes a 3-year warm-up period (2000-2002), followed by a 10 year calibration, and then a 10 year validation period. A new sensitivity analysis was conducted with regard to the version of Deliverable 3.1. For this purpose, 14 of the most commonly used SWAT+ model parameters were selected based on the reviewed literature (Table 3).

Table 3. SWAT+ parameter included in the sensitivity analysis.

Parameter	Description
Perco	Percolation coefficient
BD	Moist bulk density of the soil layer
CN3_swf	Soil water factor for CN3
Deep_seep	Percolation coefficient from shallow to deep aquifer
AWC	Available water capacity of the soil layer
Sp_yld	Specific yield of the shallow aquifer
K	Hydraulic conductivity of the soil layer
Epco	Plant uptake compensation factor
CN2	Condition II Curve Number
Esco	Soil evaporation compensation factor
Revap_co	Revap coefficient
Flo_min	Threshold depth from surface to water table for groundwater flow to occur
Revap_min	Threshold depth from surface to water table for revap to occur
Alpha	Baseflow alpha factor

This sensitivity analysis was conducted for both actual evapotranspiration and soil moisture using a multi-variable sensitivity analysis, available within the SWATplus-CUP calibration software. In order to calibrate the model, a similar multi-variable approach was used, which included both the actual evapotranspiration and soil moisture from GLEAM. This approach was combined with a multi-objective function, which included the most commonly used statistics for evaluating the goodness of fit of hydrological models, such as R^2, NSE, PBIAS, and KGE. This new version of the SWAT+ model of the Mar Menor was automatically calibrated using a novel approach, specifically a multi-objective and multivariable approach. Employing advanced sensitivity analysis and calibration techniques allows for greater confidence in the results obtained from the model, reducing the associated uncertainties. In the process of validation and evaluation the performance of the SWAT+ model of the Mar Menor, the same statistics used for calibration were also employed (R^2, NSE, PBIAS, and KGE). Furthermore, the statistical evaluation was integrated with a graphical analysis, comparing the simulated actual evapotranspiration and soil moisture with the observed data as can be observed in Section 4.

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GOTM-WET model updates

In this section, we describe the final version of the GOTM-WET model for the Mar Menor, starting from what was described in Deliverable 3.2 (including the updates that were submitted in May 2024). For a more detailed description of the GOTM and WET models, how these are coupled with SWAT+, the forcing data, the calibration method, and the testing application in Lake Erken, we refer to Deliverable 3.2.

During the calibration procedure, different variations in the food web setup were attempted. Initially, two phytoplankton groups ("floating" and "non-floating") and jellyfish were included, but we had insufficient observations to calibrate the jellyfish and separate phytoplankton groups. Moreover, the complex life cycle of the jellyfish is not fully represented in the WET model, and transport to and from the Mediterranean Sea formed another unknown. Therefore, we restructured the food web to consist of one group of phytoplankton, macrophytes, zooplankton, and zoobenthos. Zoobenthos was added due to their importance for the biogeochemical cycling. It should be clear that the GOTM-WET model for the Mar Menor aims to predict an average concentration of a certain group (e.g. phytoplankton), rather than to predict species or genera shifts within these groups (e.g. from diatoms to cyanobacteria). Although WET is technically capable to do so, it would require a long timeseries of group-specific observations to attempt to simulate this reliably.

Another change that was made during the model fitting procedure, was that we used a later version of the GOTM-WET code (version 0.2.0-4, git commit g939ec05, https://gitlab.com/wateritech-public/waterecosystemstool/wet). One major difference was that this allowed us to calibrate Secchi depth (i.e. an indication of water transparency) as well, and long-term records of Secchi depth in the Mar Menor existed (compiled from CARM monitoring and Pérez-Ruzafa et al., 2022). This prompted us to use more output from the SWAT+ model, namely inorganic sediments and dry-weight organic matter (derived from organic nitrogen using a fixed ratio). These influence light absorption inside the GOTM-WET model, and dry weight organic matter additionally contributes to oxygen consumption. To clarify, these were used in addition to discharge, nitrate, phosphate, ammonium, and organic N and P (converted to dissolved and particulate fractions) loading outputs from SWAT+.

Complex (biogeochemical) models such as WET are by definition prone to equifinality (Beven, 2006), where multiple model parameterisations, including physically unrealistic ones, can generate similar outputs. In order to assess whether the parameter values used in this study were in a realistic range, a comparison of our parameter values with previous GOTM-WET applications was performed, in addition to discussions with Dr. Dennis Trolle (co-creator of the model and involved in SMARTLAGOON). This was done iteratively and the calibration ranges were adjusted to end up with a plausible model configuration.

We extended the validation period to 2023 and updated the CTD monitoring data (data extraction from the reports at https://canalmarmenor.carm.es/ciencia/informes-monitorizacion-imida/) to be able to utilize as much as possible from the project's data buoy installed at the deepest location in the lagoon. Because of this extension, there was overlap between the model simulations and both

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the SMARTLAGOON buoy and camera observations, so these were also used to assess model performance.

As already mentioned in the updated 3.2 Deliverable, we also created a version of the GOTM-WET model that is specifically trained on temperature and oxygen, and in particular to reproduce short-term hypoxia events. The differences with the main model configuration were small, but this model is likely more reliable to simulate oxygen and temperature dynamics and will therefore be used in the short-term forecasting feature of the digital twin.

Best management practices (BMP) scenarios

Best Management Practices (BMPs) are strategies and techniques designed to mitigate the environmental impact of agricultural activities. These practices include physical constructions and land modifications to reduce or prevent the volume and speed of both surface and subsurface water runoff, thereby minimizing the risk of flooding and soil erosion. BMPs also aim to control pollution by preventing the entry of pollutants into water bodies, ensuring cleaner water and healthier ecosystems. By adopting these practices, farmers and land managers can significantly reduce environmental impacts, promote sustainable agriculture, and protect valuable natural resources. In this project, 5 different BMP scenarios have been evaluated for their effectiveness in reducing sediments and nutrients entering the Mar Menor coastal lagoon. The selected practices are vegetative filter strips, contour farming, fertilizer reduction, crop rotation management and a combined scenario, where all the individual BMPs are included simultaneously. The effectiveness of the simulated BMP scenarios in reducing sediments and nutrients entering the Mar Menor was evaluated using equation 1.

$$Effectiveness = \frac{(Y_{baseline} - Y_{BMP})}{Y_{baseline}} \cdot 100 \tag{1}$$

where Y_{BMP} and $Y_{baseline}$ are the average annual pollution loads (tons/year) produced by the selected BMP scenario and the baseline scenario, respectively.

3.1 Vegetative filter strip

Vegetative filter strips involve establishing a vegetated area along the perimeter of agricultural land to slow down surface runoff, capture sediments, and absorb nutrients. SWAT+ utilize a submodel to predict the effectiveness of filter strips under ideal uniform sheet flow conditions, based on the Vegetative Filter Strip Model (VFSMOD) (Muñoz-Carpena, 1999). This filter strip model operates at the field scale, taking into account the effects of flow concentration. To implement this BMP scenario in the SWAT+ model of the Mar Menor, a vegetative barrier 3-meter wide has been implemented for irrigated crops and 2-meter wide for rain-fed crops, in accordance with the most recent law recommendations. In the filter strip model of SWAT+, the parameter fld_vfs (ratio of field area to filter strip area) was set to 15 and 10 for the 3-meter and 2-meter vegetative filter strip, respectively, and con_vfs (fraction of flow entering the most concentrated 10% of the filter strip) was set to 0.5 for both.

3.2 Contour farming

Contour farming is a farming method where crops are planted, tilled, and harvested along the natural contours of the land. This technique improves water absorption into the soil and minimizes surface runoff, effectively reducing soil erosion and the amount of nonpoint source pollution entering streams, especially during heavy rain events (Liu et al., 2013). In this project, this conservation practice was implemented in all agricultural areas of the Mar Menor watershed using the land use management module of SWAT+.

3.3 Fertilizer Reduction

According to several authors (Lopez-Ballesteros et al., 2023b; Risal and Parajuli, 2022), reducing fertilizer application can improve the quality of nearby water bodies. For the implementation of this BMP, a 20% reduction in all applied fertilizers, including nitrogen and phosphorus, was proposed in the Mar Menor watershed. This reduction aligns with the objectives of the European Commission (EC, 2020) and the recommendations of the Code of Good Agricultural Practices of Murcia (BORM, 2018).

3.4 Crop rotation management

Crop rotation management involves modifying the standard crop rotation schedule of the study area from three to two crops, as established by the BOE (2020). The implemented BMP considers the removal of cantaloupe from the crop rotation schedule primarily due to economic criteria (Puertes et al., 2021).

3.5 Agricultural BMPs

In this project, a combined agricultural BMP scenario was simulated by combining all the previous individual BMPs. This approach allows us to understand the synergistic effect of BMPs when applied together and is usually implemented in agricultural areas to control pollution (Uniyal et al., 2020). To simulate this combined scenario, all the individual BMPs were simultaneously implemented in the SWAT+ model of the Mar Menor.

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Results

4.1 SWAT+ Mar Menor model

4.1.1 Sensitivity analysis

As can be observed in Table 4, the multi-variable sensitivity analysis carried out with SWATplus-CUP showed that of the 14 SWAT+ parameters evaluated, only two had a P-Value below 0.1, making these statistically significant to variations in actual evapotranspiration and soil moisture. These SWAT+ parameters are Perco and BD, which were then included in the calibration process due to their high sensitivity.

Table 4. P-Values of the sensitivity analysis.

Parameter	P-Value
Perco.hru	<0.1
BD.sol	<0.1
CN3_swf.hru	0.14
Deep_seep.aqu	0.16
AWC.sol	0.19
Sp_yld.aqu	0.27
K.sol	0.47
Epco.hru	0.50
CN2.hru	0.60
Esco.hru	0.63
Revap_co.aqu	0.69
Flo_min.aqu	0.85
Revap_min.aqu	0.89
Alpha.aqu	0.93

4.1.2 Calibration and validation

For the model calibration, a total of 10 years (2003-2012) were selected, and for validation, another 10 years (2013-2022) were chosen. This follows an approach of using half of the simulation period for calibration and half for validation, excluding the warm-up period (2000-2002). Through the use of SWATplus_CUP, the automatic calibration was divided into two iterations of 500 simulations each, a total of 1000 simulations. Dividing the total number of simulations into two iterations allows for an adjustment of the initial range of the selected SWAT+ parameters (Table 5). Besides the two most sensitive parameters identified in the sensitivity analysis, four additional SWAT+ parameters (CN2, Esco, Epco and AWC) were selected for automatic model calibration based on previous modeling experience in the study area (Lopez-Ballesteros et al., 2023b).

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Table 5. Range and adjusted values of the calibrated SWAT+ parameters.

Paremeter	Range	Adjusted value
Perco	0 – 1	0.96
BD	-20% – 20%	+6.72%
CN2	-20% – 20%	+6.31%
Esco	0 – 1	0.47
Epco	0 – 1	0.25
AWC	-20% – 20%	+13.25%

During the calibration procedure, four of the most common statistics were chosen as objective function (R^2, NSE, PBIAS, and KGE), resulting in a multi-objective function. Figures 1 and 2 graphically illustrate the performance of the SWAT+ model in simulating the actual evapotranspiration and soil moisture in the Mar Menor watershed for the calibration and validation period on a monthly time step.

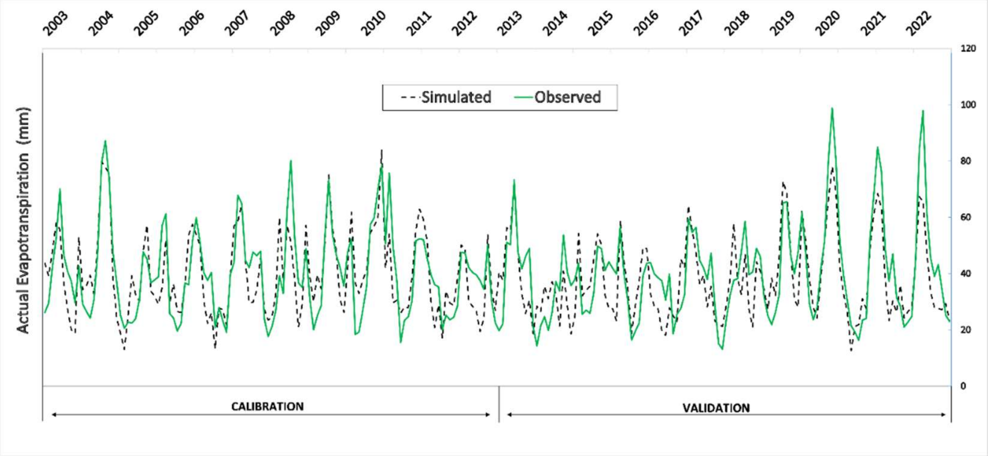

Figure 1. Comparison of monthly observed and simulated actual evapotranspiration.

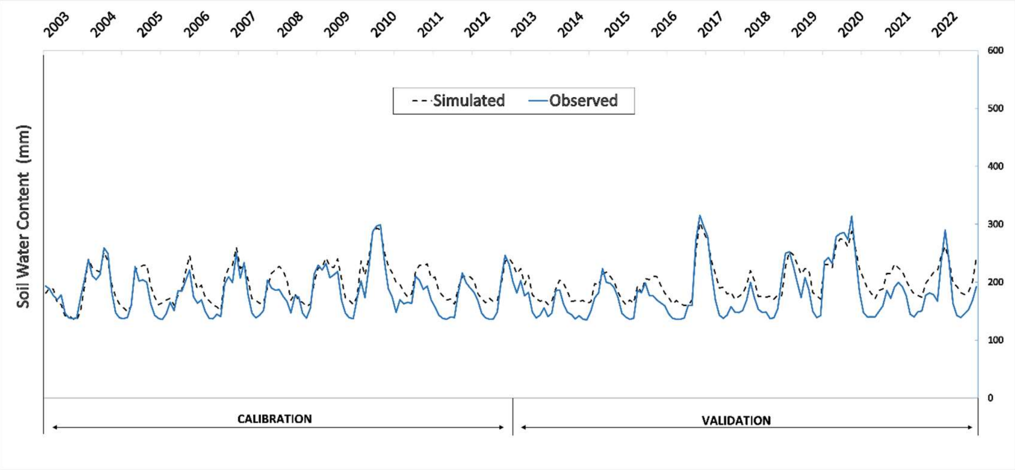

Figure 2. Comparison of monthly observed and simulated soil moisture.

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The SWAT+ model of the Mar Menor successfully captures the trend and magnitude of both actual evapotranspiration and soil moisture. These results were also obtained from a statistical perspective, as shown in Tables 6 and 7.

Table 6. Monthly calibration and validation of the actual evapotranspiration statistical values.

Period	R^2	NSE	PBIAS	KGE
Calibration	0.62	0.59	1.86 %	0.77
Validation	0.63	0.61	5.89 %	0.73

Table 7. Monthly calibration and validation of the soil moisture statistical values.

Period	R^2	NSE	PBIAS	KGE
Calibration	0.81	0.81	-0.11 %	0.85
Validation	0.87	0.81	-2.99 %	0.72

Tables 6 and 7 demonstrate that the SWAT+ model of the Mar Menor basin performed satisfactorily during both the calibration and validation periods for monthly actual evapotranspiration and soil moisture simulations, according to the statistical criteria proposed by Moriasi et al. (2015) and Kouchi et al. (2017).

4.1.3 Water balance

The average annual water balance of the Mar Menor basin is shown in Figure 3. The basin has an average annual precipitation of 291.5 mm, which, combined with an average annual irrigation of 240.37 mm, allows the actual evapotranspiration to reach 442.48 mm/year. The ratio of 1.52 between precipitation and evapotranspiration is characteristic of areas with a high percentage of irrigated agriculture such as the Mar Menor watershed. Regarding flow generation, it is observed that almost 70% of the total water generated by the basin comes from surface runoff (27.53 mm). This is typical in semi-arid regions with low precipitation concentrated in extreme storm events. Similar water balance results have been obtained in other studies of the Mar Menor basin (Senent-Aparicio et al., 2021).

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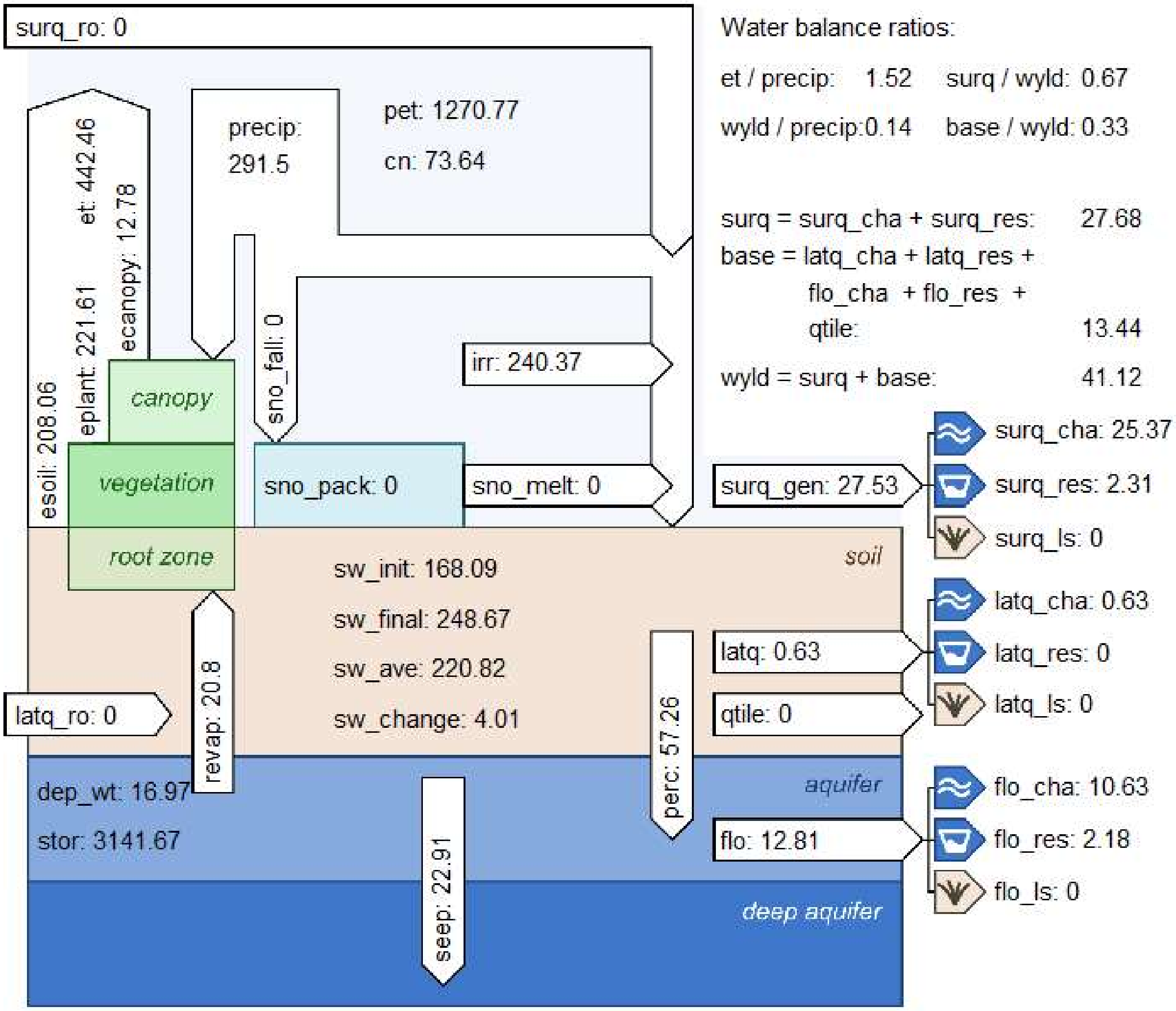

Figure 3. Water balance simulated by the SWAT+ model of the Mar Menor using SWATdoctR (Plunge et al., 2023).

4.1.4 Non-point source pollution

In this new version of the SWAT+ model of the Mar Menor watershed, the amount of sediments and nutrients entering the coastal lagoon was also assessed. For sediments, an average annual value of around 1,927 tons/year was simulated. Regarding nutrients, the model showed an average annual input of 407 tons/year of total nitrogen and 50.6 tons/year of total phosphorus. Similar values for both sediments and nutrient inputs to the Mar Menor were reported by Garcia-Pintado et al. (2007). These sediment and nutrient average annual values were used as the baseline scenario for comparison with the evaluated BMP scenarios.

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4.2 GOTM-WET model performance

4.2.1 Comparison with long-term monitoring

For the GOTM-WET model, the latest calibrated model fit (Fig. 4) is a clear improvement over the uncalibrated fit that was shown in the original 3.2 Deliverable. The temperature was simulated really well (already in the uncalibrated fit), which is rather unsurprising seen the shallow depth of the lagoon, but since a reanalysis meteorological product was used, it is an indication that the ERA5 weather dataset performs well, at least for the location of the Mar Menor. The fit for salinity has improved compared to before the calibration and is accurate in the calibration period, but the validation period shows that there is a risk of the simulations drifting away from the observations. Since 2023 and the second half of 2022 were especially dry, the drift could be the result from wrong estimations of exchange through the channels or the parameterisation of evaporation in GOTM (see section "Validation of exchange with the Mediterranean Sea"). However, for most of the simulation, salinity levels were close to observations, and even the mismatch in 2023 is unlikely to influence stratification patterns.

Another clear improvement is the oxygen concentration (Fig. 4), although most of the time the concentration oscillates around saturation levels, and so are comparably straightforward to simulate. Of particular interest, however, are periods when hypoxia (e.g. < 4 mg/l) occurs, which happened several times in the long-term monitoring record – although this is probably more common but requires high-frequency measurements to observe (see section "Comparison with buoy data"). Often, stratification is a primary contributor to these hypoxic events. Figure 4 is showing all values at 3.5 m depth, which is representative for the conditions over the entire depth of the lagoon for the majority of times. However, if we look at an indication of stratification (Schmidt stability: Schmidt, 1928; Idso, 1973), we see that there are indications of stratification events in the Mar Menor – a few intense (arbitrarily defined as >30 J/m^2) events and more common minor occurrences (Fig. 5). Simulations and observations agree that the intense events are driven by salinity stratification, while the smaller variations are solely due to temperature stratification. The long-term monitoring is too infrequent to make conclusions about the durations of such events, but the simulations suggest that while minor stratification events typically last only a short while (within one day or at most a few days), the 2019 event lasted 25 days (number of days consistently above 10 J/m^2), and indeed coincided with a mass mortality event in the Mar Menor (Zamora-López et al., 2023). However, such events are rare. The model is not far off for oxygen and stratification during the calibration period, though the simulated stratification event in the winter of 2016/2017 was probably not as intense or long-lasting. The hypoxic event in 2021 in the validation period was missed though (long-term monitoring did not suggest that stratification was the cause), and some short-lived salinity stratification events in 2023 were not captured either. Time scales of oxygen and stratification dynamics in a shallow and hyper-productive system as the Mar Menor are short-lived and therefore difficult to simulate. Our model shows potential to reproduce several of these events but is bound to also fail to predict some events.

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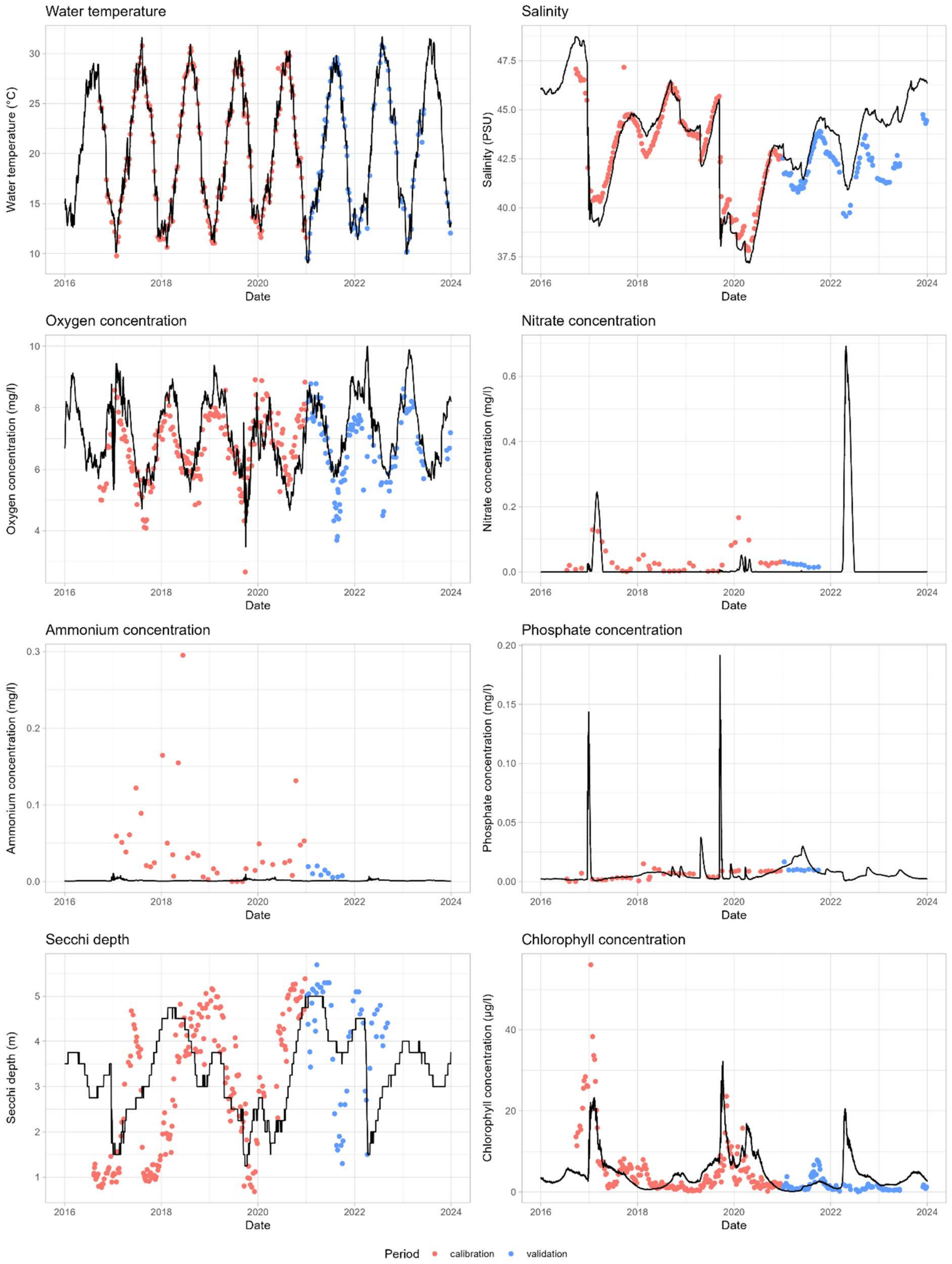

Figure 4. Comparison of the GOTM-WET simulation (black lines) and observations (dots, red = calibration, blue = validation) for water temperature, salinity, oxygen, nitrate, ammonium, phosphate, Secchi depth, and chlorophyll. All values are taken from 3.5 m depth (except Secchi depth). The validation with the high-frequency buoy observations is not included in this figure and is described in the section "Comparison with buoy data".

Figure 5. Schmidt stability in the Mar Menor, simulated (black line) and derived from temperature and salinity observations (long-term monitoring, pink dots).

At first glance, dissolved inorganic nutrient concentrations (ammonium, nitrate, phosphate) are surprisingly low for a eutrophic system such as the Mar Menor (Fig. 4), which is largely because available nutrients are quickly taken up by the food web. Observations and simulations of nitrate and phosphate therefore show mostly low values, interrupted by spikes that are caused by inflow events. The model reproduced this arguably well (an indication that also the SWAT+ model reproduced the timing of the intense inflow events quite accurately), though the precise intensity could be off, and the two high simulated peaks in the phosphate concentration could not be validated as they didn't coincide with measurements. The model failed to reproduce the observed dynamics in ammonium, which frequently showed elevated concentrations whereas the model showed almost no increases.

The dynamics of Secchi depth and chlorophyll a were largely mirrored (Fig. 4), indicating that much of the turbidity was caused by phytoplankton biomass. The model simulated the dynamics of both variables rather well, although it missed some important events. Most notable is a turbidity peak at the end of 2018 that the model failed to reproduce. Satellite images show a distinct green hue in the lagoon, indicating that the turbidity is indeed caused by phytoplankton, but the chlorophyll measurements, although they increase somewhat, do not reflect the large effect on Secchi depth. Perhaps this is caused by a different species composition and/or the formation of a surface scum, so that the chlorophyll a measurements sampled underneath the main concentration of biomass. Since the model only simulates one phytoplankton group, it was unable to fit this event. Reversely, the model simulated a bloom in 2022 that did not occur in the long-term monitoring. A low-intensity

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but long-lasting inflow event seemed to cause this model response, but in reality, either this inflow event might not have been so strong, or nutrients were taken up in another way, for example by macrophytes.

We did not have observations of zoobenthos biomass and could only compile summer macrophyte biomass estimates for 2016-2018 (Ruiz-Fernández et al., 2020; Belando et al., 2021; Bernardeau-Esteller et al., 2023), and therefore these are not presented in Fig. 4. However, both have a prominent role in the lagoon dynamics according to our model, with zoobenthos biomass estimates of about 2.5 gDW/m^2 and macrophytes commonly having less than 100 gDW/m2 but spiking in response to nutrient additions to > 200 gDW/m2 (though showing a slower response than phytoplankton). The macrophyte estimates roughly correspond to the values compiled from literature but remain difficult to validate. Still, observations by divers confirm abundant vegetation in the lagoon in the past years and both macrophytes and other zoobenthos are known to play an important role in the nutrient regulation of the lagoon (Lloret & Marín, 2009), although the 2015 mass mortality event shows that they do not have infinite resilience to nutrient addition (Belando et al., 2017).

4.2.2 Comparison with buoy data

The high-frequency (hourly observations averaged to daily values) buoy data of water temperature, oxygen, and chlorophyll were compared to the model for the period October 2022 until the end of 2023 (Fig. 6). Some data gaps are due to sensor failure or otherwise unrealistic values that were removed during data cleaning. The oxygen data were bias-corrected to the long-term monitoring, though some uncertainty remains: for example, towards the end of 2023, the 3m sensor showed consistently higher O_2 values than the 1m and 6.5m sensors, while after the bias-correction this was reversed (Fig. 6), although all three sensors should show similar O2 values during mixed periods.

The fit for water temperature was, like the long-term monitoring, very good, with only a few very short periods where the difference exceeded 1 °C. For oxygen, the fit was rather good as well, though the main observation is that the observations (even when averaged over a day) are much more variable than is shown by the model. Nevertheless, the model can simulate the long-term trend well. The deepest oxygen sensor captured a few days with lower deep-water oxygen, pointing to hypoxia for at least part of those days, and a more sustained period in early September 2023 (not accompanied by pronounced temperature stratification, Fig. 3). Such short periods are bound to occur more frequently in the Mar Menor but are missed by low-frequency sampling. The model, however, was not able to reproduce these events. This is a challenge with any model (process-based, but certainly also data-driven) that needs to be trained on observations: if the training data (in our case, the low-frequency long-term monitoring) does not contain a lot of events, it will be difficult to create a model that can simulate them. Our model did simulate some periods with oxygen drawdown (Fig. 4) but is likely to miss many of such events that occur in the lagoon and that can only be reliably observed using high-frequency sensor data.

The comparison with chlorophyll data occurred over a shorter period than for the other variables, and although model and observations are in the same order of magnitude, the model did not fit the dynamic in this period well. The model is just recovering from a peak in chlorophyll and misses an apparent increase in December 2022, although this peak was not seen in the long-term monitoring

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(Fig. 4, Fig. 6). Another chlorophyll peak in the simulations, in the fall of 2023, could not be compared with buoy data, although satellite data do suggest some phytoplankton activity in the western part of the lagoon.

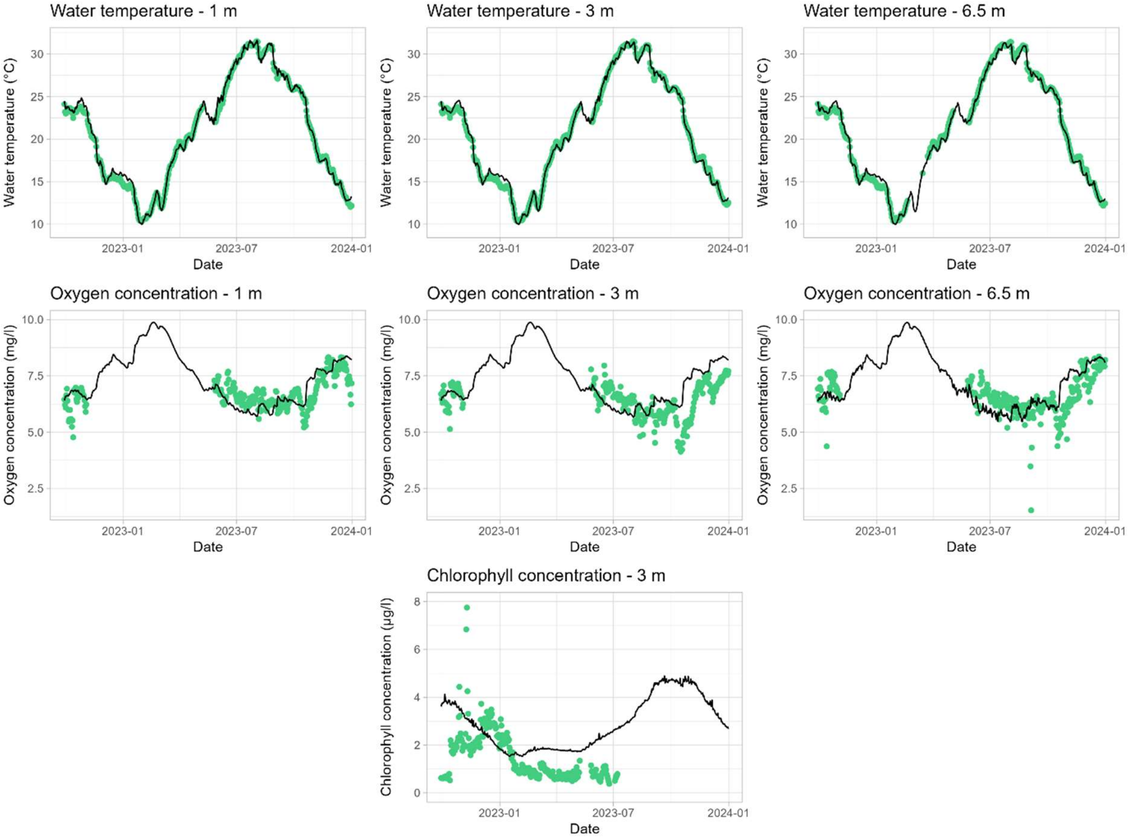

Figure 6. Comparison of the GOTM-WET simulation (black lines) with daily-averaged buoy observations (green dots) for water temperature, oxygen, and chlorophyll at different depths. The oxygen sensor data were bias-corrected to the long-term monitoring data.

4.2.3 Validation of exchange with the Mediterranean data

A separate validation was performed for the exchange between the Mar Menor and the Mediterranean Sea, as this is one of the larger uncertainties that is caused by the chosen 1D approach. The 1D model simulates horizontal averages of the entire lagoon and the residence time of the lagoon is close to 1 year, so that short-term variations in the inflow do not influence the model a lot, but it is important to get the seasonal pattern in exchange correct to get e.g. nutrient and salinity budgets correct.

The first validation we did, was to compare our simulated water residence time with previous studies. We computed residence time by dividing the total volume of the lagoon by the evaporation plus the outflow through the channel (only the outflow, not the inflow that was added to simulate the subdaily exchange). Our value of 309 days was very close to the 318 days that was reported by

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Ghezzo et al. (2015) based on 3D model simulations, which is an indication that our model performs adequately in simulating the exchange rate on a yearly scale.

For the seasonal cycle, we compared simulated average discharge rates (i.e. inflow – outflow) with SMARTLAGOON camera-derived measurements in the Albujón and Marchamalo channels (using a similar system as Peña-Haro et al., 2021). We could only compare model simulations with observations between March and October 2023, but the comparison suggested that our model simulates the correct direction and seasonality of the flow, but may underestimate exchange in the summer period (Fig. 7). Moreover, although outside our aim to simulate, the observations showed a stronger variation between days than our model. In short, our simplified approach to parameterise the exchange does a reasonable job on a yearly and seasonal time scale (also considering its simplicity), but real dynamics are more variable and complex. This is unlikely to have a strong negative influence on our model, because these shorter dynamics will have only a small influence on the horizontally-averaged concentrations, but it could lead to discrepancies between observations and simulations in some periods.

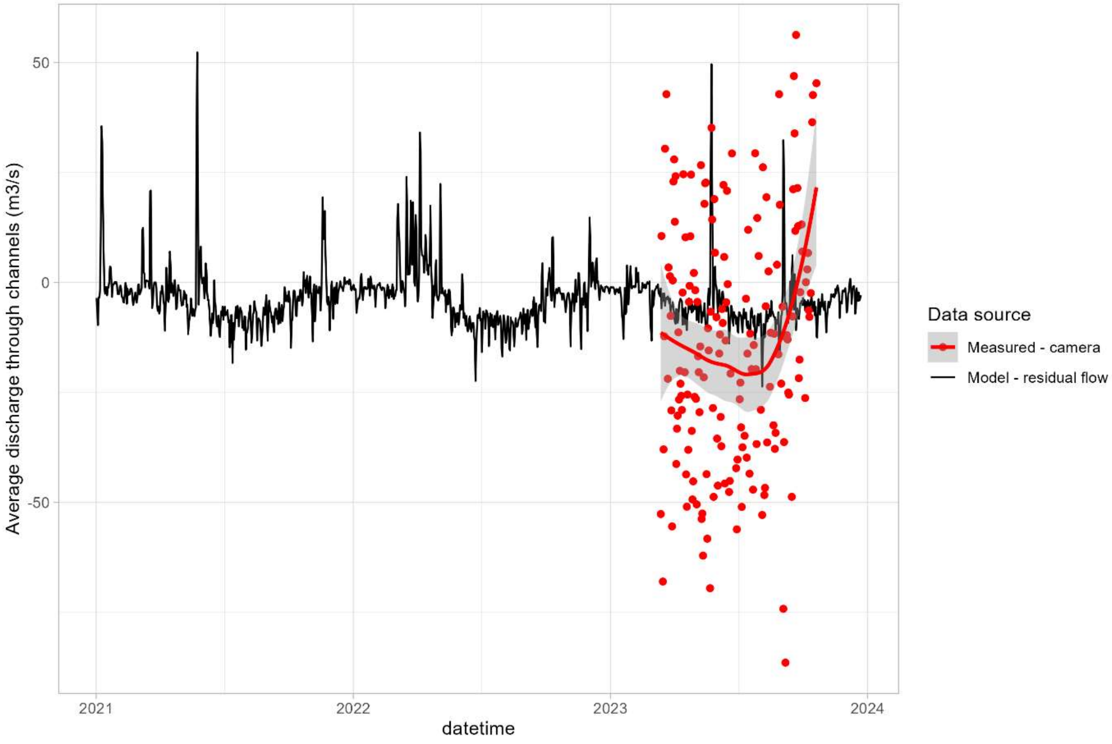

Figure 7. Comparison of the net exchange rate between the Mediterranean Sea and the Mar Menor between the GOTM-WET simulation (black line) and the camera-derived discharges (red dots). A loess smoothing function has been applied to the camera discharges, shown with the red line and the 95% confidence band in grey. Positive discharges indicate water movement from the lagoon into sea, and negative the reverse.

The salinity concentrations that are drifting away from the observations in the validation period (Fig. 4) are another indication that the exchange is not parameterised perfectly; more inflow into the lagoon (therefore getting closer to the camera observations) would bring the simulations more in line with the salinity observations, but the model could not pick up this behaviour during the calibration period. A calibration period that includes an extended dry period would likely perform better. The larger the salinity difference between the lagoon and the sea, the more effect the exchange will have on the salinity levels, so it is to some extent self-correcting, and therefore even in future climate scenarios, it is unlikely that the salinity trails off to impossible values.

4.3 Simulated scenarios

4.3.1 Impact of BMPs on the water quality of the Campo de Cartagena watershed

Regarding the results of the simulated BMP scenarios, Table 8 shows the effectiveness of these BMPs in reducing sediments and nutrients entering the Mar Menor. Vegetative Filter Strips and Contour Farming have a low impact on the reduction of total nitrogen. These low values may be associated with the behavior of nitrate, which are more prone to being lost through infiltration rather than surface runoff. Similar trends were found by Puertes et al. (2021). In contrast, the behavior of phosphorus is more closely associated with particulate surface runoff, and a notable proportion may be lost through washout. Therefore, the effectiveness of Vegetative Filter Strips in reducing total phosphorus is high due to phosphorus being retained by the vegetative barriers. The Fertilizer Reduction and Crop Rotation Management BMPs demonstrated high efficiency in reducing nutrient inputs to the Mar Menor. These results can be associated with the direct reduction in the amount of applied fertilizers. Furthermore, the BMP of Crop Rotation Management allows for a cover crop during the off-season, which acts as a nutrient sink. When all BMP scenarios are applied together (Agricultural BMPs), a synergistic effect is observed, resulting in high efficiency in reducing nutrient inputs to the Mar Menor. However, due to the predominantly low slopes in the study area, the impact of BMPs on reducing sediment inputs to the Mar Menor is moderate.

Table 8. Effectiveness of the simulated BMP scenarios.

	Effectiveness (%)		
BMP Scenario	**Sediment**	**Total Nitrogen**	**Total Phosphorus**
Vegetative filter strips	1.5	2.5	43.3
Contour farming	0.7	0.9	3.3
Fertilizer reduction	-	23.6	18.2
Crop rotation management	0.2	40.2	37.0
Agricultural BMPs	1.7	55.4	67.5

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4.3.2 Impact of BMPs on the lagoon

To evaluate the responses of phytoplankton biomass (Chl a) in the lagoon to different best management practices (BMP), we used the daily scale output data from the GOTM-WET model for the period 2003 – 2022 of Chl a and nutrients within the lagoon. Periods of high suspended chlorophyll a concentration, attributable to harmful algal blooms (HABs), were identified as those above the 90th percentile, with chlorophyll concentrations equal to or greater than 8.1 µg/L (Fig. 8).

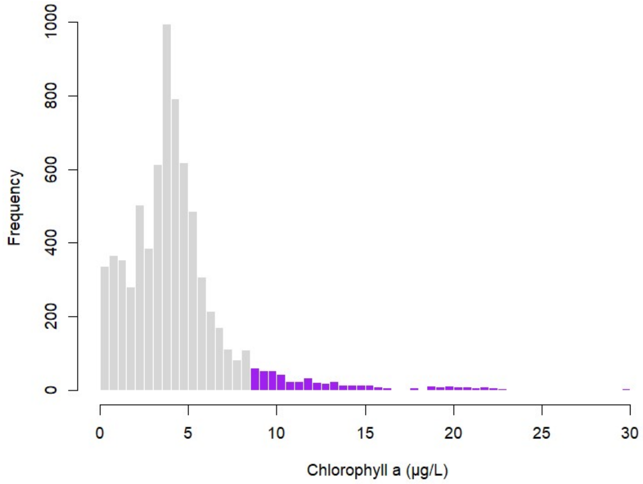

Figure 8. Histogram of chlorophyll a data frequency for the period 2003-2022 in Mar Menor from WET outputs. Bars in purple indicate chlorophyll a over the 90-percentile corresponding to values ≥ 8.1µg/L.

From 2003 to 2022, several periods of HABs, with chlorophyll a values above this limit occurred in baseline conditions (without BMP application) (Fig. 9).

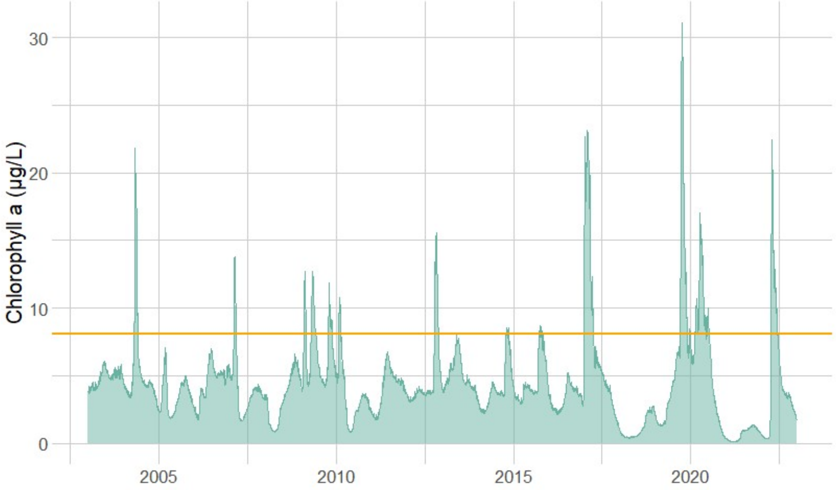

Figure 9. Chlorophyll a for the period 2003 - 2022 in Mar Menor from WET outputs for baseline conditions (no BMP applied). The orange line indicates the limit of 8.1µg/L (> 90-percentile) used to define HABs.

Different BMPs showed varying effectiveness in controlling HABs, which were reflected in different decreases in Chl a concentration and subsequently led to a reduction in days with the presence of HABs compared to the baseline. The BMPs of vegetation strips and crop rotation had a significant effect in reducing Chl a concentrations (Fig. 10, Table 9). The reduction of chlorophyll by fertilizer reduction had a lower effectiveness (reduction in Chl a= 12.8%) while contour farming had almost

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no effects on the intensity and persistence of HABs (Fig 10, table 9). As expected, the combination of all BMPs had the greatest effectiveness in reducing HABs, leading to a reduction of 50% in Chl a concentrations during HABs periods (values ≥ 8.1μg/L) and a reduction of 81% in the number of days with levels above the HAB definition limit (Table 9).

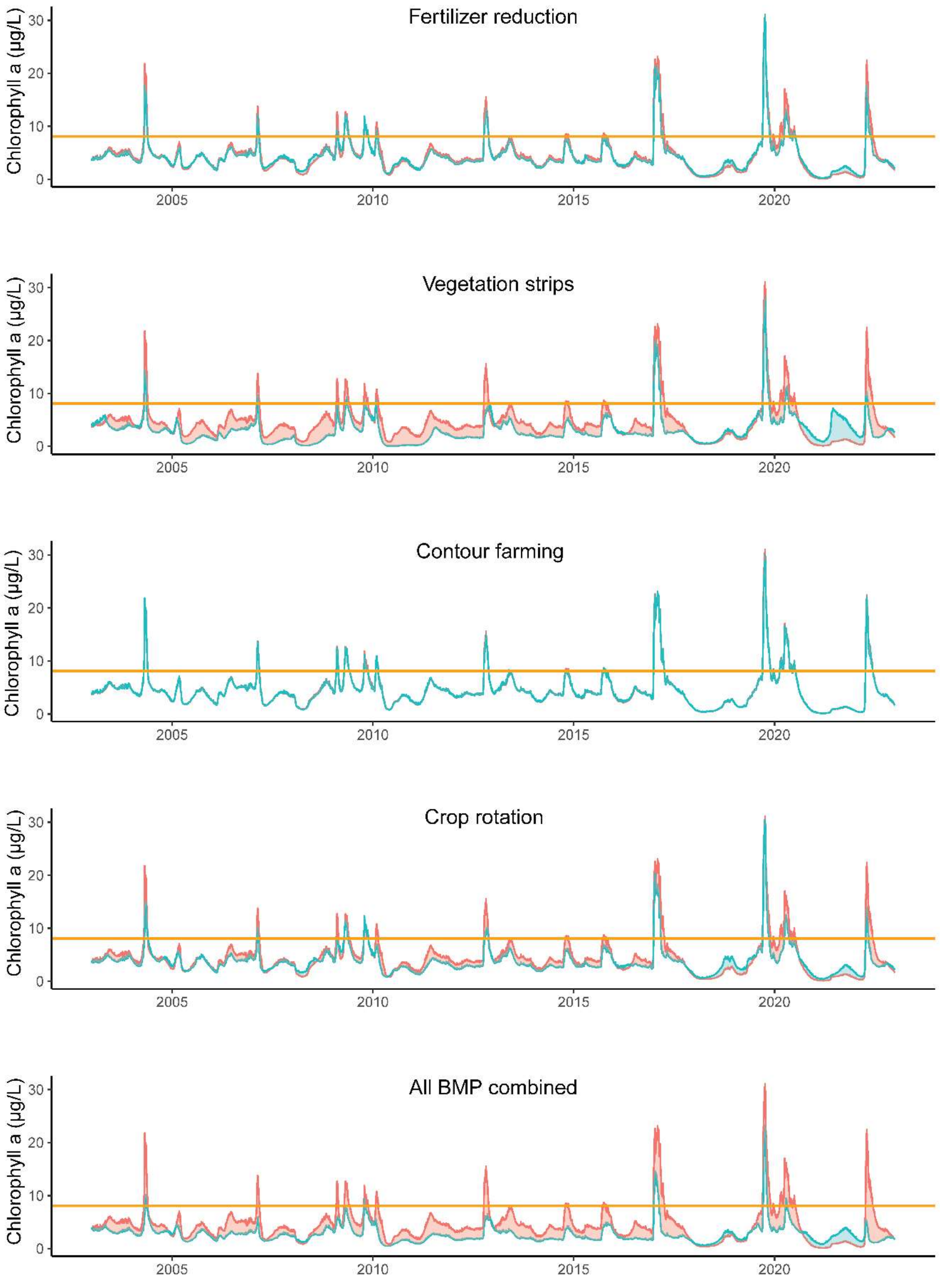

Figure 10. Chlorophyll a for the period 2003-2022 in Mar Menor from WET outputs for the different BMP (green line) compared to the baseline conditions (red line) with no BMP applied. The orange line indicates the limit of 8.1µg/L (> 90 percentile) used to define HABs. Red areas indicate a decrease in chlorophyll a values when the corresponding BMP is applied compared to the baseline, while green areas indicate an increase in chlorophyll a.

The most effective BMPs in reducing HABs were associated with a reduction in nitrogen in lake (Table 9). Here, the combination of all BMPs reduced TN by 68%, which was mostly explained by the reduction of NO_3 by 47% by crop rotation, and of NH_4 by both vegetation strips and crop rotation by 22% and 25% respectively. The reduction in TP of these BMPs was also high, but mostly associated with TP that includes particulate forms of P, which includes phytoplankton itself, while the reduction was low for bioavailable PO_4 for algal growth (Table 9).

Table 9. Effectiveness of the simulated BMP scenarios in reducing HABs intensity and persistence, and nutrient concentrations (N and P) for the period 2003 - 2022 in Mar Menor. BMP: 1. Fertilizer reduction, 2. Vegetation strips, 3. Contour farming, 4. Crop rotation and 5. All previous BMP combined. All indicators refer to HAB periods with Chl a ≥ 8.1 µg/L. Indicators: Nº Days: number of days with HAB, Days: percentage of days with HAB, Reduction in days: percentage of reduction of days with HAB, Reduction: percentage of reduction in Chl a and concentration of nutrient forms.

Indicator	Baseline	Fertilizer reduction	Veg. strips	Contour farming	Crop rotation	All BMP
Nº Days	678	494	244	639	370	127
Days (%)	9.3	6.8	3.3	8.8	5.1	1.7
Reduction in days (%)		27.1	64.0	5.8	45.4	81.3
Reduction in Chl a (%)		12.8	34.5	1.6	24.9	50.3
Reduction NH_4 (%)		12.7	22.1	1.7	25.1	41.6
Reduction NO_3 (%)		30.9	16.0	1.7	46.5	59.3
Reduction TN (%)		29.3	24.2	3.1	47.4	68.4
Reduction PO_4 (%)		4.4	10.2	-1.2	11.3	28.4
Reduction TP (%)		15.7	35.7	0.5	31.8	58.5

Generalized least squares models indicated that during HAB periods, Chl a was mostly associated with NH_4 concentrations (t: 13.8, $p < 0.001$) and to a lesser extent with PO_4 (t: 5.5, $p < 0.001$) and NO_3 (t: 2.8, $p = 0.005$). This would indicate that HAB dynamics in the Mar Menor are largely explained by N concentrations in the lagoon, and particularly by NH_4. However, this association showed temporal differences (Fig. 11). In HAB events of 2017 and late 2019, PO_4 appears to play a predominant role in triggering the onset of the HAB, while NH_4 and NO_3 increase after the increase in Chl a (Fig.

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11). Likewise, peaks of PO_4 are observed at the beginning of blooms in 2009, 2012, 2014, and 2015 (Fig. 11). This indicates that the availability of PO_4 is an important factor triggering the bloom, and that nitrogen would subsequently maintain the high algal biomasses of the HAB (Fig. 11). On the other hand, in the last observed HAB corresponding to 2022, PO_4 concentrations were high since 2021 without the presence of HAB, and it is instead the increase in N, and particularly in NO_3, that seems to trigger the HAB (Fig. 11).

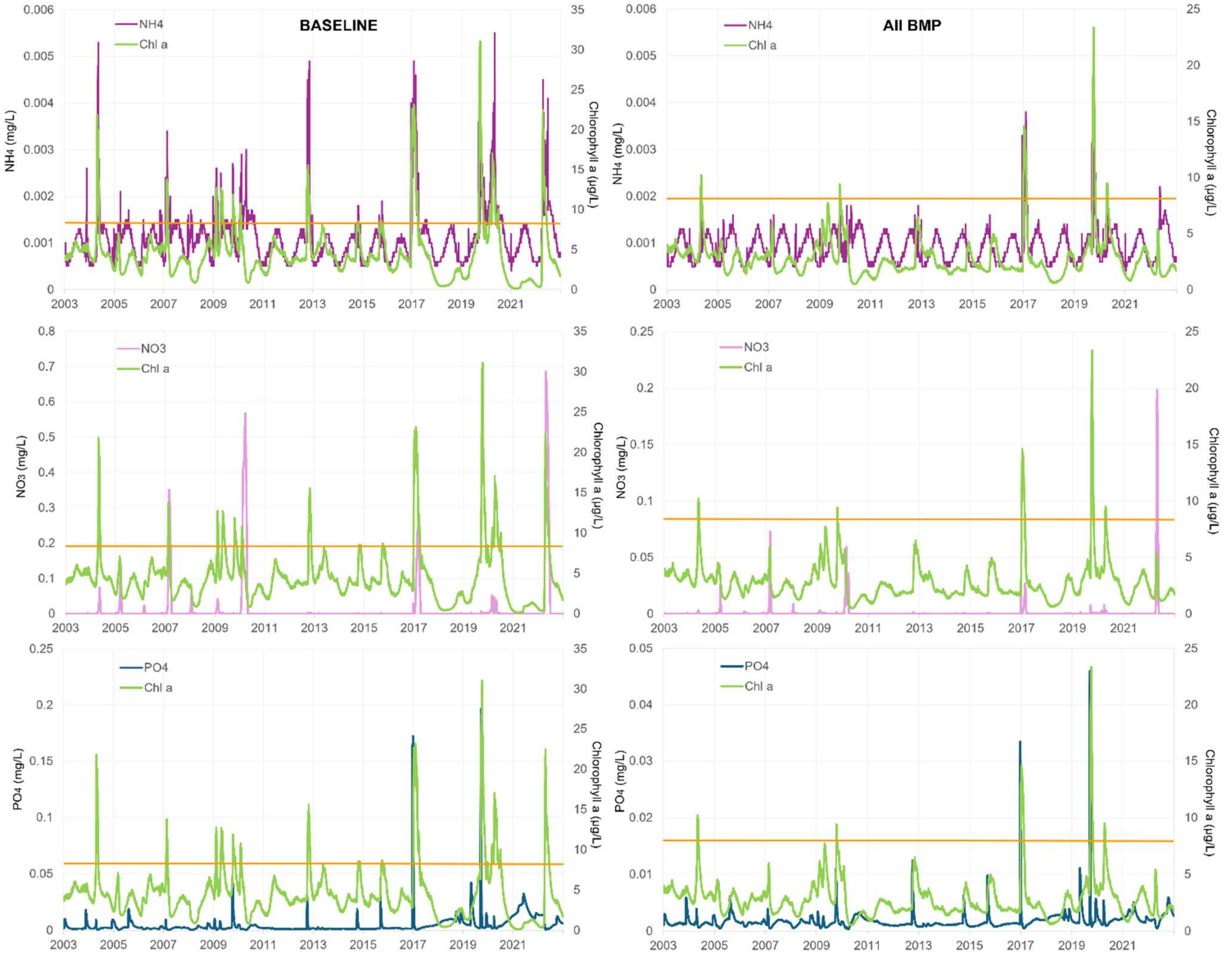

Figure 11. Nutrients (NH_4, NO_3 and PO_4) and chlorophyll a for the period 2003 – 2022 in Mar Menor from WET outputs for the baseline conditions and combination of all BMP.

BMPs have important effects in reducing HABs by limiting nutrients, where the combination of all BMPs reduces HAB events from 11 to 5 during the simulation period, suppressing some of high levels of Chl a such as those of 2004 and 2022 (Fig. 11). The decrease in these HABs was mediated by an effect of the BMPs particularly on NH_4, while the effect on PO_4 was minor (Fig. 11). Our results indicate that the dynamics of HABs in the Mar Menor are influenced by PO_4 levels as a necessary condition to trigger the HAB, but that high levels of Chl a (≥ 8.1µg/L) are maintained by high availability of nitrogen, generally as NH_4 but more recently also as NO_3. This analysis of the effect of BMPs on HABs in the Mar Menor will constitute a manuscript to be submitted during 2024.

4.3.3 Impact of Climate Change

Regarding temperature, all five GCMs show a uniform trend of increasing temperatures over time in the Campo de Cartagena area (Table 10), with a more pronounced rise under the severe SSP 5-85 scenario, averaging an increase of 3.84ºC by 2075-2099. This significant temperature rise could lead to desertification of the region. Regarding precipitation, the ensemble of GCMs indicates a general trend of decreasing precipitation in the Campo de Cartagena. The more aggressive SSP 5-85 scenario predicts a severe decrease in precipitation by about 19% in the far future.

Table 10. Annual average of precipitation and temperature, and number of days with torrential rainfall for each period and scenario of Campo de Cartagena.

	Temp (ºC)	ΔTemp (ºC)	Pcp (mm)	ΔPcp (%)	Extreme days
Historical	18.49	-	272.74	-	2
SSP 2-45 M	20.17	1.69	260.45	-4.5%	2
SSP 2-45 F	20.55	2.06	261.24	-4.2%	3
SSP 5-85 M	21.03	2.54	254.15	-6.8%	4
SSP 5-85 F	22.32	3.83	220.78	-19.1%	4

We consider it important to analyze the torrentiality of the events, evaluating the number of days with extreme rainfall defined by the World Meteorological Organization as precipitation exceeding 50 mm (WMO, 2008). Despite the overall reduction in precipitation, the models predict an increase in the intensity of torrential rainfall, particularly in the far future for both SSP 2-45 and SSP 5-85 scenarios. There is variability in predictions, indicating uncertainty about when and where this increase will be most pronounced (Fig. 12).

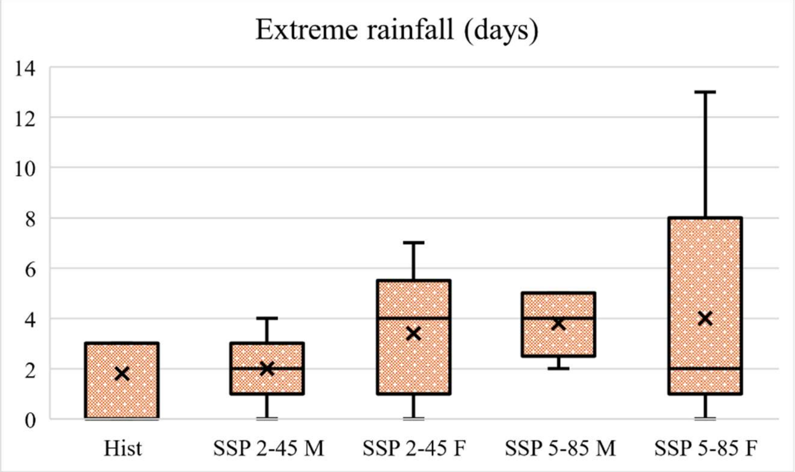

Figure 12. Predictions of the GCMs of the number of days with torrential rainfall for each period and scenario of Campo de Cartagena.

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Table 11. Annual average of hydrological variables of Campo de Cartagena for each period and scenario.

Hydrological variables	Historical	SSP 2-45 M	SSP 2-45 F	SPP 5-85 M	SSP 5-85 F
Inflow (mm)	0.621	0.567	0.586	0.556	0.474
Δ Inflow	-	-8.8%	-5.7%	-10.5%	-23.7%
Total N (tons)	573.057	543.905	575.183	556.267	355.075
Δ Total N	-	-5.1%	0.4%	-2.9%	-38.0%
Total P (tons)	11.012	13.124	25.222	17.607	25.826
Δ Total P	-	19.2%	129.0%	59.9%	134.5%
Sediment yield (t/ha)	0.027	0.029	0.041	0.035	0.036
Δ Sediment yield	-	4.4%	50.4%	27.0%	30.7%
Green water	657.412	655.464	648.210	647.736	618.146
Δ Green water	-	-0.3%	-1.4%	-1.5%	-6.0%
Blue water	129.766	112.828	105.122	104.064	73.546
Δ Blue water	-	-13.1%	-19.0%	-19.8%	-43.3%

Predictions show a decrease in both green water (GW) and blue water (BW) (Table 11 and Fig. 13), which are crucial for plants and human use. GW relates to evapotranspiration and soil water content, while BW includes water yield and aquifer recharge, both likely declining due to reduced precipitation. Inflow to the lagoon is also expected to decrease, though less so than BW, due to increased runoff from more frequent torrential events. BW is projected to decrease by about 19% under SSP 2-45 and about 43% under SSP 5-85 by the far future, while inflow reductions of around 6% and 24% respectively.

Increased runoff is reflected in a smaller decrease in inflow compared to BW and a rise in sediment yield. Phosphorus input to the lagoon, simulated by runoff in the SWAT+ model, is also expected to increase more than sediment. A decrease in nitrogen input to the lagoon is simulated, likely due to reduced water recharge to the aquifer, which is the primary nitrogen source. This reduction in nitrogen, along with decreased BW, will impact overall water availability, crucial for the region's predominantly irrigated agriculture.

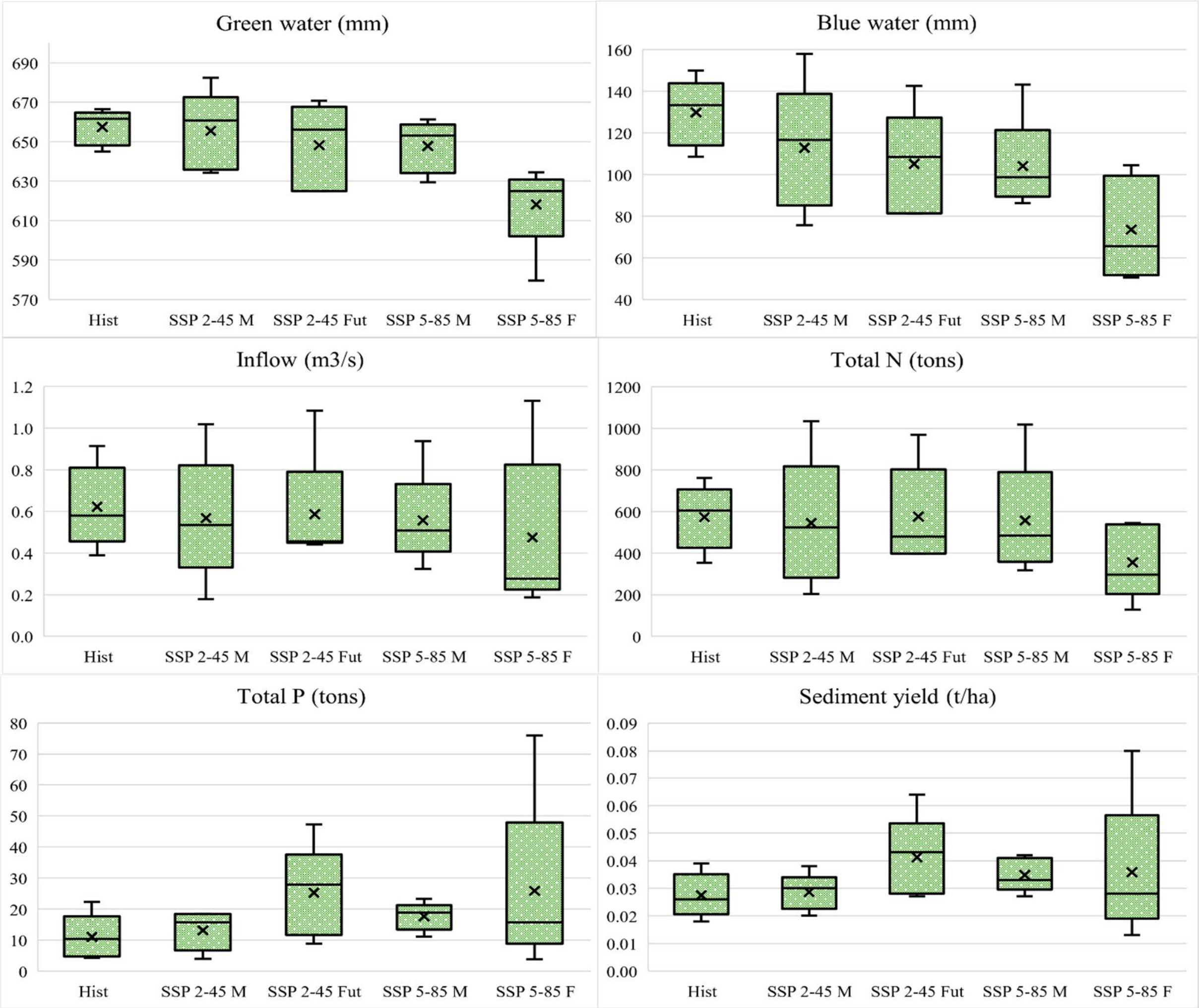

Figure 13. Predictions of the GCMs of annual average hydrological variables of Campo de Cartagena for each period and scenario.

Table 12. Annual average of water conditions affecting Mar Menor for each period and scenario.

Water conditions	Historical	SSP 2-45 M	SSP 2-45 F	SPP 5-85 M	SSP 5-85 F
Water temperature (Cº)	20.18	21.84	22.38	22.70	23.91
Δ Water temperatura (Cº)	-	1.7	2.2	2.5	3.7
Oxygen (g/m^3)	6.47	6.46	6.37	6.18	5.97
Δ Oxygen (g/m^3)	-	-0.02	-0.10	-0.29	-0.50
Total N (g/m^3)	0.080	0.071	0.075	0.063	0.042
Δ Total N (g/m^3)	-	-0.01	-0.01	-0.02	-0.04
Total P (g/m^3)	0.0021	0.0026	0.0040	0.0032	0.0043
Δ Total P (g/m^3)	-	0.0005	0.0019	0.0011	0.0022
Chlorophyll-a (mg/m^3)	0.1374	0.34	1.07	0.74	1.23
Δ Chlorophyll-a (mg/m^3)	-	0.2	0.9	0.6	1.1

Water temperature in the lagoon is expected to increase progressively (Table 12), particularly under the more severe SSP 5-85 scenario due to rising atmospheric temperatures. As for nutrients concentrations, phosphorus levels are also projected to rise, potentially doubling from 0.002 g/m³ to 0.004 g/m³ by 2075-2099, driven by increased runoff from Campo de Cartagena. In contrast, nitrogen levels are expected to decrease significantly due to reduced nitrate input from the aquifer. The largest reduction, around 50%, is anticipated under SSP 5-85, dropping from 0.08 g/m³ to 0.04 g/m³. Despite the decrease in nitrogen, chlorophyll-a levels are expected to rise, indicating an increase in phytoplankton and primary production. However, the rise in phosphate might alter the types of micro-algae who dominate the ecosystem, affecting the lagoon's biotic dynamics.

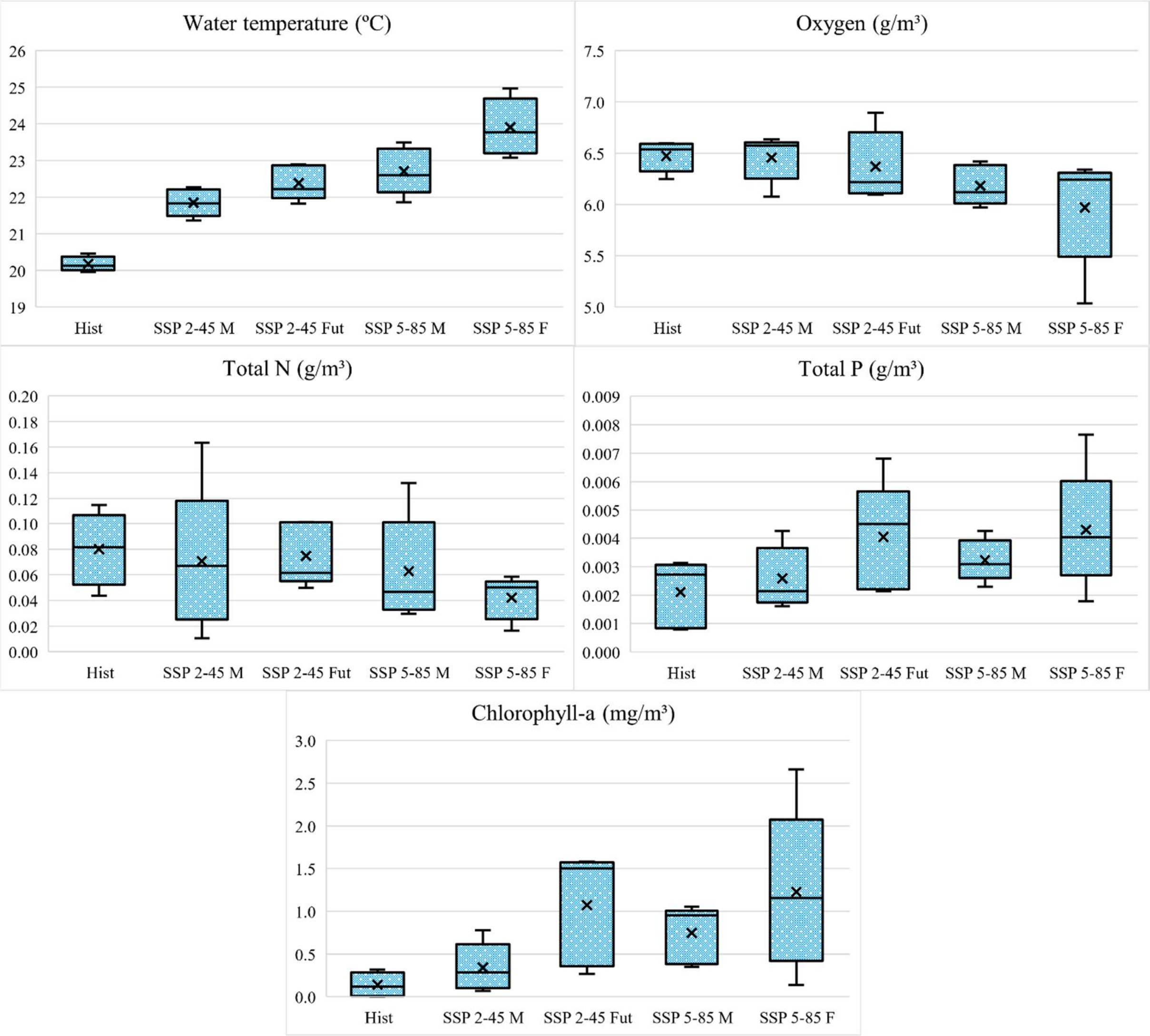

Figure 14. Predictions of the GCMs of annual average water conditions in Mar Menor lagoon for each period and scenario.

Oxygen levels in the lagoon are projected to decrease, with varying severity depending on the model (Figure 10). None predict severe hypoxia (oxygen levels below 2 g/m³) as an annual average, but specific hypoxia events could increase, particularly in the mid-term of the SSP 5-85 scenario (Table 13).

Table 13. Number of days for each period when extreme conditions are expected: chlorophyll-a concentration above 10 mg/m3 and oxygen concentration below 2g/m³.

	Historical	SSP 2-45 M	SSP 2-45 F	SSP 5-85 M	SSP 5-85 F
Blooms (days)	4	18	97	59	94
Hipoxia (days)	8	13	24	40	45

Hypoxia events, where oxygen concentration falls below 2 g/m³, are expected to increase, particularly under SSP 5-85. The number of days with chlorophyll-a concentrations exceeding 10 mg/m³ (indicating algal blooms) is also predicted to rise in the distant future for both scenarios.

4.3.4 Impact of Climate Change and BMPs on Floods

One of the main concerns is how climate change may affect flooding in Campo de Cartagena, more considering the increase of torrential events. Among all the BMPs simulated, contour farming has the greatest impact on flood reduction. As can be seen in Figures 15 and 16 the annual maximum daily flows could be significantly reduced if this BMP is applied.

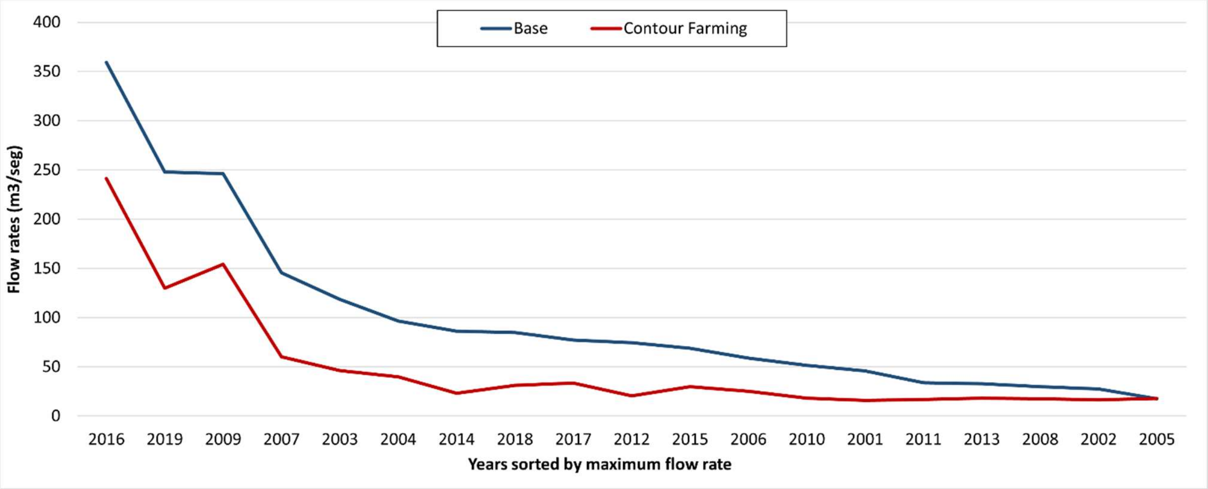

Figure 15. Annual maximum daily flow curve for the study period.

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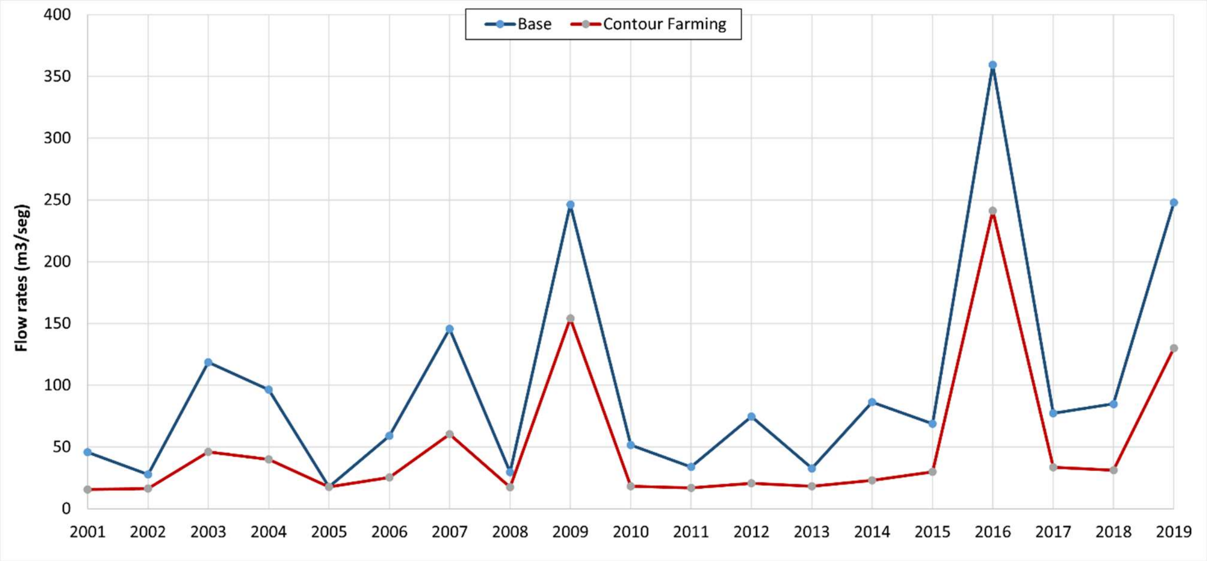

Figure 16. Simulated maximum daily flow rates (m^3/sec) for each year in order from highest to lowest.

When we compare the annual maximum daily flow simulated by SWAT+, the results indicate that for the simulated study period it can be reduced on average by about 49% by applying the crop planting BMP following contour lines (Fig. 15). In the most extreme events, such as those that occurred in 2009, 2016 and 2019, this reduction in peak flows is around 40% (Fig. 16), which would mean a significant reduction in flood damage. Analyzing the predicted maximum daily flow in each period (Fig. 17) indicates that it tends to increase in climate change scenarios, especially in the most aggressive one (SSP 5-85). An increase in the maximum daily flow would imply an increase in the magnitude of the floods that take place in the Campo de Cartagena when torrential events occur. However, this increase can be mitigated with the application of BMPs in the basin, as discussed in Figures 15 and 16.

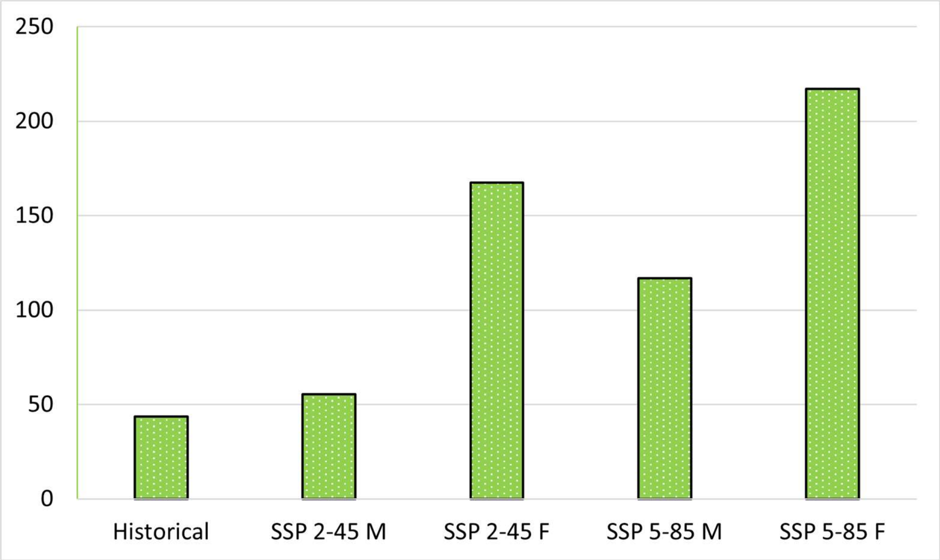

Figure 17. Prediction of the ensemble of GCMs for the maximum daily flow for each period.

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Conclusions

Related to the GOTM-WET model, the model presented here improved significantly relative to the uncalibrated version presented in Deliverable 3.2. Moreover, changes in the model code and model configuration allowed us to simulate more relevant processes and variables, and the extension to year 2023 meant that we could validate the model over a longer period and compare it using two other SMARTLAGOON products: the buoy data and camera-derived discharges. The model performance reveals that many aspects of the lagoon are simulated well, but also that certain variables and/or events are not (e.g. ammonium concentrations, or the end-of-2017 turbidity event), or that the model can describe the overall pattern of some variables but misses some aspects of it (e.g. the salinity levels and sea-lagoon exchange).

The GOTM-WET model is the first of its kind that has been applied to the Mar Menor and had to be trained on a limited number and duration of observations, and especially the boundary conditions of nutrients are highly uncertain. With biogeochemical models in particular, it is difficult to say when a model is “good enough”, but we consider this model to be satisfactory considering the approach and available resources, and definitely useful for future projections and scenario studies. Without a doubt, continued monitoring and data collection of other relevant variables can lead to further improvement of the models and simulation of additional variables that are relevant for the management of the lagoon (e.g. jellyfish or shifts in phytoplankton groups). The GOTM-WET model for the Mar Menor presented in SMARTLAGOON is a promising tool for management support and, coupled to the SWAT+ catchment model, can be used for long-term scenario studies regarding e.g. nutrient reduction or climate warming. It shows that coupled physical-biogeochemical models can be set up in such a system and linked to its surrounding catchment and the sea and demonstrates the potential of modelling and other data-driven tools to shed more light on the dynamics of the Mar Menor.

Climate change in the Campo de Cartagena is projected to cause rising temperatures, decreased overall precipitation, and more intense extreme rainfall events, leading to significant decreases in water availability (both green and blue water), increased runoff, sediment yield, and altered nutrient inputs to the Mar Menor lagoon. These changes will reduce the region's resilience to extreme weather events and cause significant changes in the lagoon: increases in water temperature and phosphorus levels, decreases in nitrogen and oxygen levels, and more frequent hypoxia events and algal blooms, further stressing an already damaged ecosystem. Implementing agricultural Best Management Practices (BMPs) can help preventing harmful algal blooms and hypoxia in the lagoon and mitigate some effects of climate change such as floods, by reducing the maximum daily flow rates.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101017861.

APPENDIX I: Bibliography

- Arnold, J.G., Bieger, K., White, M.J., Srinivasan, R., Dunbar, J.A., Allen, P.M. 2018. Use of Decision Tables to Simulate Management in SWAT+. Water, 10, 713. https://doi.org/10.3390/w10060713
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment Part I: model development. J. Am. Water Resour. As. 34, 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x
- Belando, M.D., Bernardeau-Esteller, J., García-Muñoz, R., Ramos-Segura, A., Santos-Echeandía, J., García-Moreno, P., Carreño, F., Ruiz, J.M., 2017. Evaluación del estado de conservación de las praderas de Cymodocea nodosa en la laguna costera del Mar Menor. 2014-2016. Informe del Instituto Español de Oceanografía y la Asociación de Naturalistas del Sureste. Murcia. 157pp.
- Belando, M.D., Bernardeau-Esteller, J., Paradinas, I., Ramos-Segura, A., García-Muñoz, R., García-Moreno, P., Marín-Guirao, L., Ruiz, J.M., 2021. Long-term coexistence between the macroalga Caulerpa prolifera and the seagrass Cymodocea nodosa in a Mediterranean lagoon. Aquatic Botany 173 103415 doi:10.1016/j.aquabot.2021.103415.
- Bernardeau-Esteller, J., Sandoval-Gil, J.M., Belando, M.D., Ramos-Segura, A., García-Muñoz, R., Marín-Guirao, L., Ruiz, J.M., 2023. The Role of Cymodocea nodosa and Caulerpa prolifera Meadows as Nitrogen Sinks in Temperate Coastal Lagoons. Diversity 15(2) 172 doi:10.3390/d15020172.
- Beven, K., 2006. A manifesto for the equifinality thesis. Journal of Hydrology 320(1-2) 18-36 doi:10.1016/j.jhydrol.2005.07.007.
- BOE. Boletín ofical del Estado, 2004. ORDEN APA/1657/2004, de 31 de mayo, por la que se establece la norma técnica específica de la identificación de garantía nacional de producción integrada de cítricos. Boletín Oficial del Estado: Spain. (In Spanish)
- BOE. Boletín ofical del Estado, 2020. Ley 3/2020, de 27 de julio, de recuperación y protección del Mar Menor. Boletín Oficial del Estado: Spain. (In Spanish)
- BORM. Boletín Oficial de la Región de Murcia, 2012a. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de lechuga. Boletín Oficial de la Región de Murcia: Murcia, Spain. (In Spanish)
- BORM. Boletín Oficial de la Región de Murcia, 2012b. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de melón y sandía. Boletín Oficial de la Región de Murcia: Murcia, Spain. (In Spanish)
- BORM. Boletín Oficial de la Región de Murcia, 2012c. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de bróculi. Boletín Oficial de la Región de Murcia: Murcia, Spain. (In Spanish)
- BORM. Boletín Oficial de la Región de Murcia, 2018. Ley 1/2018, de 7 de Febrero, de medidas urgentes para garantizar la sostenibilidad ambiental en el entorno del Mar Menor. Boletín Oficial de la Región de Murcia: Murcia, Spain. (In Spanish)
- Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., & Allen, P. M. 2019. Representing the connectivity of upland areas to floodplains and streams in SWAT+. JAWRA

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017861.

Journal of the American Water Resources Association, 55(3), 578-590. https://doi.org/10.1111/1752-1688.12728

- Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., Allen, P.M., Volk, M., Srinivasan, R., 2017. Introduction to SWAT+, a completely revised version of the Soil and Water Assessment Tool. J. Am. Water Resour. Assoc. 53, 115–130. https://doi.org/10.1111/1752-1688.12482
-
- EC. European Commission, 2020. Farm to Fork strategy for a fair, healthy and environmentally-friendly food system. European Commission. https://ec.europa.eu/food/farm2fork_en (accessed 07 July 2022)
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., Taylor, K. E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 9(5):1937–1958. https://doi.org/10.5194/gmd-9-1937-2016
- García-Pintado, J., Martínez-Mena, M., Barberá, G.G., Albaladejo, J., Castillo, V.M., 2007. Anthropogenic nutrient sources and loads from a Mediterranean catchment into a coastal lagoon: Mar Menor, Spain. Sci. Total Environ. 373 (1), 220–239. https://doi.org/10.1016/j.scitotenv.2006.10.046
- Ghezzo, M., De Pascalis, F., Umgiesser, G., Zemlys, P., Sigovini, M., Marcos, C., Pérez-Ruzafa, A., 2015. Connectivity in Three European Coastal Lagoons. Estuaries and Coasts 38(5) 1764-1781 doi:10.1007/s12237-014-9908-0.
- Idso, S.B., 1973. On the concept of lake stability. Limnology and Oceanography 18(4) 681-683 doi:10.4319/lo.1973.18.4.0681.
- Jiménez-Navarro, I.C., Jimeno-Sáez, P., López-Ballesteros, A., Pérez-Sánchez, J., Senent-Aparicio, J., 2021. Impact of climate change on the hydrology of the forested watershed that drains to Lake Erken in Sweden: an analysis using SWAT+ and CMIP6 scenarios. Forests 12 (12), 1803. https://doi.org/10.3390/f12121803
- Kouchi, D.H., Esmaili, K., Faridhosseini, A., Sanaeinejad, S.H., Khalili, D., Abbaspour, K.C., 2017. Sensitivity of calibrated parameters and water resource estimates on different objective functions and optimization algorithms. Water 9 (6), 384. https://doi.org/10.3390/w9060384
- Liu, Y., Wang, R., Guo, T., Engel, B.A., Flanagan, D.C., Lee, J.G., Li, S., Pijanowski, B.C., Collingsworth, P.D., Wallace, C.W., 2019. Evaluating efficiencies and cost-effectiveness of best management practices in improving agricultural water quality using integrated SWAT and Cost Evaluation Tool. J. Hydrol. 577, 123965. https://doi.org/10.1016/j.jhydrol.2019.123965
- Lloret, J., Marin, A., 2009. The role of benthic macrophytes and their associated macroinvertebrate community in coastal lagoon resistance to eutrophication. Marine Pollution Bulletin 58(12) 1827-1834 doi:10.1016/j.marpolbul.2009.08.001.
- López-Ballesteros, A., Nielsen, A., Castellanos-Osorio, G., Trolle, D., Senent-Aparicio, J. 2023a. DSOLMap, a novel high-resolution global digital soil property map for the SWAT+ model: Development and hydrological evaluation. Catena, 231, 107339. https://doi.org/10.1016/j.catena.2023.107339
- López-Ballesteros, A., Trolle, D., Srinivasan, R., Senent-Aparicio, J., 2023b. Assessing the effectiveness of potential best management practices for science-informed decision support at the watershed scale: The case of the Mar Menor coastal lagoon, Spain. Sci. Total Environ. 859, 160144. https://doi.org/10.1016/j.scitotenv.2022.160144

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017861.

- Martens, B., Miralles, D.G., Lievens, H., Van Der Schalie, R., De Jeu, R.A.M., Fernández-Prieto, D., Beck, H.E., Dorigo, W.A., Verhoest, N.E.C., 2017. GLEAM v3: satellite-based land evaporation and root-zone soil moisture. Geosci. Model Dev. 10, 1903–1925. https://doi.org/10.5194/gmd-10-1903-2017
- Miralles, D.G., Holmes, T.R.H., De Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J., 2011. Global land-surface evaporation estimated from satellite-based observations. Hydrol. Earth Syst. Sci. 15, 453–469. https://doi.org/10.5194/hess-15-453-2011
- Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. T. ASABE 58 (6), 1763–1785. https://doi.org/10.13031/trans.58.10715
- Muñoz-Carpena, R., Parsons, J. E., & Gilliam, J. W., 1999. Modeling hydrology and sediment transport in vegetative filter strips. Journal of hydrology, 214(1-4), 111-129. https://doi.org/10.1016/S0022-1694(98)00272-8
- O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., Sanderson, B. M., 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci Model Dev 9(9):3461–3482. https://doi.org/10.5194/gmd-9-3461-2016
- Peña-Haro, S., Carrel, M., Lüthi, B., Hansen, I., Lukes, R., 2021. Robust Image-Based Streamflow Measurements for Real-Time Continuous Monitoring. Frontiers in Water 3 doi:10.3389/frwa.2021.766918.
- Pérez-Ruzafa, 2022. Informe de seguimiento del estado ecológico del Mar Menor en septiembre de 2022. Universidad de Murcia.
- Plunge, S., Schürz, C., Čerkasova, N., Strauch M., Piniewski, M., 2023. SWAT+ model setup verification tool: SWATdoctR. Environ. Model. Softw. 171, 105878. https://doi.org/10.1016/j.envsoft.2023.105878
- Puertes, C., Bautista, I., Lidón, A., Francés, F., 2021. Best management practices scenario analysis to reduce agricultural nitrogen loads and sediment yield to the semiarid Mar Menor coastal lagoon (Spain). Agric. Syst. 188, 103029. https://doi.org/10.1016/j.agsy.2020.103029
- Risal, A., Parajuli, P.B., 2022. Evaluation of the impact of best management practices on streamflow, sediment and nutrient yield at field and watershed scales. Water Resour. Manag. 36, 1093–1105. https://doi.org/10.1007/s11269-022-03075-7
- Ruiz-Fernández, J.M., Albentosa, M., Aldeguer, B., Álvarez-Rogel, J., Antón, J., Belando-Torrentes, M.D., Bernardeau-Esteller, J., Campillo-González, J.A., Domínguez-Yanes, J.F., Ferrera, I., Fraile-Nuez, E., Gárcia-Cancela, R., Gómez-Ballesteros, M., Gómez, F., González-Barcerá, G., Gómez-Jakobsen, F.J., León, V.M., López-Pascual, C., Marín-Guirao, L., Martínez-Gómez, C., Mercado-Carmona, J.M., Nebot-Colomer, E., Ramos-Cartelle, A., Rubio, E., Santos-Echeandia, J., Santos, F., Vázquez-Luis, M., Yebra, L., 2020. Informe de evolución y estado actual del Mar Menor en relación al proceso de eutrofización y sus causas. Instituto Espanol de Oceanografia.
- Samimi, M., Mirchi, A., Moriasi, D., Ahn, S., Alian, S., Taghvaeian, S., Sheng, Z., 2020. Modeling arid/semi-arid irrigated agricultural watersheds with SWAT: Applications, challenges, and solution strategies. J. Hydrol. 590, 125418. https://doi.org/10.1016/j.jhydrol.2020.125418
- Schmidt, W., 1928. Über die Temperatur- und Stabilitätsverhältnisse Von Seen. Geografiska Annaler 10(1-2) 145-177 doi:10.1080/20014422.1928.11880475.
- Senent-Aparicio, J., López-Ballesteros, A., Nielsen, A., Trolle, D., 2021. A holistic approach for determining the hydrology of the mar menor coastal lagoon by combining hydrological &

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017861.

hydrodynamic models. J. Hydrol. 603, 127150. https://doi.org/10.1016/j.jhydrol.2021.127150

- Uniyal B., Jha M.K., Verma A.K., Anebagilu P.K., 2020. Identification of critical areas and evaluation of best management practices using SWAT for sustainable watershed management. Sci. Total Environ. 744, 140737. https://doi.org/10.1016/j.scitotenv.2020.140737
- WMO, World Meteorological Organization, 2008. Chapter 14; Observation of present and past weather; state of the ground. Guide to Meteorological Instruments and Methods of Observation, I-14.
- Zamora-López, A., Guerrero-Gómez, A., Torralva, M., Zamora-Marín, J.M., Guillén-Beltrán, A., Oliva-Paterna, F.J., 2023. Shallow waters as critical habitats for fish assemblages under eutrophication-mediated events in a coastal lagoon. Estuarine, Coastal and Shelf Science 291 doi:10.1016/j.ecss.2023.108447

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SMARTLAGOON

End of Deliverable 5.5

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