

# TESIS DOCTORAL



**UCAM**

UNIVERSIDAD CATÓLICA  
DE MURCIA

## ESCUELA INTERNACIONAL DE DOCTORADO

*Programa de Doctorado en Tecnologías de la Computación e  
Ingeniería Ambiental*

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New approaches in modeling coastal lagoons affected by human  
activity to predict the evolution of their social and  
environmental setting

*Autora:*

Inmaculada C. Jiménez Navarro

*Directores/as:*

Dr. D. Javier Senent Aparicio

Dra. D<sup>a</sup>. Catia Prandi

*Murcia, julio de 2025*



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## AUTORIZACIÓN DE LOS DIRECTORES DE LA TESIS PARA SU PRESENTACIÓN

El Dr. D. Javier Senent Aparicio y la Dra. D<sup>a</sup>. Catia Prandi como Directores de la Tesis Doctoral titulada “New approaches in modeling coastal lagoons affected by human activity to predict the evolution of their social and environmental setting” realizada por D<sup>a</sup>. Inmaculada C. Jiménez Navarro en el Programa de Doctorado Tecnologías de la Computación e Ingeniería Ambiental, **autoriza su presentación a trámite** dado que reúne las condiciones necesarias para su defensa.

Lo que firmo, para dar cumplimiento al, Real Decreto 99/2011, de 28 de enero, modificado por el R.D. 576/2023, de 4 de julio, por el que se regulan las enseñanzas oficiales de doctorado.

En Murcia a 15 de julio de 2025.





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Esta memoria se presenta en la modalidad de compendio de publicaciones. Los artículos publicados que constituyen la tesis son los siguientes:

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- **Publicación 2:** Jiménez-Navarro, I. C., Mesman, J. P., Pierson, D., Trolle, D., Nielsen, A., & Senent-Aparicio, J. (2023). Application of an integrated catchment-lake model approach for simulating effects of climate change on lake inputs and biogeochemistry. *Science of the Total Environment*, 885, 163946. <https://doi.org/10.1016/j.scitotenv.2023.163946>.
- **Publicación 3:** Jiménez-Navarro, I. C., Pierson, D. & Senent-Aparicio, J. (2024). The implications of the use of ET remote sensing data for calibrating hydrological models: a comparison of single and multi-criteria calibration in SWAT+. *Earth Systems and Environment*, 8, 831–847. <https://doi.org/10.1007/s41748-024-00438-5>.
- **Publicación 4:** Jiménez-Navarro, I. C., Prandi, C., Pérez-Lucia, J. G., Cecilia, J. M. & Senent-Aparicio, J. (2024). Ecological crisis from children's perspective: Lessons learned and their importance in shaking up social awareness. *Sustainability*, 16 (24), 10824. <https://doi.org/10.3390/su162410824>.
- **Publicación 5:** Jiménez-Navarro, I. C., López-Ballesteros, A., Mesman, J. P., Trolle, D., Pierson, D. & Senent-Aparicio, J. Modeling Climate Impacts on Ecosystem Services in an Anthropized Coastal Lagoon for Effective Planning and Adaptation. *Climatic Change*, 178, 92 (2025). <https://doi.org/10.1007/s10584-025-03926-3>.



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“Si fuéramos seres lógicos, el mundo sería desolador. Pero  
somos más que lógicos. Somos seres humanos, tenemos fe y  
esperanza, y eso nos permite trabajar conjuntamente.”  
Jaques Cousteau (1910-1997).





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**SIGLAS Y ABREVIATURAS**

|                      |                                                                                                                                                                |
|----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>BW</b>            | Agua azul, Blue water                                                                                                                                          |
| <b>CIMP6</b>         | Fase 6 del Proyecto de Intercomparación de Modelos Acoplados, Coupled Model Intercomparison Project phase 6                                                    |
| <b>ERA5</b>          | Reanálisis del Centro Europeo de Previsiones Meteorológicas a Medio Plazo 5, European Centre for Medium-Range Weather Forecasts Reanalysis 5                   |
| <b>ET</b>            | Evapotranspiración                                                                                                                                             |
| <b>GCMs</b>          | Modelos climáticos globales, Global Climate Models                                                                                                             |
| <b>GLEAM</b>         | Evaporación terrestre global Modelo de Amsterdam, Global Land Evaporation Amsterdam Model                                                                      |
| <b>GOTM</b>          | Modelo general de turbulencia oceánica, General Ocean Turbulence Model                                                                                         |
| <b>GW</b>            | Agua verde, Green water                                                                                                                                        |
| <b>HRU</b>           | Unidad de Respuesta Hidrológica, Hydrological Response Unit                                                                                                    |
| <b>LOADEST</b>       | Load Estimator                                                                                                                                                 |
| <b>NSE</b>           | Eficiencia de Nash–Sutcliffe                                                                                                                                   |
| <b>PBIAS</b>         | Sesgo porcentual                                                                                                                                               |
| <b>R<sup>2</sup></b> | Coefficiente de determinación                                                                                                                                  |
| <b>RMSE</b>          | Error Cuadrático Medio, Root Mean Squared Error                                                                                                                |
| <b>Q</b>             | Caudal                                                                                                                                                         |
| <b>SE</b>            | Servicios Ecosistémicos                                                                                                                                        |
| <b>SEC</b>           | Servicios Ecosistémicos Culturales                                                                                                                             |
| <b>SER</b>           | Servicios Ecosistémicos de Regulación                                                                                                                          |
| <b>SMARTLAGOON</b>   | Enfoques innovadores de modelización para predecir la evolución socioambiental en lagunas costeras altamente antropizadas, Innovative modelling approaches for |

---

|             |                                                                                |
|-------------|--------------------------------------------------------------------------------|
|             | predicting socio-environmental evolution in highly anthropized coastal lagoons |
| <b>SSP</b>  | Vías de desarrollo socioeconómico compartidas, Shared Socioeconomic Pathway    |
| <b>SWAT</b> | Herramienta de evaluación del suelo y el agua, Soil and Water Assessment Tool  |
| <b>SWC</b>  | Contenido de agua del suelo, Soil Water Content                                |
| <b>WET</b>  | Herramienta del ecosistema acuático, Water Ecosystem Tool                      |

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## RESUMEN

Las lagunas costeras son ecosistemas que ofrecen gran cantidad de servicios, al ser cruciales para la biodiversidad y la economía local. Sin embargo, son altamente vulnerables debido a su complejidad ecológica y a la presión humana a la que se ven sometidas, agravada por el cambio climático. Este es el caso del Mar Menor, una de las lagunas costeras más grandes de Europa y que presenta una gran complejidad socioeconómica. Para gestionar y conservar adecuadamente estos ecosistemas, surge el proyecto SMARTLAGOON, cuyo objetivo es desarrollar un "gemelo digital" que permita modelizar y predecir los procesos socioambientales en tiempo real, facilitando la toma de decisiones informadas en las lagunas costeras. Esta tesis, enmarcada en dicho proyecto y presentada por compendio, se centra en desarrollar nuevos enfoques de modelización bajo escenarios de cambio climático. A lo largo de la investigación, que incluye tres artículos publicados y dos bajo revisión, se realizaron estudios en el Lago Erken, un ecosistema menos alterado y con un extenso historial de monitorización, para probar las metodologías propuestas antes de aplicarlas al Mar Menor, una zona mucho más compleja de modelizar. En la cuenca del Lago Erken se realizaron predicciones de cambio climático combinando modelos hidrológicos, hidrodinámicos y ecológicos y se compraron distintos tipos de calibración. Con lo obtenido en estos estudios, se procedió a la modelización del Mar Menor y el Campo de Cartagena mediante la combinación de modelos SWAT+, GOTM y WET para mejorar la precisión de las simulaciones, con técnicas de calibración aptos para ambientes con escasez de datos. Los resultados muestran que, en ambas zonas, el cambio climático afecta gravemente a los ecosistemas acuáticos, provocando alteraciones en la escorrentía y la entrada de nutrientes en la cuenca, así como fenómenos de estratificación, hipoxia y cambios en la calidad del agua en la laguna. Estos impactos afectan tanto a los servicios ecosistémicos como a la población local, y pueden ser especialmente graves en el Mar Menor, debido a la variedad de actividades humanas que dependen de este ecosistema.

**Palabras clave:** Cambio climático, hidrología, ingeniería y tecnología del medio ambiente, servicios ecosistémicos.



## ABSTRACT

Coastal lagoons are ecosystems that provide many services, as they are crucial for biodiversity and the local economy. However, they are highly vulnerable due to their ecological complexity and the human pressure to which they are subjected, aggravated by climate change. This is the case of the Mar Menor, one of the largest coastal lagoons in Europe and one of the most socioeconomically complex. In order to properly manage and preserve these ecosystems, the SMARTLAGOON project aims to develop a “digital twin” that allows modeling and predicting socio-environmental processes in real time, facilitating informed decision-making in coastal lagoons. This thesis, framed in that project and presented by compendium, focuses on developing new modeling approaches under climate change scenarios. Throughout the research, which includes three published papers and two under review, studies were conducted in Erken Lake, a less altered ecosystem with an extensive monitoring history, to test the proposed methodologies before applying them to the Mar Menor, a much more complex area to model. In the Erken Lake basin, climate change predictions were made by combining hydrological, hydrodynamic and ecological models and different types of calibration were purchased. With the results of these studies, the Mar Menor and Campo de Cartagena were modeled by combining SWAT+, GOTM and WET models to improve the accuracy of the simulations, using calibration techniques adequate for data-scarce areas. The results show that, in both areas, climate change seriously affects aquatic ecosystems, causing alterations in runoff and nutrient inputs into the basin, as well as stratification phenomena, hypoxia and changes in water quality in the lagoon. These impacts affect both ecosystem services and the local population, and can be particularly severe in the Mar Menor, due to the variety of human activities that depend on this ecosystem.

**Keywords:** Climate change, hydrology, environmental engineering and technology, ecosystem services.





# I – INTRODUCCIÓN

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## I - INTRODUCCIÓN

### 1.1. EL PROYECTO SMARTLAGOON

Las lagunas costeras son ecosistemas fundamentales en nuestro planeta y, además, son comparativamente escasos en relación con otros tipos de ecosistemas. Se estima que las lagunas costeras ocupan un 13% del litoral mundial (Barnes, 1995) y únicamente un 5,3% en Europa (Kjerfve, 1994). Estos ecosistemas desempeñan un papel crucial a diversos niveles. A nivel ambiental, las lagunas costeras regulan las entradas de agua dulce al medio marino, actuando como reservorios de nutrientes, sedimentos y sustancias tóxicas provenientes del medio terrestre a través del arrastre de ríos. Además, sirven como criaderos para diversas especies marinas y aves migratorias. Su condición de ecosistema de transición entre el medio terrestre y el medio marino les confiere equilibrios, dinámicas y características ecológicas únicas y distintas a las de otros ecosistemas (McLusky & Elliot, 2007). Esta singularidad propicia el desarrollo de procesos ecosistémicos exclusivos, vitales para una amplia variedad de especies que dependen de estas condiciones específicas para su supervivencia. Por otro lado, a nivel socioeconómico, las lagunas costeras son uno de los ecosistemas más productivos del planeta (Bas-Silvestre et al., 2020; Pérez-Ruzafa et al., 2024). Durante décadas han mantenido actividades locales como la pesca, la acuicultura tanto de animales como de plantas o la extracción de sal, entre otras. En las últimas décadas, las lagunas costeras también sirven de escenario a diversas actividades recreativas y de ocio, principalmente ligadas al turismo.

A pesar de su papel fundamental en el medio ambiente y en las poblaciones humanas, las lagunas costeras también son ecosistemas especialmente vulnerables, debido principalmente a su complejidad. El alto grado de heterogeneidad de los procesos hidrológicos, hidrodinámicos, ecológicos y socioeconómicos que se dan en ellas las clasifica como sistemas altamente complejos; cuyo equilibrio puede verse afectado y alterado con facilidad (García-Ayllón, 2017). A esto se le añade que, debido a su papel fundamental para los asentamientos humanos, son ecosistemas sometidos a una alta presión antropogénica que solo ha visto su explotación aumentada en las últimas décadas (Le Moal et al., 2019). En los últimos

años, también se enfrentan a la amenaza del cambio climático, que ya está suponiendo nuevas fuentes de alteraciones que afectan a las delicadas dinámicas ecosistémicas, como la estratificación (Woolway et al., 2021). Es por todo esto que, debido a su alta complejidad y vulnerabilidad, las lagunas costeras demandan métodos novedosos para lograr una comprensión integral de las interacciones socioambientales que las afectan. Nuevas soluciones para evaluar sus aspectos socioeconómicos y medioambientales pueden obtenerse a través de la vigilancia, el análisis y la gestión de los recursos y características del ecosistema. Sin embargo, la obtención y análisis de estos datos es compleja, ya que provienen de fuentes muy diversas, tanto físicas (meteorología, datos históricos) como sociales (encuestas, medios de comunicación, legislación). Mediante el desarrollo y diseño de modelos de inteligencia artificial, dinámicas de sistemas y modelos físicos avanzados, se podrían realizar predicciones más precisas a partir del análisis de los datos. No obstante, estas tareas, al ser tan computacionalmente intensivas, tienen un impacto significativo en la huella de carbono.

El desarrollo de la presente tesis doctoral se ha llevado a cabo dentro del marco del proyecto Europeo Horizonte 2020 “Innovative modelling approaches for predicting socio-environmental evolution in highly anthropized coastal lagoons” (abreviado como proyecto SMARTLAGOON). Este proyecto tiene como objetivo principal desarrollar una tecnología transversal y ecológica de “gemelos digitales” que permita modelizar y predecir los procesos socioambientales a distintas escalas temporales y espaciales de las lagunas costeras. Un gemelo digital es una réplica virtual de un producto, servicio o proceso que simula el comportamiento de su contraparte física para analizar su reacción a ciertas situaciones y mejorar su rendimiento y eficiencia (El Saddik, 2018). Al concluir el proyecto, el gemelo digital desarrollado proporcionará a los investigadores, partes interesadas y responsables políticos datos actualizados y en tiempo real de manera más rentable. Además, facilitará una toma de decisiones más informada y acertada, gracias a las predicciones mejoradas sobre el funcionamiento del ecosistema proporcionadas por el gemelo. En consecuencia, estas herramientas permitirán una comprensión más profunda del funcionamiento de las lagunas costeras y una gestión integral más efectiva de las mismas.

El Mar Menor fue elegido como campo para desarrollar el proyecto SMARTLAGOON por distintas razones. Por un lado, se enfrenta a distintas

presiones intensificadas en las últimas décadas (agricultura, turismo, pesca, urbanización, eutrofización, contaminación, inundaciones repentinas, cambio climático) que han provocado un deterioro medioambiental, el cual, a través de una retroalimentación negativa, repercute en los motores socioeconómicos. Además, la zona del Mar Menor supone un reto desde el punto de vista tecnológico debido a su gran extensión geográfica (135 km<sup>2</sup>), que limita la conectividad a internet en muchas regiones. Por lo tanto, es necesario desarrollar nuevas metodologías de seguimiento, modelización y previsión de los cambios en el entorno y las interacciones socioambientales, con el objetivo de restaurar, proteger y gestionar la zona de manera efectiva en el future. Por último, el Mar Menor presenta muchas partes interesadas, que serán clave en el proyecto, proporcionando información cualitativa basada en sus preocupaciones, opiniones y perspectivas subjetivas.

Uno de los aspectos más innovadores del proyecto SMARTLAGOON es su enfoque holístico del ecosistema lagunar. Desarrollar una solución tecnológica centrada en los datos proporcionará monitoreo en tiempo real y pronóstico de los compromisos socioambientales en estos ecosistemas, con el objetivo de ayudar a los responsables de la toma de decisiones en sus procesos. También permitirá aumentar la conciencia de la gente sobre estos compromisos, lo cual beneficiará la comprensión y el cumplimiento de la legislación aplicable, como la Directiva Marco del Agua de la UE (2000/60/CE), la Directiva de Inundaciones de la UE (2007/60/CE) y el RD 2/2019, de 26 de diciembre, de Protección Integral del Mar Menor.

Dentro del proyecto SMARTLAGOON existen distintos objetivos para llegar al desarrollo del gemelo digital del ecosistema. Algunos de los objetivos fundamentales son: permitir el seguimiento en tiempo real de datos socioambientales mediante tecnologías verdes, desarrollar nuevos enfoques de modelización que combinen datos de detección, modelos físicos e inteligencia artificial para entornos costeros, y crear una herramienta de aprendizaje dinámico para mejorar la gestión socioambiental de las lagunas costeras. Además, pretende esclarecer la interacción entre sistemas ambientales y sociales, tanto a tiempo real como para desarrollar predicciones. Por último, se busca la difusión de los resultados a audiencias clave, aumentando la concienciación sobre impactos medioambientales a través de actividades de ciencia ciudadana. Debido al carácter multidisciplinar de este proyecto, diversos equipos han trabajado en cada objetivo de este. La presente tesis doctoral se centra en el objetivo de desarrollar nuevos

enfoques de modelización en lagunas costeras, aunque también se trabaja de forma parcial en la difusión de resultados.

## 1.2. EL ENFOQUE MULTIDISCIPLINAR DEL PROYECTO SMARTLAGOON

SMARTLAGOON es un proyecto interdisciplinar, y uno de sus principales retos es solventar la distancia existente entre distintas disciplinas como son el modelado medioambiental, la investigación de sensores avanzados, las ciencias sociales y la inteligencia artificial para lograr el desarrollo de una plataforma para el gemelo digital del Mar Menor. Por ello se ha trabajado en combinar cinco aproximaciones metodológicas distintas:

1. Técnicas eficientes de tecnología de la información y la comunicación para la recogida de datos: se han desarrollado herramientas y algoritmos eficientes para recopilar información socioambiental en tiempo real. En cuanto al equipo necesario, se han desarrollado infraestructuras eficientes de internet de las cosas con tecnologías de detección basadas en inteligencia artificial, que finalmente se desplegarán en la laguna del Mar Menor y su cuenca hidrográfica.
2. Técnicas de modelización y simulación basadas en procesos: El proyecto ha mejorado y fortalecido las capacidades de modelado, superando las limitaciones de las herramientas actuales. Esto se ha logrado mediante la acoplamiento y combinación de diferentes modelos. Esto ha permitido ampliar la variedad de preguntas que se pueden explorar y responder.
3. Modelos impulsados por el aprendizaje automático (Machine Learning): además de los modelos ya existentes se han desarrollado nuevos métodos para crear modelos ambientales utilizando técnicas de machine learning que puedan estimar relaciones complejas entre variables ambientales. Estas técnicas se combinarán con modelos de base física para construir modelos predictivos híbridos más eficientes.
4. Modelización dinámica de sistemas participativa para el análisis estratégico de políticas y gestión: las capacidades mejoradas de modelización se han aplicado en una configuración multimodelo. Mediante la modelización dinámica de sistemas y estudios de escenarios,

esto nos permite analizar diferentes perspectivas de futuro, riesgos ambientales y prácticas de gestión.

5. Participación ciudadana, diálogo con las partes interesadas e interacciones: Se han organizado diversas actividades participativas, como talleres, seminarios con expertos y actividades de ciencia ciudadana. De esta forma se han reunido a partes interesadas y ciudadanos para recoger sus opiniones y conocimientos, para involucrarles en un proceso continuo que permita entender mejor las necesidades, presentar los resultados y desarrollar conjuntamente soluciones y productos.

El desarrollo de un proyecto tan ambicioso e interdisciplinar ha requerido la colaboración de hasta ocho equipos de investigación tanto de instituciones académicas como de empresas, procedentes de distintas ubicaciones de Europa (Dinamarca, Italia, Noruega, España, Suecia y Suiza). Debido a la necesidad de trabajar en todas estas perspectivas de forma coordinada el proyecto SMARTLAGOON se encuentra dividido en siete grupos de trabajo, cada uno con sus propios objetivos. La autora de la presente tesis ha trabajado de forma más notable en el grupo de trabajo 3, que se dedica a la modelización innovadora de procesos ambientales, y el grupo de trabajo 7, que está enfocado en el compromiso ciudadano, la colaboración, la comunicación y la difusión del proyecto. En esta tesis se presentan resultados obtenidos al trabajar en dos objetivos principales del proyecto.

Primero, relacionado con el grupo de trabajo 3, mejorar las capacidades de modelado mediante la combinación de modelos de base física y la simulación de escenarios de cambio climático con los modelos acoplados. Para ello se ha trabajado en esta tesis en el desarrollo y acoplamiento de tres modelos distintos: el modelo hidrológico SWAT+ (Soil and Water Assessment Tool) y el modelo hidrodinámico GOTM (General Ocean Turbulence Model), en combinación con el modelo WET (Water Ecosystem Tool). La integración de estos modelos permite obtener una visión holística de las distintas variables que afectan al Mar Menor y a su cuenca.

Segundo, relacionado con el grupo de trabajo 7 llevar a cabo actividades de ciencia ciudadana con los habitantes del entorno del Mar Menor para asegurar su participación en el proyecto, contar con su colaboración y mantenerlos informados sobre el proyecto y las actividades del proyecto. Aunque el foco principal ha sido

el de la modelización y simulación de escenarios también se ha realizado una publicación relacionada con la parte de comunicación.

Un componente clave en la gestión sostenible del agua es que las partes interesadas y los ciudadanos tengan conciencia y un sentido de responsabilidad sobre el problema y las soluciones. Las actividades de ciencia ciudadana son fundamentales para el proyecto SMARTLAGOON porque permiten la participación activa de la comunidad local, en este caso, los habitantes del entorno del Mar Menor, en la recolección de datos y la monitorización del ecosistema. Esta colaboración no solo enriquece la calidad y cantidad de los datos obtenidos, sino que también fomenta un mayor compromiso y conciencia ambiental entre los ciudadanos. Además, al involucrar a los voluntarios en el proceso científico, se asegura que los resultados del proyecto sean más relevantes y ajustados a las necesidades y preocupaciones de la sociedad local. La integración de la ciencia ciudadana también facilita la comunicación de los hallazgos y avances del proyecto, creando un vínculo más estrecho entre la investigación científica y la comunidad, lo cual es esencial para la difusión efectiva y la implementación de soluciones sostenibles en la región.

### 1.3. MODELIZACIÓN HOLÍSTICA

Durante décadas, los modelos hidrológicos de base física se han utilizado para la gestión y planificación de recursos hídricos en todo el mundo. Actualmente, se han convertido en una herramienta indispensable para comprender la interacción de los procesos hidrológicos y los problemas ambientales, y han experimentado notables mejoras tecnológicas en los últimos años, integrando más procesos y proporcionando herramientas de calibración más completas (Rouholahnejad et al., 2014). Estos modelos de base física permiten comprender la interacción de los procesos hidrológicos y los problemas ambientales, simulando componentes clave del balance hidrológico. A través de estas simulaciones, los modelos ayudan a estimar los recursos hídricos disponibles y a predecir el impacto de cambios en el uso del suelo o el clima sobre estos recursos. Siempre y cuando se disponga de suficientes datos para su calibración y validación, estos modelos son capaces de adaptarse a las condiciones climáticas, geográficas y humanas específicas de cada cuenca. Este proceso es esencial para garantizar que el modelo



sea preciso y útil para la gestión local de los recursos hídricos, lo que es crucial para implementar medidas adecuadas (Brekke et al., 2004). De esta forma, cuando se aplican a escala de cuenca, los modelos hidrológicos se convierten en poderosas herramientas de apoyo a la toma de decisiones locales, proporcionando información valiosa para la gestión del agua (Francesconi et al., 2016). Tanto los modelos de cuenca como los de lagos pueden simular la variabilidad espacial y temporal de los procesos hidrodinámicos, así como la respuesta de la cuenca y el cuerpo de agua (Munar et al., 2018). Esta capacidad para simular diversos escenarios, como el cambio climático y diferentes usos del suelo, permite la realización de predicciones, y por lo tanto ayuda a la elaboración de planes hidrológicos efectivos (Tan et al., 2020).

En esta tesis se han utilizado tres tipos de modelos: un modelo hidrológico y un modelo de ecosistemas acuáticos, combinado con un modelo hidrodinámico. Tanto el modelo hidrológico como el hidrodinámico son modelos de base física. La principal diferencia entre ellos es que mientras que un modelo hidrológico es una representación matemática de una cuenca hidrográfica, un modelo hidrodinámico simula el transporte hidrodinámico dentro de una masa de agua. Por otro lado, el modelo de ecosistemas acuáticos simula las relaciones entre los distintos componentes, tanto bióticos como abióticos, del ecosistema.

En la última década, diversos estudios han integrado modelos hidrológicos e hidrodinámicos en distintas partes del mundo (Inoue et al., 2008; Dargahi y Setegn, 2011; Zhang et al., 2017; Lopes et al., 2018; Coppens et al., 2020). Esta metodología es muy útil, ya que las dinámicas y predicciones de un cuerpo de agua están intrínsecamente ligadas a las de su cuenca vertiente (Nielsen et al., 2012). Dado que los cambios en el entorno afectan tanto a la cuenca, es crucial considerar las alteraciones en ambos sistemas y su interacción para hacer predicciones precisas sobre las dinámicas del lago.

#### 1.4. EL PAPEL DEL CAMBIO CLIMÁTICO

El cambio climático es un fenómeno a escala planetaria que ha sido ampliamente reconocido por la comunidad científica en las últimas décadas (Cook et al., 2016). Debido a este fenómeno actualmente sufrimos un período de inestabilidad climática en muchas partes del planeta, cuyas consecuencias ya se

están sintiendo y están afectando a nuestros ecosistemas, los servicios que ofrecen y las vidas humanas en general (Marengo y Espinoza, 2016; Wehner et al., 2017; Wuebbles et al., 2017; Harvey et al., 2020; Lesk et al., 2022). En los próximos años, se espera que estas alteraciones se vuelvan más severas como consecuencia de este fenómeno antrópico (Pulido-Velázquez et al., 2012; López-Ballesteros et al., 2020; Zittis et al., 2022).

Una de las áreas más afectadas por el cambio climático es y será la hidrología (Kiesel et al., 2019), ya que los procesos hidrológicos dependen directamente de diversas condiciones climáticas, como la precipitación y la temperatura, entre otros. Existen numerosos ejemplos de cómo el cambio climático, al alterar los patrones de temperatura y precipitación, afecta procesos como la evapotranspiración, la escorrentía, la erosión y los patrones de inundaciones, lo que influirá significativamente en ríos, lagunas, lagos y acuíferos (Bouraoui et al., 2004; Simonovic y Li, 2004; Zhang et al., 2005; Zierl y Bugmann et al., 2005; Blanco-Gómez et al., 2019). La alteración del régimen de precipitación puede llevar a cambios en el flujo y la escorrentía; mientras que los cambios en la temperatura afectarán al deshielo y a la evapotranspiración (Akter et al., 2018; Javadinejad et al., 2020). De igual forma, las lagunas y lagos se pueden ver afectados por el cambio climático de diversas maneras, por ejemplo, un incremento en la temperatura atmosférica puede provocar cambios en la estratificación térmica del agua y afectar así a las dinámicas ecosistémicas (Woolway et al., 2021). Todas estas variaciones tendrán consecuencias negativas a largo plazo sobre los ecosistemas y las actividades humanas. En general, la gestión de los recursos hídricos puede verse seriamente comprometida por el cambio climático.

La modelización de escenarios de cambio climático es una buena forma de predecir los efectos que este fenómeno tendrá sobre el ciclo hidrológico y los cuerpos de agua, lo que nos permitiría tomar decisiones acordes para paliar estos efectos. Dado que las circunstancias hidrológicas varían entre localizaciones, los efectos del cambio climático pueden ser diferentes incluso bajo escenarios de predicciones similares. Por ejemplo, la predicción de un aumento de precipitación puede estar relacionada con inundaciones y empantanamientos del terreno en zonas llanas, húmedas y con vegetación; sin embargo, en zonas áridas y con presencia de pendientes, puede provocar un incremento de la erosión del suelo. En ambos casos, las medidas paliativas para adaptarse al aumento de precipitación

deben ser diferentes. Por ello, a la hora de planificar los recursos hídricos a nivel local de forma eficaz, es importante comprender las condiciones regionales y elaborar evaluaciones del cambio climático específicas para cada área (Cubasch et al., 1995; Brekke et al., 2004; Xie et al., 2015).

### 1.5. SERVICIOS ECOSISTÉMICOS

El término "servicio ecosistémico" (SE) hace referencia a los beneficios que la naturaleza aporta a las personas (Carpenter et al. 2009) y surge de la necesidad de considerar estas contribuciones en los ámbitos político, científico y de gestión. Identificar y medir los diferentes SE que un ecosistema ofrece permite mejorar la planificación y gestión del paisaje, subrayando la importancia de preservar y mantener los ecosistemas (Kull et al. 2015). Por ello, es un concepto que ha ganado popularidad en la última década.

Los estudios al respecto suelen clasificar los SE en tres categorías: servicios de provisión, regulación y culturales, siguiendo la Clasificación Internacional Común de Bienes y Servicios de los Ecosistemas (<https://cices.eu/>). Esta clasificación se basa en el tipo de beneficio que el ecosistema aporta al bienestar humano e incluye tanto componentes bióticos como abióticos.

Los servicios de provisión cubren la necesidad de materiales, recursos y energía que la población requiere, siendo algunos ejemplos la biomasa obtenida de la agricultura y la ganadería, el agua dulce para uso y consumo humano, minerales o energía solar y geotérmica, entre muchos otros. Los servicios ecosistémicos de regulación (SER) ayudan a mantener y preservar los ecosistemas, regulando el ciclo hidrológico, la calidad del agua, el suelo y la atmósfera, mitigando desastres naturales y controlando enfermedades y plagas, por ejemplo. Por su parte, los servicios ecosistémicos culturales (SEC) abarcan los aspectos inmateriales de los ecosistemas que tienen un efecto en el bienestar físico y mental, como el enriquecimiento espiritual, el desarrollo cognitivo, la recreación, la mejora de la salud física, el contacto con la naturaleza o las experiencias estéticas. Algunos estudios proponen subdividir los SER en "regulación" y "soporte" (Hirons et al., 2016; Cheng et al., 2019) o incluir una categoría "ecológica" para destacar la integridad ecológica y su rol en otros SE (Frank et al., 2014). Sin embargo, todas estas clasificaciones coinciden en la categoría general de SER.

## 1.6. ANTECEDENTES

En este apartado se abordará tanto la problemática del Mar Menor como la metodología principal utilizada en esta tesis. Primero, se discutirá la situación concreta del Mar Menor, el objeto de estudio principal del proyecto SMARTLAGOON, cuya problemática ambiental ha motivado este proyecto. Así, en el apartado 1.6.1, se tratará la historia reciente del Mar Menor hasta su estado actual para proporcionar contexto al estudio. En los apartados 1.6.2, 1.6.3, 1.6.4, 1.6.5 y 1.6.6 se revisarán estudios previos que han empleado metodologías similares de modelización a la de esta tesis, ofreciendo un marco metodológico comparativo. Finalmente, en el apartado 1.6.7, se expondrá el marco metodológico que incluye la parte de ciencia ciudadana desarrollada en esta tesis doctoral.

### 1.6.1. El Mar Menor y su entorno

El Mar Menor, así como su entorno, tienen un valor ecológico y socioeconómico considerable, además de ser de una gran relevancia para la Región de Murcia y sus habitantes. Actualmente la integridad de la laguna se ha visto comprometida por una grave crisis ambiental. Esta situación está deteriorando la calidad del agua y causando un impacto significativo en la economía local.

El Mar Menor y sus alrededores son considerados un lugar especial debido a sus aguas hipersalinas y su flora y fauna adaptadas a las condiciones singulares de este ecosistema (Martínez et al. 2007). Además, abarca ecosistemas adyacentes de gran importancia ambiental, incluidos diversos humedales y arenales a lo largo de sus costas. Por ello, en su entorno confluyen hasta diez figuras de protección ambiental distintas, entre ellas: Zonas Especiales de Conservación y Zona de Especial Protección para las Aves en la Red Natura 2000; Humedal de Importancia Internacional conforme al convenio Ramsar; Zona Especialmente Protegida de Importancia para el Mediterráneo, Área de Protección de Fauna Silvestre y Zona Especial de Conservación. Además, dentro del Mar Menor se dan distintas actividades de gran significancia para los habitantes y la economía de la región. Estas actividades incluyen la pesca tradicional y la extracción de sal, mientras que la laguna también es un importante destino turístico en la Región de Murcia. Algunos autores cuantifican el valor económico no utilizado en más de 40 millones de euros al año (Velasco et al., 2018). Todo esto subraya el gran valor ecológico y

socioeconómico de esta laguna costera (Senent-Aparicio, López-Ballesteros et al., 2021).

Tradicionalmente, el Mar Menor presentaba aguas transparentes y oligotróficas. En el siglo XVIII, la laguna recibía un bajo aporte de nutrientes, y su semi-aislamiento con respecto al Mar Mediterráneo propició un aumento de la salinidad. Estas condiciones singulares limitaron la diversidad de especies y dieron lugar a un ecosistema lagunar caracterizado por el estrés térmico, salino y la escasez de materia orgánica, resultando en una laguna oligotrófica e hipersalina, con aguas muy transparentes y baja biodiversidad, cuyos fondos estaban cubiertos por praderas dispersas y poco densas de fanerógamas (Giménez Casalduero et al., 2016).

Sin embargo, desde finales del siglo XIX, la laguna ha estado sometida a presiones antrópicas que han alterado su ecología. Por un lado, la ampliación de las golas naturales para facilitar la entrada de embarcaciones redujo la salinidad de la laguna, permitiendo la entrada de nuevas especies (Navarro, 1927; Conesa y Jiménez-Cárceles, 2007). Para la década de 1980, las praderas dispersas de fanerógamas fueron reemplazadas por densas praderas de *Caulerpa prolifera*, que colonizaron el fondo del Mar Menor, provocando cambios en el sedimento y un grado significativo de anoxia en la capa profunda (Pérez-Ruzafa et al., 1987). Por otro lado, en las últimas décadas, el aumento en la carga de nutrientes ha llevado a una severa eutrofización que ha alterado su ecología (Velasco et al., 2006). Estos aportes de nutrientes están relacionados con la expansión de actividades humanas en su cuenca vertiente, principalmente el turismo estacional y la agricultura intensiva con uso de fertilizantes. Como consecuencia, el Mar Menor ha experimentado aguas turbias, proliferaciones de medusas, floraciones algales frecuentes, cambios en la distribución de especies y anoxia en sus niveles más profundos (Anderson et al., 2002).

En 2016, el Mar Menor sufrió su mayor crisis eutrófica registrada, debido a una floración algal dañina dominada por dinoflagelados del género *Gymnodinium* sp. Este episodio provocó un estado de anoxia generalizada en agosto, que destruyó el 85% de la vegetación del fondo y el 94% de la población de *Pinna nobilis*, una especie amenazada en todo el Mediterráneo (Giménez-Casalduero et al., 2020). Este evento desencadenó una fuerte respuesta de la población local y los sectores científico, ecológico y turístico (García-Ayllon, 2018; Pérez-Rufaza et al., 2019).

Desde entonces, la transparencia del agua ha disminuido considerablemente debido a la eutrofización, afectando negativamente al sector turístico y la economía local. Otro episodio catastrófico se registró en septiembre de 2019, cuando una tormenta originada por una depresión aislada en niveles altos provocó severas inundaciones, causando una brusca disminución de la salinidad y un aumento de la turbidez del agua, lo que resultó en un evento de anoxia que provocó la muerte de miles de peces.

La situación actual no solo supone una grave pérdida ecológica, sino también social y económica. Estudios recientes indican que cada aumento de 1 mg/m<sup>3</sup> en la concentración de clorofila incrementa en un 5,5% la probabilidad de fracaso de las empresas ubicadas en la zona (Jimeno-Sáez et al., 2020; Mate-Sánchez-Val y Aparicio-Serrano, 2023). Las medidas propuestas por los gobiernos regionales y nacionales para mejorar las prácticas agrícolas, principal fuente de materia orgánica a la laguna, como muestran López-Ballesteros, Trolle et al. (2023), tendrían un costo mucho menor que el valor de los productos y servicios que genera este ecosistema. Sin embargo, los conflictos de interés entre las partes involucradas han dificultado alcanzar un consenso sobre las soluciones (Guaita-García et al., 2022).

En conclusión, el Mar Menor es un enclave singular que ofrece grandes beneficios a la región y sus habitantes. No obstante, las múltiples presiones que enfrenta han impedido la implementación de soluciones efectivas para frenar su degradación. Por ello, resulta imprescindible estudiar el Mar Menor desde una perspectiva holística que contemple las distintas variables de la cuenca, la laguna y los efectos del cambio climático, incluyendo además la perspectiva de la ciudadanía local.

### **1.6.2. Simulación de escenarios de cambio climático**

Con anterioridad se ha destacado la importancia de simular escenarios de cambio climático a escala local para lograr una gestión eficiente del agua. Debido a esto, numerosos estudios han empleado modelos hidrológicos y/o hidrodinámicos con este propósito. El modelo Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012) ha sido utilizado ampliamente con este objetivo en todo el mundo desde su lanzamiento en 1994. Su versión más reciente, SWAT+ (Bieger et al., 2017), ha sido aplicado desde 2020 con el mismo objetivo.

En 2021, cuando se inició esta tesis, existían solo tres estudios publicados que analizaban el impacto del cambio climático en cuencas hidrológicas utilizando el modelo SWAT+. El primero de estos estudios fue realizado por Chawanda et al. (2020), quienes emplearon la calibración del balance de masa del modelo SWAT+ y la representación de embalses para evaluar los efectos del cambio climático en el sur de África. Otro estudio significativo fue el de Senent-Aparicio, George et al. (2021), que analizaron el impacto del cambio climático en los caudales ambientales del noroeste de España, empleando una nueva herramienta de post-procesamiento diseñada específicamente para modelos SWAT+, lo que permitió evaluar cómo las alteraciones climáticas podrían afectar los flujos ambientales en esa región. Por su parte, Kiprotich et al. (2021) estudiaron la respuesta de la escorrentía superficial al cambio climático y al cambio de uso del suelo en Nairobi, utilizando también el modelo SWAT+. En los últimos años, se han publicado muchos más estudios sobre este tema utilizando metodologías similares (ej: Pulighe et al., 2021; Zhu et al., 2023; Naik y Abiodun, 2024; Abate et al., 2024). Este incremento en la investigación refleja el creciente interés en comprender y predecir los impactos del cambio climático en diferentes contextos hidrológicos.

### **1.6.3. Acoplamiento de modelos hidrológicos e hidrodinámicos**

Teniendo en cuenta las ventajas de acoplar modelos hidrológicos, como SWAT+, con modelos hidrodinámicos (ver apartado 1.3.), no sorprende encontrar numerosos estudios previos que han aplicado esta metodología. Un ejemplo temprano de este enfoque es Inoue et al. (2008), quienes utilizaron lo utilizaron para simular los cambios en la salinidad de la Cuenca de Barataria, en Luisiana (EE. UU.). Lopes et al. (2018) propusieron un método basado en un modelo que integra la hidrología y la hidrodinámica en la Laguna de los Patos (Brasil-Uruguay). Su modelo permitió simular de manera eficiente el hidrograma, el nivel del agua y las áreas de inundación de la laguna y su cuenca.

Existen también varios estudios que han utilizado la primera versión del modelo SWAT para simular cuencas de cuerpos de agua e integrarlo con un modelo hidrodinámico. Dargahi y Setegn (2011), combinaron el modelo SWAT con el modelo GEMSS para simular en 3D el nivel del agua del Lago Tana (Etiopía), con el objetivo de lograr un uso sostenible del recurso hídrico. Zhang et al. (2017)

combinaron SWAT con el modelo Delft3D para crear un modelo completo del Lago Poyang (China), calibrando SWAT con datos de una estación en la cuenca.

Sin embargo, son menos comunes los estudios que, además de integrar estos dos tipos de modelos, combinan también modelos físicos y ecológicos para analizar la variación de nutrientes y otras variables biogeoquímicas, como es el caso de este estudio. Un ejemplo de esta combinación es el trabajo de Coppens et al. (2020) en el Lago Mogan (Turquía), donde se utilizó el modelo para realizar previsiones sobre el cambio climático.

#### **1.6.4. Calibración con ET y multicalibración**

Establecer modelos hidrológicos funcionales tradicionalmente requiere calibración con registros históricos de cuencas aforadas, pero en casos como la cuenca del Mar Menor, donde solo existen ramblas estacionales en lugar de ríos de flujo continuo, estos datos no están disponibles. Por ello, esta tesis explora alternativas para calibrar el modelo SWAT+, incluyendo el uso de la evapotranspiración (ET) como fuente de datos, dada su importancia en el ciclo hidrológico. La ET, junto con la precipitación, escorrentía e infiltración, es crucial ya que cerca del 60% de la humedad de las precipitaciones se evapotranspira, y alrededor del 50% de la energía solar absorbida se destina a este proceso (Hunt et al., 1986; Kiehl y Trenberth, 1997). Esto cobra aún más importancia en entornos semi-áridos, como el Mar Menor. Con los avances en teledetección, como el Modelo Global de Evaporación Terrestre de Ámsterdam (GLEAM) (Miralles et al., 2011), ahora es más fácil obtener datos de ET a escala global. Esta tecnología es útil tanto para calibrar modelos en cuencas sin datos de aforo (Alemayehu et al. 2022) como para aplicar técnicas de multi-calibración en cuencas aforadas, como el Lago Erken. La calibración multicriterio, que usa múltiples datos del ciclo hidrológico, mejora la precisión del modelo al manejar variabilidad espacial y temporal, y ayuda a enfrentar la equifinalidad, donde diferentes combinaciones de parámetros pueden dar resultados similares. Incorporar datos de teledetección puede reducir tanto la equifinalidad, al ampliar el conjunto de observaciones y parámetros del modelo, como la incertidumbre de las predicciones (Rajib et al., 2018; Her y Seong, 2018).

En estudios previos, se ha investigado la calibración del caudal y la ET utilizando la versión inicial del modelo SWAT. Por ejemplo, Odusanya et al. (2021)



realizaron dos calibraciones en una gran cuenca, una basada en caudal y otra en ET. La calibración con caudal replicó mejor la dinámica del flujo, pero fue menos precisa para la ET, mientras que la basada en ET mostró el comportamiento opuesto. A pesar de esto, la calibración solo con ET representó adecuadamente la dinámica temporal de la escorrentía en ausencia de mediciones de caudal. Varios estudios han explorado estrategias de calibración múltiple para SWAT en diferentes regiones. Franco et al. (2020) compararon la calibración multisitio en una cuenca brasileña con una calibración multicriterio que incluía caudal y ET, observando que, aunque la calibración multivariable no mejoró significativamente el rendimiento del modelo, sí redujo la incertidumbre. Tobin y Bennett (2017), al usar datos satelitales de ET en una cuenca de Oklahoma, resaltaron la utilidad de combinar ET y caudal para refinar el modelo, sugiriendo la necesidad de nuevas estrategias de calibración. Además, se ha evaluado la eficacia de calibrar SWAT solo con caudal o solo con ET. Parajuli et al. (2018) encontraron que la calibración con ET es efectiva, mientras que Sirisena et al. (2020) obtuvieron resultados opuestos. Algunos estudios, como el de Koltsida y Kallioras (2022), proponen que la ET derivada de teledetección es una opción viable para cuencas con datos limitados.

#### **1.6.5. Aplicación en los casos de estudio**

Tanto en el proyecto SMARTLAGOON como en la presente tesis se han realizado dos modelos: uno en el Mar Menor y otro en el Lago Erken. Esto es debido a que cada área de estudio aporta beneficios específicos al desarrollo y validación de las tecnologías y herramientas de modelado que se están creando.

El Lago Erken, en Suecia, se ha utilizado como campo de pruebas y desarrollo porque es uno de los lagos mejor monitoreados en Europa, con un programa de vigilancia a largo plazo realizado por el departamento de Limnología de la Universidad de Uppsala (<https://www.uu.se/en/departament/ecology-and-genetics/research/erken-laboratory/lake-monitoring-programme>). Este lago es especialmente útil para la calibración y validación de los modelos debido a su monitoreo detallado y a que su cuenca no está muy influenciada por la actividad humana, lo que lo hace un entorno predecible (ver apartado 4.1.1.). Precisamente por estas características existen diversos estudios previos en el lago (Malmaeus y

Håkanson, 2004; Persson y Jones, 2008; Pierson et al., 2011; Blenckner et al., 2006; Moras et al., 2019; Ayala et al., 2020; Mesman et al., 2024). Utilizar el lago Erken como campo de estudio nos ha permitido desarrollar y ajustar los modelos en un entorno controlado y bien documentado antes de aplicarlos en un entorno más complejo como el Mar Menor.

El Mar Menor, por otro lado, es el objetivo principal de aplicación de los modelos. Como se menciona en el apartado 4.1.2., este ecosistema presenta complicaciones específicas que se deben abordar, y representa un entorno muy diferente, con mayor influencia humana y desafíos ambientales más complejos. Al aplicar las técnicas y modelos que ya se han probado y validado en el Lago Erken, se pueden utilizar con mayor seguridad bajo las diferentes condiciones naturales, sociales y climáticas que presenta el Mar Menor.

#### **1.6.6. Servicios ecosistémicos**

Al analizar los antecedentes de los SE, es fundamental considerar varios aspectos clave. En primer lugar, los SE han sido estudiados desde enfoques diversos que han evolucionado en la última década. Una metodología común es la simulación de escenarios a través de modelos. Por ejemplo, Frank et al. (2014) evalúa el impacto de la erosión como SER en otros seis SE mediante simulaciones de distintos manejos del suelo con el software GISCAME. Duarte et al. (2016) emplean el software InVEST para investigar la superposición de diferentes SE en Brasil. Zhan et al. (2023) analiza SE de las tres categorías en un lago utilizando un modelo propio y propone dos escenarios de restauración. En general, en las últimas dos décadas, el uso del modelo SWAT ha crecido rápidamente en la evaluación de los servicios ecosistémicos, como destacan las revisiones de Francesconi et al. (2016) y Zhao et al. (2024), en las que se refleja la efectividad de SWAT para integrar procesos ecosistémicos. Francesconi et al. (2016) señalan que la mayoría de los estudios que utilizan SWAT se centran en los servicios de provisión y regulación, donde el modelo muestra un buen desempeño. Por su parte, Zhao et al. (2024) subrayan que SWAT es especialmente útil para cuantificar procesos relacionados con el agua, como la producción hídrica, la retención de suelo y el almacenamiento de carbono.

En segundo lugar, dado que los SE están estrechamente ligados al ciclo hidrológico, el modelo SWAT ha sido ampliamente utilizado para estudiar los SER. Existen numerosos ejemplos de su aplicación. Logsdon y Chaubey (2013) utiliza varios índices para evaluar cinco SE en distintos escenarios con el modelo SWAT. Aznarez et al. (2021) también emplea SWAT, enfocándose en los SE relacionados con el ciclo hidrológico y analizándolos bajo diferentes escenarios de cambio climático. De manera similar, Uniyal et al. (2023) utiliza SWAT para simular escenarios climáticos y estudiar el impacto de estos cambios en los SE. Finalmente, varios estudios han documentado el daño que el cambio climático causa en los SE (Bakure et al., 2022), así como los obstáculos que plantea para la efectividad de las medidas de remediación (Zhan et al., 2023). Por lo tanto, para una adecuada gestión y planificación territorial, es crucial comprender la relación entre los SE y cómo estos se verán afectados por el cambio climático (Shaw et al., 2011). El modelo hidrológico SWAT se presenta como una herramienta eficaz para simular el impacto del cambio climático, como se ha demostrado en los ejemplos previamente mencionados (Aznarez et al., 2021; Uniyal et al., 2023).

#### **1.6.7. Ciencia ciudadana**

La ciencia ciudadana es una herramienta valiosa para involucrar a la población local en la producción de conocimiento científico. En el proyecto SMARTLAGOON, se ha puesto un gran énfasis en desarrollar este tipo de comunicación. Aunque se han llevado a cabo actividades con diversos sectores implicados en el Mar Menor, esta tesis se centrará en las actividades realizadas con la población local de la región, específicamente con los estudiantes de un colegio público en una localidad del Mar Menor.

Los antecedentes respaldan ampliamente la importancia de incluir a los niños en actividades de ciencia ciudadana, destacando tanto los beneficios científicos como educativos. La participación infantil en proyectos científicos puede aportar perspectivas innovadoras y preguntas nuevas, debido a su curiosidad natural y su forma única de ver el mundo. Wells y Lekies, (2006) argumentan que los niños, al observar su entorno de manera distinta a los adultos, pueden ofrecer nuevas ideas que enriquecen la creación, procesamiento y presentación de datos científicos. Además, Frew et al. (2017) señalan que los niños pueden tener prioridades

diferentes en la evaluación de ecosistemas, lo que puede contribuir a una valoración más completa y equitativa, favoreciendo la equidad intergeneracional en la evaluación de ecosistemas (Goodwin et al., 2019).

Diversos estudios destacan cómo la participación de los niños no solo enriquece el proceso científico en sí, sino que también contribuye a su propio desarrollo personal y a la sensibilización comunitaria. Investigaciones como las de Bowker (2007) y Maagerø & Sunde (2016) han utilizado el dibujo como una herramienta para captar las opiniones y conocimientos de los niños, revelando que los dibujos infantiles ofrecen una visión valiosa de su comprensión y percepción del entorno. Estos estudios muestran que los niños, al representar su entorno a través del arte, pueden aportar ideas y perspectivas innovadoras, facilitando una comprensión diferente de los problemas actuales y posibles soluciones. Además, otros estudios, como los de Ballantyne et al. (1998) y Gommerman & Monroe (2012), subrayan que la participación de los niños en actividades científicas puede influir significativamente en su círculo cercano, aumentando la conciencia sobre temas ambientales entre amigos y familiares. Esto es especialmente relevante cuando los niños están familiarizados con el ecosistema en cuestión, lo que les permite discutir de manera más efectiva la importancia de su conservación. Así, involucrar a los niños en ciencia ciudadana no solo favorece su educación y desarrollo, sino que también promueve la equidad intergeneracional en la evaluación de los ecosistemas y refuerza la conciencia ambiental a nivel comunitario.

## II – JUSTIFICACIÓN

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## II - JUSTIFICACIÓN

La presente tesis doctoral surge de la necesidad de abordar la complejidad y vulnerabilidad de las lagunas costeras, ecosistemas cruciales pero delicados debido a su interacción única entre el medio terrestre y marino. Estos ecosistemas enfrentan presiones crecientes debido a actividades humanas y al cambio climático. Comprender cómo interactúan los procesos socioambientales en estos entornos es esencial para su preservación, ya que su degradación podría tener consecuencias irreversibles para la biodiversidad, la economía local y la calidad de vida de las comunidades adyacentes.

En respuesta a esta necesidad, el proyecto SMARTLAGOON busca abordar la complejidad y fragilidad del ecosistema del Mar Menor mediante la creación de un "gemelo digital", que permitirá modelar y predecir procesos socioambientales. Este enfoque es esencial para mejorar la gestión y conservación del área, ya que proporciona una herramienta avanzada para la toma de decisiones basada en datos en tiempo real. Dado que la gestión de estos ecosistemas requiere un conocimiento preciso y actualizado, el desarrollo de este gemelo digital es un paso crítico para asegurar su sostenibilidad a largo plazo.

Para enfrentar los desafíos inherentes a la gestión de las lagunas costeras, SMARTLAGOON adopta un enfoque multidisciplinar que combina recogida de datos en tiempo real, simulación a través de modelos de base física, modelización de gestión y políticas, machine learning, participación ciudadana y diálogo con las partes interesadas. Esta integración es fundamental porque los problemas que enfrenta el Mar Menor son multifacéticos, involucrando factores hidrológicos, ambientales y sociales que no pueden ser abordados de manera aislada. Es también por este motivo que la presente tesis aborda distintos puntos clave de este proyecto, en especial la simulación de escenarios de cambio climático y la ciencia ciudadana.

La participación de la comunidad local y la ciencia ciudadana son pilares esenciales del proyecto SMARTLAGOON. Este enfoque no solo permite la recopilación de datos valiosos a escala local, sino que también aumenta la conciencia y el compromiso comunitario con la preservación del ecosistema del Mar Menor. Involucrar a los ciudadanos en el proceso de monitoreo y gestión es

crucial para garantizar que las soluciones propuestas sean socialmente aceptadas y efectivas a largo plazo. Esta participación directa justifica la integración de la comunidad en la toma de decisiones ambientales. Debido a esto, la alumna ha realizado una publicación dirigida a este objetivo del proyecto SMARTLAGOON.

Por último, el impacto del cambio climático en las lagunas costeras es un desafío global que requiere una comprensión profunda y precisa de los procesos que afectan estos ecosistemas. SMARTLAGOON aborda este reto mediante la aplicación de modelos hidrológicos e hidrodinámicos que permiten prever cómo las alteraciones climáticas influirán en el Mar Menor. De esta forma se puede suplir la necesidad de prever y mitigar los efectos negativos antes de que estos provoquen daños irreversibles, asegurando así la resiliencia del ecosistema frente a futuros cambios ambientales.

La integración de modelos hidrológicos e hidrodinámicos, junto con modelos de ecosistemas acuáticos, se justifica por la necesidad de comprender y predecir las dinámicas complejas entre la cuenca y el cuerpo de agua en las lagunas costeras. Este enfoque permite realizar predicciones más precisas que son esenciales para la gestión sostenible y la toma de decisiones informadas.

Por último, el uso de SE para analizar el impacto del cambio climático es una aproximación que pone en el punto de mira la conservación del ecosistema por los beneficios que tiene sobre la población local. Además, abre la puerta a continuar la investigación con los SEC, de los que se puede obtener información a través de la ciencia ciudadana, lo que permitiría estrechar aún más relaciones con la población local y las partes interesadas en el área del Mar Menor.



## III – OBJETIVOS

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### III - OBJETIVOS

El objetivo primordial de esta tesis es realizar una contribución significativa al conocimiento y la práctica en la conservación de las lagunas costeras. Con este fin, se presenta un modelo integral del Mar Menor y su cuenca vertiente, destacando la importancia de una colaboración sostenida entre la ciencia, la tecnología y la comunidad. Esta cooperación es esencial para alcanzar una gestión ambiental exitosa y perdurable. Los objetivos específicos que se derivan de este objetivo general son:

1. Desarrollar técnicas avanzadas de simulación de escenarios de cambio climático mediante el uso de Modelos de Clima Global (GCMs, por sus siglas en inglés). Se identificarán las variables críticas de estos modelos para su integración en modelos hidrológicos e hidrodinámicos.
2. Optimizar la calibración de modelos hidrológicos utilizando y comparando diversas variables, considerando la falta de datos de aforo en la región del Mar Menor. Este objetivo se centrará en el modelo SWAT+.
3. Implementar técnicas de acoplamiento entre modelos hidrológicos, hidrodinámicos y ecosistémicos, con el fin de generar predicciones holísticas y precisas. En este contexto, se emplearán los modelos SWAT+, GOTM y WET.
4. Aplicar las técnicas desarrolladas al entorno del Mar Menor, un desafío dada su complejidad y dinámicas particulares. Esto implica la simulación de los impactos del cambio climático en esta área, utilizando predicciones de diversos GCMs y el acoplamiento de los modelos SWAT+, GOTM y WET, a pesar de la carencia de datos de aforo.
5. Relacionado con el objetivo anterior, aplicar el análisis de SE en el área del Mar Menor para comprobar su utilidad en el área y preparar el terreno para potenciales estudios de SE relacionados con la población local y las partes interesadas.

6. Evaluar métodos de participación ciudadana para la divulgación del proyecto y la recolección de datos de la población local, promoviendo así la colaboración comunitaria y el intercambio de conocimiento.

## **IV - MATERIAL Y MÉTODO**

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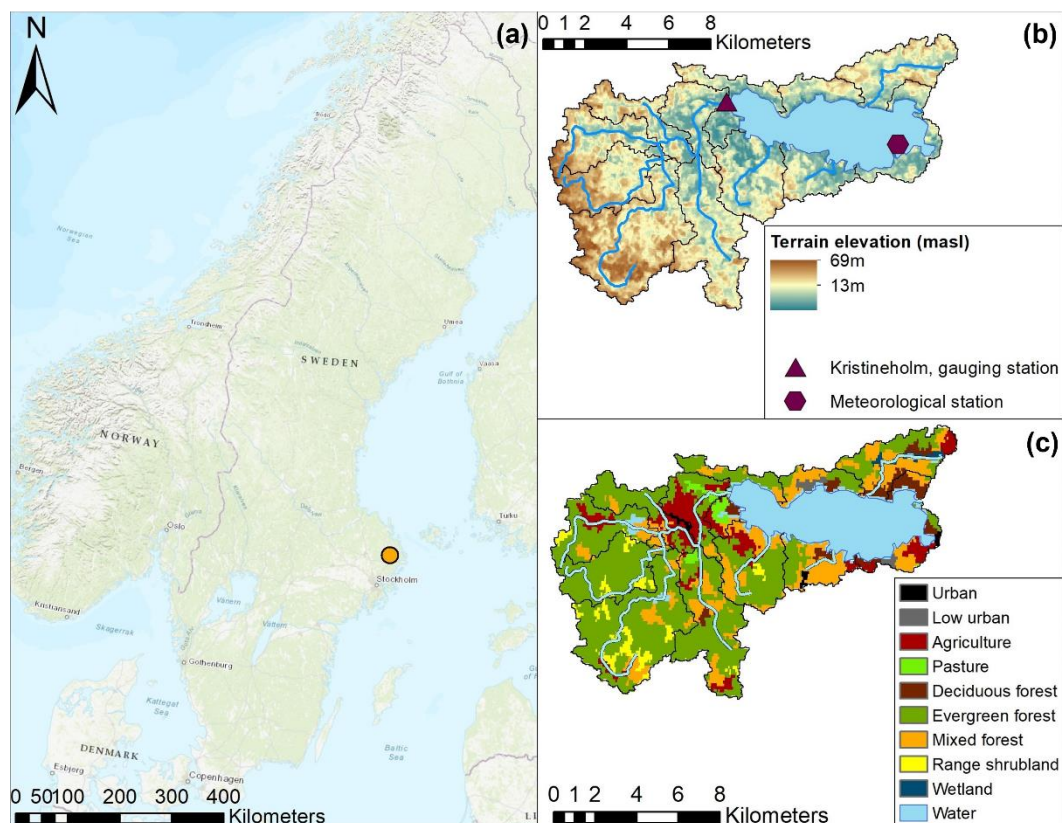


## IV -MATERIAL Y MÉTODO

### 4.1. ÁREAS DE ESTUDIO

En este apartado se describirá con más detalle las dos áreas que han sido campo de estudio en esta tesis: El Lago Erken y el Mar Menor. Se describirá tanto su cuenca vertiente y sus características como las propiedades principales de su masa de agua, la climatología de ambos sitios y las actividades humanas que en ellas se dan.

#### 4.1.1. El lago Erken



*Figura 1. Mapa del lago Erken y su cuenca vertiente. (a) Localización del lago Erken dentro de la península escandinava. (b) Mapa de elevación del terreno de la cuenca vertiente al lago Erken, y localización de la principal entrada de agua al lago (estación de aforo) y estación meteorológica. (c) Mapa de usos del suelo de la cuenca.*

El lago Erken es un lago moderadamente eutrófico con un nivel intermedio de productividad. Su superficie suele estar cubierta de hielo durante el invierno, mientras que en verano el agua se estratifica. Ambos fenómenos han sido ampliamente estudiados por la Universidad de Uppsala (Pierson et al., 2011; Blenckner et al., 2017; Moras et al., 2019; Ayala et al., 2020; Mesman et al., 2024). Es un lago poco profundo, con una profundidad media de aproximadamente 9 m, y su punto más profundo alcanza los 21 m bajo el agua. Su superficie es de aproximadamente 24 km<sup>2</sup> y el tiempo de residencia del agua en el lago es de 7,4 años. El lago Erken se encuentra ubicado en la parte oriental de Suecia (59°50'37"N, 18°35'38"E) a una altitud de 10 m sobre el nivel del mar (Figura 1).

La cuenca del lago Erken se orienta hacia el este y carece de pendientes pronunciadas (Figura 1(b)). Con una extensión de 135 km<sup>2</sup>, la cuenca es relativamente pequeña y está mayormente cubierta de bosques, con áreas limitadas de pastizales agrícolas (Malmaeus & Håkanson, 2004). La cuenca incluye zonas de bosque caducifolio y perenne, aunque predominan los bosques mixtos (Figura 1(c)). El principal afluente del lago es Kristineholm (Figura 1(b)), donde se realizan las mediciones de descarga de agua.

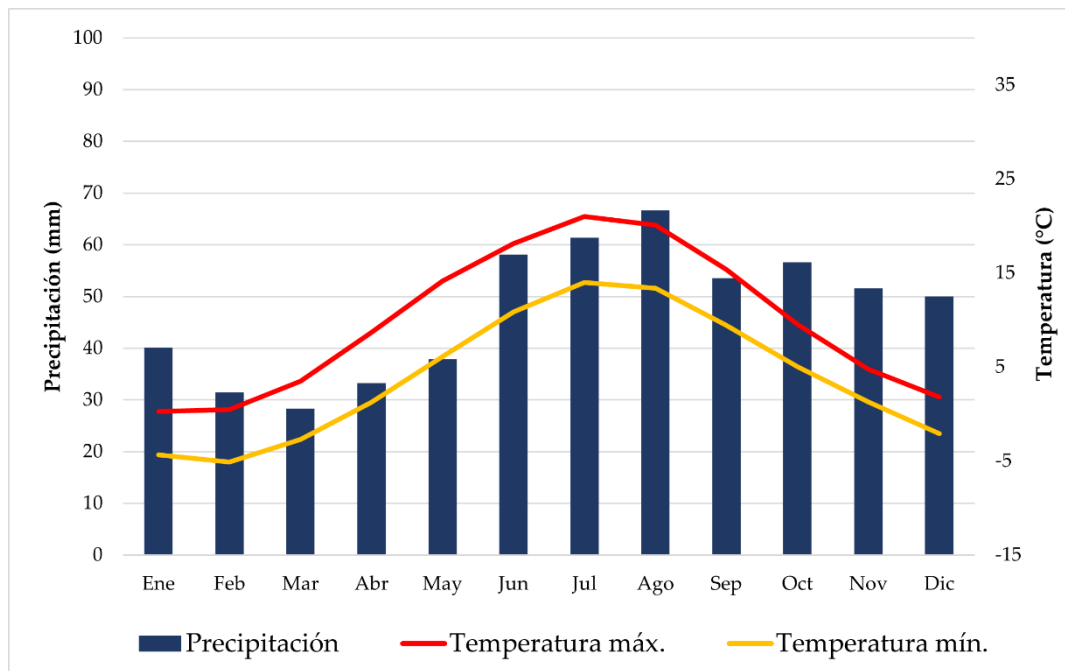


Figura 2. Distribución anual de la media mensual de la temperatura y precipitaciones en la cuenca del lago Erken.



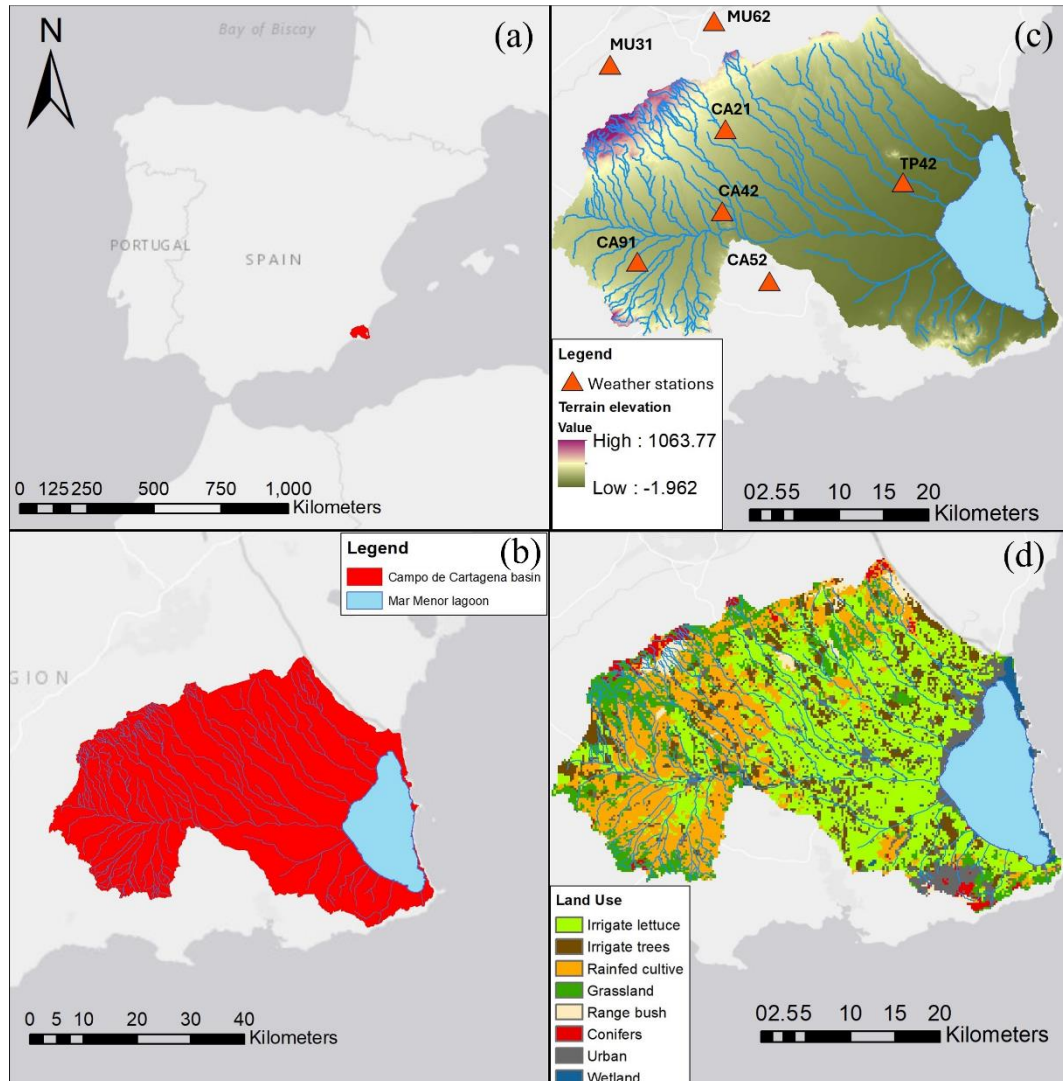
En la región centro-sur de Suecia, donde se encuentra el lago Erken, el clima es húmedo y continental, con veranos cálidos e inviernos moderados (Figura 2), a pesar de la alta latitud del país. La duración de la luz diurna varía entre 18 horas en junio y 6 horas en diciembre. Según los datos históricos del Laboratorio Erken (indicado como 'estación meteorológica' en la figura 1(b)) el mes más cálido en la cuenca de Erken es julio, con una temperatura media de 17,5 °C, mientras que el mes más frío es febrero, con una temperatura media de -2,32 °C. La precipitación anual promedio es de 519 mm, con un ligero incremento durante el verano (junio, julio y agosto). La precipitación en forma de nieve se presenta entre diciembre y marzo, y la cuenca suele estar cubierta de nieve entre 75 y 100 días al año.

#### **4.1.2. El Mar Menor**

Debido a la importancia del contexto social del Mar Menor y debido a que es el objeto de estudio del proyecto SMARTLAGOON, ya se ha ofrecido una contextualización de la historia reciente del Mar Menor, así como su contexto actual, los distintos beneficios que los humanos (y más concretamente los murcianos) obtenemos de él, y la gravedad de la crisis actual que sufre (Ver apartado 1.6.1.). En el apartado actual nos limitaremos a complementar la información ya ofrecida con datos de su geografía, su hidrología y la climatología de su cuenca.

El Mar Menor es una laguna costera hipersalina ubicada en el sureste de la Península Ibérica, en la Región de Murcia (España). Es una laguna superficial, con una profundidad media de aproximadamente 4.4 m y una profundidad máxima de 7 m (Umgiesser et al. 2014). Se encuentra separada del Mar Mediterráneo por La Manga, una gran barra de arena urbanizada de 20 km de largo y entre 100 y 700 m de ancho. Con una superficie de aproximadamente 135 km<sup>2</sup>, es una de las lagunas costeras más grandes de Europa. La cuenca de drenaje del Mar Menor es conocida como el Campo de Cartagena, una llanura que abarca aproximadamente 1600 km<sup>2</sup>, caracterizada por pendientes suaves. En esta región es común la presencia de ramblas estacionales. El Campo de Cartagena no cuenta con cursos de agua permanentes; sus flujos de agua solo se activan durante eventos de lluvia intensa, provocando una fuerte escorrentía (León et al., 2017). La única excepción se da en la rambla del Albujón, que presenta un flujo continuo en su tramo final que

descarga en el Mar Menor debido a un aumento en el nivel piezométrico (García-Pintado et al., 2007). Tres canales artificiales conectan el Mar Menor con el Mar Mediterráneo, siendo el más importante el canal de Estacio, inaugurado en 1973.



**Figura 3.** Mapa del Mar Menor y el Campo de Cartagena. (a) Localización dentro de la Península Ibérica. (b) Campo de Cartagena y ramblas estacionarias. (c) Mapa de elevación del terreno de la cuenca vertiente al lago Erken, y localización de las estaciones meteorológicas. (d) Mapa de usos del suelo del Campo de Cartagena.

El Campo de Cartagena es una cuenca antropizada, dominada por la agricultura intensiva (Fig. 3(d)). Es considerada una de las principales áreas de cultivo hortícola en Europa (Velasco et al., 2018). El uso del suelo se distribuye principalmente en agricultura irrigada intensiva (45% de la cuenca), agricultura de

secano (30%) y bosques de coníferas y arbustos (15%). La agricultura irrigada depende de una combinación de recursos hídricos subterráneos, aguas residuales reutilizadas, desalación de agua de mar y el trasvase Tajo-Segura (Álvarez-Rogel et al., 2020). Los cultivos predominantes son cítricos, invernaderos y hortalizas. Las prácticas agrícolas comunes incluyen la aplicación de fertilizantes (nitrógeno y fósforo) mediante fertirrigación y la rotación anual de cultivos como lechuga, brócoli y melón (López-Ballesteros, Trolle et al., 2023).

Bajo el Campo de Cartagena existen un acuífero superficial libre de edad Cuaternaria que se utiliza para extraer agua para riego. Sin embargo, este acuífero ha estado expuesto a la contaminación por nitratos debido al retorno de riego, producido por la poca profundidad del nivel piezométrico y las actividades agrícolas realizadas sobre él (Baudron et al., 2014). El alto nivel piezométrico del acuífero Cuaternario también provoca que el agua cargada con nitratos acumulados aflore al final del curso de agua del Albuñón (Silva et al., 2017).

El clima en Murcia es mediterráneo y semiárido, caracterizado por precipitaciones inferiores a la evapotranspiración potencial. Los veranos son secos y calurosos, mientras que los inviernos son suaves (Figura 4). El Campo de

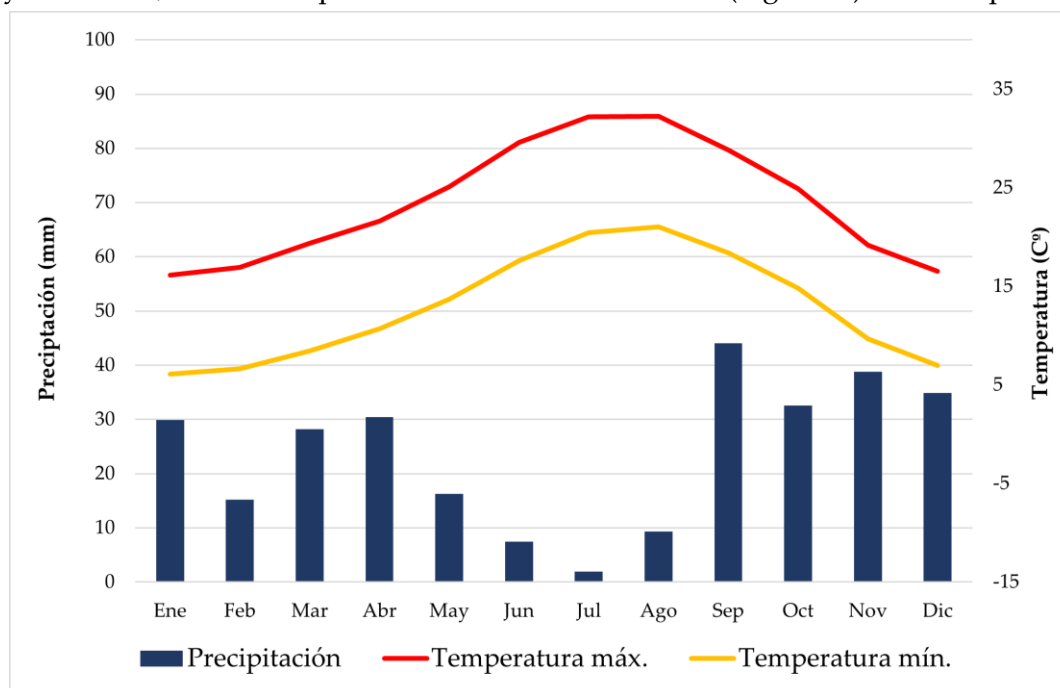


Figura 4. Distribución anual de la media mensual de la temperatura y precipitaciones en el Campo de Cartagena.

Cartagena se encuentra entre las cuencas más áridas de la región mediterránea. El mes más cálido es agosto, con una temperatura media de 26,6°C, mientras que enero es el mes más frío, con una media de 11,1°C. La precipitación anual oscila entre 166 mm y 469 mm, con un promedio inferior a 300 mm por año. Las precipitaciones están distribuidas de manera desigual en el año, concentrándose estacionalmente en otoño y primavera, principalmente en eventos puntuales y torrenciales.

#### 4.2. DESARROLLO DEL MODELO SWAT+

El modelo SWAT (Arnold et al., 2012) es un software diseñado para desarrollar modelos hidrológicos de cuencas hidrográficas, operando como un modelo de simulación continua con una escala temporal diaria. Los componentes principales de SWAT abarcan la hidrología, el clima, el ciclo de nutrientes, el transporte de sedimentos, el desarrollo de cultivos, la gestión agrícola y la dinámica de pesticidas. A lo largo de las últimas dos décadas, esta herramienta ha sido utilizada globalmente en una amplia variedad de escenarios, condiciones y escalas.

La dinámica del agua se modela a través de las fluctuaciones en las Unidades de Respuesta Hidrológica (HRU por sus siglas en inglés). Cada HRU representa una combinación única de uso del suelo, pendiente, tipo de suelo y medidas de gestión del terreno, todas ellas integradas mediante una interfaz de sistema de información geográfica. Como resultado, SWAT se considera un modelo "semi-distribuido", en el que se asume que una misma combinación de uso del suelo, pendiente, tipo de suelo y prácticas generará una respuesta hidrológica similar (Mohammed et al., 2018). El balance hídrico es el principal motor del modelo SWAT, y se representa mediante la siguiente ecuación:

*Ecuación 1. Balance hídrico del modelo SWAT.*

$$SW_t = SW_o + \sum (V_i - Q_i - E_i - P_i - QR_i) \times \Delta t$$

donde  $SW_t$  y  $SW_o$  representan el contenido de agua en el suelo final e inicial (en mm/día);  $V_i$  representa la precipitación (en mm/día);  $Q_i$  representa la escorrentía superficial (en mm/día);  $E_i$  representa la evapotranspiración (en mm/día);  $P_i$  representa la percolación (en mm/día);  $QR_i$  representa el flujo de retorno (en mm/día); y  $\Delta t$  es el intervalo de tiempo (en días). El término  $i$  hace referencia al índice.

La heterogeneidad espacial de una cuenca es representada mediante la subdivisión de la cuenca en múltiples subcuencas, que a su vez se dividen en diferentes HRUs. Este proceso se realiza a través del software QSWAT, que opera en una interfaz QGIS, integrando y combinando datos espaciales. Las cuencas más grandes generalmente se dividen en más subcuencas debido a la diversificación de los usos del suelo y los tipos de suelo dentro de la misma cuenca, así como a la mayor variedad. Estas subdivisiones permiten al modelo reflejar diferencias en la evapotranspiración para distintos tipos de cultivos y suelos (Neitsch et al., 2011).

En 2017, el modelo SWAT experimentó una evolución significativa con la introducción de SWAT+ (Bieger et al., 2017). Este desarrollo surgió en respuesta a las crecientes demandas de la comunidad científica, dado que las mejoras adicionales al modelo SWAT original habían alcanzado su límite. SWAT+ mejora las capacidades de enrutamiento de la escorrentía, al tiempo que mantiene la eficiencia computacional y la facilidad de uso del modelo. En esta versión actualizada, los elementos de la cuenca, como acuíferos, unidades de uso del suelo, HRUs, estanques y embalses, se definen como objetos espaciales. Esta característica distintiva mejora notablemente las capacidades de configuración y discretización de la cuenca en comparación con la versión anterior de SWAT.

#### **4.2.1. Datos de entrada**

Tal como se ha descrito previamente, el modelo SWAT+ opera mediante la creación de HRUs que resultan de la combinación de las características del suelo, el uso del suelo y la topografía. Por ello los datos de entrada que necesita el modelo se dividen en información geográfica detallada de la región de estudio y datos meteorológicos del período de simulación. En este apartado se detallan los conjuntos de datos específicos, sus fuentes y métodos de adquisición para el modelo de la cuenca del lago Erken y el modelo del Campo de Cartagena. Todos los datos se describen en las tablas 1 y 2.

Para empezar, los datos de entrada geográficos que requiere SWAT+ incluyen un mapa de elevación del terreno, un mapa de usos del suelo y un mapa de tipos de suelo. Para el modelo del lago Erken, se utilizaron bases de datos de cobertura global con una resolución adecuada, como se muestra en la tabla 1. En cambio, para el modelo del Campo de Cartagena, se emplearon principalmente mapas y bases

de datos nacionales, con la excepción del mapa de tipos de suelo (Tabla 2). Este último fue desarrollado específicamente para su aplicación en el modelo SWAT (López-Ballesteros, Nielsen et al., 2023).

*Tabla 1. Datos de entrada del modelo SWAT+ de la cuenca vertiente al lago Erken.*

| Datos de entrada                                                        | Resolución | Fuente                                                                                               |
|-------------------------------------------------------------------------|------------|------------------------------------------------------------------------------------------------------|
| Mapa de elevación del terreno                                           | 30 m       | Shuttle Radar Topography Mission (Farr y Kobrick, 2000)                                              |
| Base de Datos Mundial de Suelos Armonizada (Harmonized World Soil Date) | 1 Km       | Organización de las Naciones Unidas para la Alimentación y la Agricultura (Nachtergaele et al. 2010) |
| Corine land cover                                                       | 100 m      | Copernicus Land Monitoring Service (CLC 2018)                                                        |
| Datos climáticos (precipitación y temperatura)                          | Diaria     | Estación meteorológica del laboratorio Erken (Fig. 1(b))                                             |

*Tabla 2. Datos de entrada del modelo SWAT+ del Campo de Cartagena.*

| Datos de entrada                                                                                        | Resolución      | Fuente                                                                                                                                      |
|---------------------------------------------------------------------------------------------------------|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Mapa de elevación del terreno                                                                           | 25 m            | Instituto Geográfico Nacional de España                                                                                                     |
| Mapa de Cultivos y Aprovechamientos 2000-2010                                                           | Escala 1:50.000 | Ministerio de Agricultura, Pesca y Alimentación del Gobierno de España                                                                      |
| Digital Soil Open Land Map                                                                              | 250 m           | López-Ballesteros, Nielsen et al., 2023                                                                                                     |
| Datos climáticos (precipitación, temperatura, humedad relativa, radiación solar y velocidad del viento) | Diaria          | Estaciones meteorológicas MU62, CA21, CA42, CA91, CA52 y TP42 del Instituto Murciano de Investigación y Desarrollo Agrario y Medioambiental |

Respecto a los datos meteorológicos de entrada, SWAT requiere datos diarios de precipitación, temperatura máxima y mínima, humedad relativa, radiación solar y velocidad del viento. A partir de este conjunto de datos el programa calcula la ET. SWAT+ ofrece varios métodos para estimar la ET, como Penman-Monteith, Priestley-Taylor y Hargreaves. Para el modelo del lago Erken se ha utilizado el método Hargreaves (Hargreaves, 1994) que solo requiere de precipitación y temperatura como datos de entrada. Aunque el método Hargreaves es menos complejo y requiere menos datos que los otros métodos, estudios como el de Oudin et al. (2005) han demostrado que los modelos hidrológicos que utilizan métodos basados en temperatura con requisitos de datos reducidos pueden ofrecer un rendimiento comparable al de los métodos más intensivos en datos. Por otro lado, para el modelo del Mar Menor se ha utilizado el método Penman-Monteith (Penman, 1948; Monteith, 1965), ya se disponía de un mayor número de datos diarios. En ambos casos los datos climáticos han sido obtenidos de estaciones meteorológicas situadas en las respectivas cuencas, cómo se puede comprobar en las figuras 1(b) y 3(c).

#### **4.2.2. Análisis de sensibilidad, calibración y validación**

Para obtener los modelos SWAT+, se han seguido tres pasos principales. Primero, identificar los parámetros más influyentes que afectan el caudal u otras variables a calibrar, mediante un análisis de sensibilidad. Segundo, ajustar los parámetros sensibles con una calibración automática utilizando datos reales de un período concreto. Finalmente, usar los mismos datos, pero para un período no calibrado con el fin de validar la fiabilidad el modelo SWAT+. La metodología de estos tres pasos se describe a continuación.

Dentro del modelo SWAT+, existen numerosos parámetros que se pueden calibrar. Para evitar la sobre-parametrización y determinar cuáles son los más relevantes en el proceso hidrológico de nuestras áreas de estudio, se han realizado análisis de sensibilidad (Arnold et al., 2012) antes de proceder con la calibración y validación. Este tipo análisis permite evaluar cómo las variaciones en los parámetros del modelo afectan sus resultados. Es un paso crucial para identificar los parámetros clave necesarios para la calibración y para seleccionar aquellos que

tienen un impacto significativo en los resultados del modelo que se desean estudiar.

Para desarrollar un modelo hidrológico preciso se requieren datos observados reales para compararlos con los datos generados por el modelo. Esto permite ajustar los parámetros del modelo para que sus resultados se asemejen lo más posible a la realidad (calibración) y verificar la fiabilidad del modelo (validación). La calibración y validación del modelo suelen estar limitadas por la disponibilidad y el período de los datos reales. En el caso de la cuenca del lago Erken, existe una estación de aforo automatizada que proporciona un registro histórico de entrada de agua diaria al lago (fig. 1(b)) desde mediados de 2006. Esta es la serie de datos que se ha utilizado para la calibración y validación del modelo. En cuanto al Campo de Cartagena, no cuenta con un registro semejante ya que no presenta cursos de agua permanentes, por eso se ha optado por la calibración con ET y el contenido hídrico del suelo (SWC, por sus siglas en inglés). Para ello se han obtenido datos vía satélite de GLEAM v3.7b (Miralles et al. 2011), una base de datos de ET por teledetección desarrollado por la Universidad Libre de Ámsterdam. La versión más reciente ofrece una cobertura global completa durante un período de dos décadas, desde el 1 de enero de 2003 hasta el 31 de diciembre de 2022. GLEAM (v3.7b) se caracteriza por su robustez, ya que se construye mediante una fusión de observaciones de teledetección de múltiples satélites y se valida rigurosamente utilizando torres de covarianza de Eddy y sensores in-situ (Martens et al. 2017). Este método se ha empleado con éxito en diversos estudios (López-Ballesteros et al. 2019; Odusanya et al. 2021; Ningthoujam and Romeji 2024; Jiménez-Navarro et al., 2024).

Por último, el proceso de validación consiste en ejecutar el modelo fuera del período de calibración utilizando los parámetros ajustados durante la calibración para comprobar que el modelo es lo suficientemente preciso para el caso de estudio (Moriassi et al., 2007). Este proceso de validación implica introducir los parámetros calibrados en el modelo SWAT+ y comparar los datos reales con los datos simulados por el modelo.

Para el modelo del lago Erken, el periodo de simulación fue limitado por la disponibilidad de datos de aforo, de 2005 hasta el 2022, a escala diaria, dividido en tres fases: un período inicial de calentamiento (2005-2006), un período de calibración (2007-2015) y un período de validación (2016-2021). La calibración y



validación fueron realizados en el software Toolbox (Chawanda et al., 2021). La calibración fue automática y enfocada en la variable de la descarga de agua.

En el modelo del Campo de Cartagena, el período de simulación se extendió desde el 2000 hasta el 2022, dividido en tres fases: un período inicial de calentamiento (2000-2002), un período de calibración (2003-2012) y un período de validación (2013-2022). Tanto la calibración como la validación se llevaron a cabo utilizando el software SWATplus-CUP v3.0 (<https://www.2w2e.com/home/SwatPlusCup>). La calibración fue automática y multivariable (ET y SWC), y el intervalo de tiempo para ambos procedimientos se estableció a escala mensual.

El funcionamiento de los modelos SWAT+ se evaluó gráfica y estadísticamente para los periodos de calibración y validación de cada uno. Para ello, se utilizaron tres índices estadísticos: el coeficiente de determinación ( $R^2$ ), la eficiencia de Nash–Sutcliffe (NSE; Nash y Sutcliffe, 1970) y el sesgo porcentual (PBIAS). Siguiendo la clasificación propuesta por Moriasi et al. (2015) y Kouchi et al. (2017), se evaluó la calidad del ajuste del modelo, logrando umbrales satisfactorios ( $R^2 > 0.6$ ,  $PBIAS \leq \pm 25\%$  y  $NSE \geq 0.5$ ).

#### 4.3. DESARROLLO DEL MODELO GOTM-WET

El Modelo General de Turbulencia Oceánica (GOTM) es un modelo de columna de agua con malla vertical que se utiliza en lagos y océanos. Este modelo emplea ecuaciones de cierre de turbulencia para simular la dinámica de mezcla vertical (Umlauf et al., 2005). GOTM ha sido aplicado en diversas áreas de estudio, como la dinámica de mezcla cerca de los sedimentos (Umlauf et al., 2015), los cambios en la estructura térmica de los lagos debido al clima (Ayala et al., 2020) y el transporte de trazadores y sustancias biogeoquímicas (Jung et al., 2019). GOTM puede integrarse con modelos biogeoquímicos mediante el Framework for Aquatic Biogeochemical Models (Bruggeman y Bolding, 2014). En esta configuración, GOTM regula la mezcla de sustancias entre capas utilizando cálculos de turbulencia, mientras que las ecuaciones biogeoquímicas se aplican a cada capa en cada paso temporal. Además, la difusión y la convección se incorporan en el cálculo de las tasas de movimiento vertical de partículas inorgánicas y fitoplancton. Como ejemplo de esta integración, se puede acoplar el modelo GOTM con el modelo

WET, un modelo modular de ecosistema acuático que simula la dinámica biogeoquímica (como oxígeno, fósforo y nitrógeno) y los organismos (como fitoplancton, zooplancton y zoobentos) tanto en la columna de agua como en el sedimento (Schnedler-Meyer et al., 2022).

#### 4.3.1. Datos entrada

El modelo GOTM-WET es una herramienta avanzada para simular dinámicas acuáticas en lagos y océanos, requiriendo varios tipos de datos y configuraciones para su funcionamiento adecuado. Para iniciar, el modelo necesita datos meteorológicos que pueden ser horarios o diarios, dependiendo del caso. Estos datos incluyen variables clave como la temperatura del aire, velocidad del viento, radiación solar, presión atmosférica, humedad relativa, nubosidad y precipitación. Además, el modelo requiere datos de la entrada al lago o laguna que comprenden descargas de agua y concentraciones de nutrientes, tales como nitrógeno y fósforo orgánicos, así como sedimentos inorgánicos. La configuración del modelo incluye la discretización vertical, que determina el número de capas y la profundidad de cada una, y el tiempo de integración, que es el intervalo temporal para las simulaciones.

En el caso del Lago Erken, el modelo GOTM-WET se configuró utilizando datos meteorológicos diarios. Los datos de descarga se basaron en niveles de agua medidos. El modelo fue ajustado con un tiempo de integración de 1 hora y utilizó 42 capas verticales de 0.5 metros de profundidad. La web alimentaria del modelo para el Lago Erken incluía cuatro grupos de fitoplancton (diatomeas, cianobacterias, algas verdes y flagelados), macrófitos y zooplancton, con parámetros ajustados según literatura y valores predeterminados del caso de estudio del Lago Ravn (WET, 2022). No obstante, los parámetros fueron incluidos en la calibración si el análisis de sensibilidad mostraba que eran sensibles, asegurándose de que no se desviaran demasiado de los valores basados en la bibliografía. En las simulaciones de los escenarios de cambio climático, se utilizaron los valores de los parámetros calibrados, pero los archivos de forzamiento fueron modificados en consecuencia.

En contraste, en el Mar Menor se utilizó el modelo GOTM-WET con datos meteorológicos horarios proporcionados por el Reanálisis 5 del Centro Europeo de

Previsiones Meteorológicas a Plazo Medio (ERA5, Muñoz-Sabater et al. 2021). Las entradas de descarga se obtuvieron del modelo SWAT+, que incluía descargas y concentraciones de nutrientes, asumiendo que el 90% de los nitrógenos y fósforos orgánicos eran particulados y el 10% disueltos. La salinidad se ajustó utilizando mediciones de conductividad en el curso de agua Albuñón, con variaciones dependiendo del flujo. La web alimentaria en el Mar Menor comprendía macrófitos, fitoplancton, zoobentos y zooplancton, pero se simplificó para evitar la simulación de múltiples grupos funcionales dentro de los módulos.

#### **4.3.2. Análisis de sensibilidad, calibración y validación**

Para ajustar el modelo GOTM-WET, aplicado tanto en el lago Erken como en el Mar Menor, también se aplicaron análisis de sensibilidad, calibración y validación, adaptados a las características específicas de cada ecosistema. Para ello se usó el software ParSAC (Bruggeman y Bolding, 2020).

El análisis de sensibilidad fue fundamental para ambos casos, permitiendo identificar los parámetros más influyentes en las salidas del modelo y, al mismo tiempo, reducir el número de parámetros a calibrar. En el lago Erken, se incluyeron 275 parámetros del modelo en el análisis, utilizando el método delta-sensibilidad de Borgonovo (Borgonovo, 2007; Andersen et al., 2021). A través de este proceso, se lograron seleccionar 165 parámetros que demostraron ser los más relevantes para la calibración, excluyendo aquellos cuya sensibilidad no superó el umbral estadístico. En el Mar Menor, se utilizó el mismo enfoque, con un análisis de más de 200 parámetros. Además de los parámetros biogeoquímicos, se prestó especial atención a factores como los coeficientes de extinción de la luz y el nivel mínimo de turbulencia, lo cual es crítico en un sistema lagunar como el Mar Menor. En este modelo también se tuvo que corregir el intercambio de agua con el Mar Mediterráneo.

La calibración del modelo en ambos entornos fue iterativa, implicando múltiples rondas de ajustes de parámetros hasta que las mejoras en el ajuste del modelo se volvieron marginales. En el lago Erken, se utilizó un enfoque de calibración escalonada con un método de evolución diferencial para maximizar una función de verosimilitud, centrada en variables como la temperatura del agua, fosfatos, nitratos, y clorofila, entre otras. El período de 2000 a 2015 se empleó como

fase de calibración. En el Mar Menor, la aproximación fue similar. Se permitió un margen del 25% en las concentraciones de nutrientes debido a la incertidumbre en el modelo de cuenca y la contribución de aguas subterráneas, lo que subraya las complejidades asociadas con la modelización de un sistema lagunar con influencias tanto continentales como marinas. Los datos utilizados para la calibración abarcaron de 2016 a 2020. En ambos casos la calibración y validación del modelo se llevaron a cabo utilizando datos reales (Erken laboratory; Pérez-Ruzafa, 2022), que pueden incluir mediciones de salinidad, temperaturas y concentraciones de nutrientes, ajustando los parámetros según la literatura existente y realizando extrapolaciones cuando sea necesario (Erken: Pettersson, 2001; Malmaeus, 2004; Weyhenmeyer et al., 2007; Haglund et al., 2003; Rydin, 2000; Reitzel et al., 2007; Coles & Jones, 2000; Gibson et al., 2003; Reynolds et al., 2001; De Nobel et al., 1998; Kelly et al., 2021; Nalewajko & Murphy, 2001; Renstrom, 1979; Moss, 1973; Wirth et al., 2019. Mar Menor: Ruiz-Fernández et al., 2020; Belando et al., 2021; Bernardeau-Esteller et al., 2023).

En el lago Erken, la validación cubrió el período de 2016 a 2021, utilizando las mismas estadísticas que en el modelo SWAT+ para evaluar la bondad de ajuste. En contraste, para el Mar Menor, se validó el modelo utilizando datos de 2021 a 2023, incluyendo datos adicionales de alta frecuencia provenientes de una boya de monitoreo y datos de flujo de cámaras en los canales principales para evaluar el intercambio laguna-mar; ambos aparatos de medición siendo parte del proyecto SMARTLAGOON. Para ambas validaciones, se calcularon el Error Cuadrático Medio (RMSE) y el coeficiente de determinación  $R^2$ , ofreciendo una medida cuantitativa de la precisión del modelo.

#### 4.4. PREDICCIONES DE CAMBIO CLIMÁTICO

Con el objetivo de aplicar los modelos SWAT+ y GOTM-WET desarrollados para obtener predicciones futuras se ha recurrido a GCMs, obteniendo así los datos climáticos de entrada necesarios para los modelos en periodos futuros. Los datos fueron obtenidos a través del Proyecto de Intercomparación de Modelos Acoplados (Coupled Model Intercomparison Project, CIMP6) (<https://esgf-node.llnl.gov/search/cmip6/>, accedido por última vez en junio de 2024). Se puede encontrar más información sobre la fase 6 del CMIP en su documento general

(Eyring et al., 2016). En el primer estudio en el que se utilizó GCMs (Jiménez-Navarro et al., 2021), se empleó el análisis de McSweeney et al. (2015) para seleccionar los GCMs específicos a utilizar. De esta manera, se seleccionaron siete modelos distintos cuyo rendimiento para Europa se consideraba satisfactorio: BCC-CSM2-MR, CanESM5, EC-Earth-Veg, GFDL, INM-CM5-0, MiroC6, and MRI-ESM2-0. En este primer estudio solo se aplicó el modelo SWAT+ en el lago Erken, por lo que únicamente fue necesario extraer datos de precipitación y temperatura. Sin embargo, en los dos siguientes que se aplicó cambio climático (Jiménez-Navarro et al., 2023; Jiménez-Navarro, López-Ballesteros et al., under review), se utilizó el acoplamiento con el modelo GOTM-WET, que requiere una mayor cantidad de datos climáticos de entrada. Por lo tanto, de los siete GCMs seleccionados originalmente, solo se utilizaron cinco (BCC-CSM2-MR, CanESM5, INM-CM5-0, MiroC6 y MRI-ESM2-0) que contenían todas las variables necesarias: velocidad del viento, presión atmosférica, radiación solar, nubosidad, humedad relativa, temperatura media, temperatura máxima y mínima, y precipitación. Para considerar la variabilidad entre GCMs y minimizar la incertidumbre de las predicciones, se emplearon todos los GCMs seleccionados para crear un conjunto y así obtener una estimación promedio de las predicciones futuras.

En primer lugar, se extrajeron datos históricos de cada GCM con el fin de realizar una corrección de sesgo, utilizando datos observados como referencia. En el primer estudio realizado (Jiménez-Navarro et al., 2021) se compararon cinco transformaciones estadísticas en el programa R, todas basadas en alinear la distribución de los datos simulados con la de los datos climáticos observados, técnicas que son ampliamente utilizadas en estudios hidrológicos y climáticos (Vigna et al., 2020). El rendimiento de estos métodos se evaluó mediante el error absoluto medio entre los datos observados y los corregidos, siguiendo la recomendación de Gudmundsson et al. (2012). La transformación paramétrica resultó ser la que mejor se ajustó a los datos históricos observados. En el siguiente estudio realizado en la misma cuenca (Jiménez-Navarro et al., 2023) se utilizó el mismo método. Sin embargo, al aplicar esta metodología en el Campo de Cartagena, se realizaron ajustes específicos. Fueron necesarios dos métodos distintos de corrección de sesgo. El primero fue el mapeo de cuantiles empíricos, una técnica comúnmente empleada para corregir variables atmosféricas en estudios de cambio climático (Enayati et al. 2020). Este método se aplicó para la

corrección de sesgo de la velocidad del viento, presión atmosférica, temperatura, humedad relativa, cobertura de nubes y radiación solar. Para la precipitación, debido a la baja pluviosidad de la región, excepto en días de tormenta, se utilizó una corrección lineal mensual para evitar la amplificación de valores extremos (Thiemeßl et al. 2011; Maraun 2013; Maurer y Pierce 2014; Cannon et al. 2015). A diferencia del lago Erken, en esta cuenca no se disponía de un registro histórico del clima, por lo que la corrección de sesgo se realizó utilizando datos del conjunto ERA5 (ej, Zhai et al. 2020; Xu et al. 2021; Carvalho et al. 2021; Jamal et al. 2023).

Tras la corrección de sesgo se extrajeron los datos climáticos futuros de cada GCMs, a los que también se aplicó la corrección de sesgos. Para evaluar la incertidumbre de las predicciones, se descargaron datos de dos escenarios diferentes de cambio climático, utilizando dos Trayectorias Socioeconómicas Compartidas (Shared Socioeconomic Pathways, SSPs). Los dos escenarios utilizados fueron el SSP 2-45 y SSP 5-85. Ambos escenarios ofrecen una visión de cómo podría evolucionar el clima bajo diferentes trayectorias socioeconómicas. SSP 2-45 sigue los patrones actuales de emisiones globales con barreras moderadas para la reducción del cambio climático, mientras que SSP 5-85 prioriza el desarrollo económico sobre el impacto ambiental, lo que lleva a desafíos climáticos más severos. Al comparar un escenario de cambio climático donde no se aplican mitigaciones frente al cambio climático (SSP 5-85) con uno en el que se aplican mitigaciones moderadas (SSP 2-45), podemos evaluar las implicaciones de diferentes enfoques políticos y económicos para el cambio climático (O'Neill et al. 2014).

Para poder analizar las predicciones futuras, se dividieron en periodos de la misma duración que el histórico de cada estudio. De esta forma se han obtenido periodos de futuro a medio plazo y a largo plazo comparables con el histórico.

#### 4.5. SERVICIOS ECOSISTÉMICOS

En nuestro último estudio se ha utilizado un enfoque de Servicios Ecosistémicos (SE) en el Mar Menor para estudiar la amenaza del cambio climático. Cómo ya se ha hablado en el apartado 4.1.2. el Mar Menor y su entorno posee una relevancia especial en la región lo que hace que esté asociado a diversos servicios ecosistémicos que benefician a la población local.

Tabla 3. Definición y fuente de los SER analizados en el Campo de Cartagena y el Mar Menor.

| Localización                      | SER                                                     | Definición                                                                             | Salidas del modelo SWAT+ o GOTM-WET                                                                                    |
|-----------------------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| <b>Campo de Cartagena (SWAT+)</b> | Control de la erosión del suelo                         | Capacidad del ecosistema para retener sedimentos y prevenir su transporte              | Producción de sedimentos t/ha (SYLD)                                                                                   |
|                                   | Protección frente riesgos naturales                     | Mitigación de inundaciones, tormentas y eventos extremos                               | Caudal medio diario de salida de la cuenca a la laguna mm (FLO_OUT)                                                    |
|                                   | Regulación del caudal                                   | Agua verde (GW): agua en el suelo no saturado disponible para la evapotranspiración    | Evapotranspiración mm (ET) y Contenido de agua del suelo mm (SW_AVE)                                                   |
|                                   |                                                         | Agua azul (BW): masas de agua superficiales y subterráneas disponibles para uso humano | Rendimiento hídrico mm (WYLD) y Recarga del acuífero profundo mm (RCHRG)                                               |
|                                   | Mediación de sustancias nocivas de origen antropogénico | Transformación de los aportes de nitrógeno al ecosistema                               | Nitrógeno orgánico transportado KgN (ORGN_OUT), nitrato transportado KgN (NO3_OUT) y amonio transportado KgN (NH3_OUT) |
|                                   |                                                         | Transformación de los aportes de fósforo al ecosistema                                 | Fósforo orgánico transportado KgP (SEDP_OUT) y fósforo mineral transportado KgP (SOLP_OUT)                             |
| <b>Mar Menor (GOTM-WET)</b>       | Condiciones del agua                                    | Regulación de las condiciones físicas, químicas y biológicas                           | Clorofila-a mg/m <sup>3</sup>                                                                                          |
|                                   |                                                         |                                                                                        | Temperatura del agua C°                                                                                                |
|                                   |                                                         |                                                                                        | Concentración de O <sub>2</sub> g/m <sup>3</sup>                                                                       |
|                                   |                                                         |                                                                                        | Nitrógeno total g/m <sup>3</sup>                                                                                       |
|                                   |                                                         |                                                                                        | Fósforo total g/m <sup>3</sup>                                                                                         |

Por ello, se han identificado diferentes SE del Campo de Cartagena y de la laguna del Mar Menor a través de las simulaciones obtenidas de los modelos SWAT+ y GTOM-WET, lo cual nos ha permitido analizar cómo el cambio climático afectará a estos SE. Se eligieron cinco SER específicos para su análisis en el Campo de Cartagena (tabla 3), utilizando salidas del modelo SWAT+. Estos cinco SER ya han sido estimados previamente en otros estudios que emplearon modelos SWAT (Kauffman et al., 2014; Cong et al., 2020; Aznarez et al., 2021). Además, se analizó el SER relacionado con las condiciones del agua en la laguna a través del análisis de cinco variables del Mar Menor, utilizando salidas del modelo GOTM-WET (tabla 3).

Al analizar los SER en periodos de futuro a medio y largo plazo y bajo dos escenarios de cambio climático distintos (SSP 2-45 y SSP 5-85), podemos extraer conclusiones de cómo la severidad del cambio climático afectará al ecosistema y qué consecuencias tendrá esto para la población local y las partes interesadas.



## **V – PUBLICACIONES**

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## V - PUBLICACIONES

De esta tesis se derivaron cinco artículos científicos. A continuación, se ofrece un breve resumen de cada artículo y como contribuye al conjunto de la tesis.

- **Publicación 1:** La primera publicación se titula “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”. En ella se reflejan los primeros pasos de la autora en la modelización hidrológica: una aplicación sencilla del modelo SWAT+ en la cuenca del Lago Erken (Suecia) para evaluar el impacto del cambio climático. El área de estudio presenta una cuenca forestal con un nivel bajo de antropización, lo cual la convierte en el campo de pruebas ideal. Al ser una zona muy cercana al círculo polar ártico, la nieve juega un papel importante en esta cuenca, por lo que también se tuvo en cuenta como componente del ciclo hidrológico y se analizó cómo se vería afectada por el cambio climático. De esta forma se desarrolló un modelo SWAT+, cuyos parámetros sensibles al flujo fueron calibrados de forma automática y diaria. También se calibraron manualmente dos parámetros relacionados con la nieve y su acumulación en la cuenca. El rendimiento del modelo resultó satisfactorio tanto para la calibración como para la validación. La siguiente parte del estudio consistió en desarrollar una metodología de análisis de cambio climático: selección y acoplamiento de distintos GCMs para crear un conjunto de predicciones en el área de estudio. Siete GCMs fueron seleccionados y se les aplicó una corrección de sesgo con distintas metodologías, seleccionando la más efectiva. Dentro de cada GCM se extrajeron datos históricos y de dos predicciones de cambio climático distintas, una más moderada (SSP 2-45) y otra más extrema (SSP 5-85). Así el periodo histórico se comparó con predicciones de tres periodos futuros: a corto (2026–2050), medio (2051–2075) y largo (2076–2100) plazo, bajo ambos escenarios de predicción. Los resultados obtenidos indican un aumento previsto de la temperatura de 2 a 4 °C y de la precipitación

de un 6% a un 20%, lo que incrementaría el caudal de agua en un 18% en el mejor de los casos y hasta un 50% en el peor. Además, el aumento de la temperatura provocaría una reducción preocupante en la acumulación de nieve, entre el 65% y el 92%. Estos cambios podrían llevar a un empobrecimiento del suelo y una menor disponibilidad de agua en la cuenca, afectando negativamente a los bosques y ecosistemas locales.

- **Publicación 2:** El segundo artículo publicado se titula “Application of an integrated catchment-lake model approach for simulating effects of climate change on lake inputs and biogeochemistry” y es la continuación de la investigación iniciada en la publicación anterior. El foco de este estudio fue el efecto del cambio climático en la biogeoquímica del lago Erken. Para ello se desarrolló otro modelo SWAT+ de la misma cuenca, aplicando algunas mejoras con respecto al anterior, y se desarrolló un modelo GOTM-WET para simular la hidrodinámica del lago y sus relaciones ecosistémicas. Ambos modelos fueron acoplados, utilizando los datos de salidas del modelo SWAT+ como datos de entrada del modelo GOTM-WET. Debido a que el modelo SWAT+ aún se encontraba en desarrollo y la predicción de sedimentos y nutrientes no resultaba del todo fiable, se optó por la simulación de esos datos de entrada del modelo GOTM-WET mediante la aplicación de Load Estimator (LOADEST). Para la obtención de predicciones de cambio climático se utilizaron los GCMs seleccionados en la Publicación 1 (a excepción de dos que no contaban con datos de entrada necesarios para el modelo GOTM-WET), así como el mismo método de corrección de sesgo y los mismos escenarios de predicción de cambio climático. Los resultados obtenidos muestran un aumento de la temperatura, la precipitación y la evapotranspiración en la cuenca hidrográfica, lo que en conjunto se traducirá en un mayor caudal de entrada de agua al lago. La creciente escorrentía superficial repercutirá negativamente en el suelo de la cuenca, en los cauces hidrológicos y en la aportación de nutrientes al lago. Por su parte, en el lago aumentará la temperatura del agua, lo que provocará una mayor estratificación y un descenso de los niveles

de oxígeno. Se prevé que los niveles de nitrato no varíen, mientras que los de fosfato y amonio aumentarían. Una configuración integrada de la cuenca y el lago, como la que se presenta aquí, permite predecir las futuras condiciones biogeoquímicas de un lago, teniendo en consideración cómo los cambios en el uso del suelo influyen en las condiciones del lago, ofreciendo una visión mucho más holística de las consecuencias que el cambio climático tendría en el ecosistema. Además, el poder observar la variación de nutrientes facilita la comprensión de los procesos de eutrofización.

- **Publicación 3:** El tercer artículo publicado se titula “The Implications of the Use of ET Remote Sensing Data for Calibrating Hydrological Models: A Comparison of Single and Multi-criteria Calibration in SWAT +”. En ella se compararon distintas formas de calibrar un modelo SWAT+ en la cuenca del lago Erken. Se plantearon tres calibraciones distintas, una en la que se usaron solo datos de caudal, otra con datos de evapotranspiración y una multicalibración utilizando ambas variables. Se compararon las tres con el modelo sin calibrar, para dilucidar las ventajas e inconvenientes de cada una. Los datos de evapotranspiración se obtuvieron vía satélite, a través de técnicas de teledetección. Para ello se usó usaron datos de GLEAM. Los resultados muestran que las tres simulaciones son estadísticamente aceptables tanto para el caudal como para la evapotranspiración. En las calibraciones individuales, se observa una mejora en la variable calibrada, pero un peor ajuste en la otra. Sin embargo, el enfoque de la multi-calibración produce valores intermedios para el caudal y la ET, demostrando su utilidad. La calibración utilizando únicamente ET presenta algunas limitaciones para simular el flujo lateral y la retención de agua en el suelo, aunque se muestra como un potencial método robusto para cuencas sin mediciones.
- **Publicación 4:** El cuarto artículo publicado se titula “Ecological crisis from children’s perspective: Lessons learned and their importance in shaking up social awareness” y es el único de esta tesis que se centra en las actividades de ciencia ciudadana del proyecto

SMARTLAGOON. En este estudio consideramos el efecto que la crisis eutrófica del Mar Menor tiene sobre la población local, en concreto los niños, y su papel a la hora de divulgar conocimiento y los potenciales efectos sociales de trabajar con ellos. La primera parte del estudio consistió en dos campañas de ciencia ciudadana con los estudiantes del colegio de Los Nietos. El objetivo fue evaluar su conocimiento sobre la crisis del Mar Menor, conocer sus opiniones y experiencias, y medir el impacto social de estas actividades. Se les pidió realizar un dibujo relacionado con el Mar Menor mientras estaban en la playa de Los Nietos, semanas después rellenaron una encuesta sobre la actividad. Analizando las respuestas y los dibujos de los niños se extraen varias conclusiones: aunque los niños no entiendan completamente qué está causando la catástrofe sí son conscientes de ella y continúan mostrando una perspectiva optimista con respecto al futuro de la laguna. La segunda parte consistió en un análisis del impacto que la actividad tuvo en las redes sociales. Nuestros resultados apuntan a que la actividad principal tuvo un impacto en los niños y que sus acciones se transmiten también a la sociedad, convirtiéndolos en altavoz del problema medioambiental.

- **Publicación 5:** El último artículo que compone esta tesis se titula “Modeling Climate Impacts on Ecosystem Services in an Anthropized Coastal Lagoon for Effective Planning and Adaptation” y actúa a modo de culminación de la tesis, aplicando todo lo testado previamente en el lago Erken al Campo de Cartagena y el Mar Menor. Para ello se utilizó el marco de los SE. De esta forma se desarrolló un modelo SWAT+ para el Campo de Cartagena utilizando datos de ET satelital. También se desarrolló un modelo GTOM-WET para el Mar Menor y ambos fueron acoplados. Gracias a esto se extrajeron estimaciones de algunos SER del área. Utilizando cinco GCMs y predicciones de dos escenarios de cambio climáticos distintos, se obtuvo una estimación de cómo se verá afectado el Mar Menor y su entorno en el futuro lejano. Nuestros resultados muestran que debido al cambio climático las temperaturas aumentarán aproximadamente 2°C y las precipitaciones se reducirán entre un 4 y un 19% en el Campo

de Cartagena, a pesar del aumento de los días torrenciales. Esto afectará negativamente a todos los SER analizados, alterando la dinámica de nutrientes (el aporte de fósforo se incrementará en más de un 100% y el de nitrógeno se reducirá en un 38%), disminuyendo la disponibilidad de agua (la entrada de agua se reducirá en un 6-23%, el GW hasta un 6% y el BW hasta en un 43%) y aumentando el riesgo de inundaciones, comprometiendo así la resiliencia de este ecosistema. Además, se prevé un empeoramiento de las condiciones del RES de las condiciones del agua debido a cambios en las características físicas, químicas y biológicas de la laguna, incluido un aumento de la temperatura de 2,2-3,7°C, una disminución de los niveles de oxígeno y un aumento de la clorofila de aproximadamente 1 mg/m<sup>3</sup>. Como consecuencia, se prevé que la hipoxia y la proliferación de algas sean más frecuentes, lo que supondrá un mayor estrés para el ecosistema.

5.1. RESEARCH PAPER 1: 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

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.

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## Article

# 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

Inmaculada C. Jiménez-Navarro <sup>1</sup>, Patricia Jimeno-Sáez <sup>1</sup>, Adrián López-Ballesteros <sup>1</sup>, Julio Pérez-Sánchez <sup>2</sup> and Javier Senent-Aparicio <sup>1,\*</sup>

<sup>1</sup> Department of Civil Engineering, Catholic University of San Antonio, Campus de los Jerónimos s/n, 30107 Guadalupe, Spain; icjimenez@ucam.edu (I.C.J.-N.); pjimeno@ucam.edu (P.J.-S.); alopez6@ucam.edu (A.L.-B.)

<sup>2</sup> Department of Civil Engineering, Universidad de Las Palmas de Gran Canaria, Campus de Tafira, 35017 Las Palmas de Gran Canaria, Spain; julio.sanchez@ulpgc.es

\* Correspondence: jsenent@ucam.edu; Tel.: +34-968278769



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**Abstract:** Precipitation and temperature around the world are expected to be altered by climate change. This will cause regional alterations to the hydrological cycle. For proper water management, anticipating these changes is necessary. In this study, the basin of Lake Erken (Sweden) was simulated with the recently released software SWAT+ to study such alterations in a short (2026–2050), medium (2051–2075) and long (2076–2100) period, under two different climate change scenarios (SSP2-45 and SSP5-85). Seven global climate models from the latest projections of future climates that are available (CMIP 6) were compared and ensembled. A bias-correction of the models' data was performed with five different methods to select the most appropriate one. Results showed that the temperature is expected to increase in the future from 2 to 4 °C, and precipitation from 6% to 20%, depending on the scenario. As a result, water discharge would also increase by about 18% in the best-case scenario and by 50% in the worst-case scenario, and the surface runoff would increase between 5% and 30%. The floods and torrential precipitations would also increase in the basin. This trend could lead to soil impoverishment and reduced water availability in the basin, which could damage the watershed's forests. In addition, rising temperatures would result in a 65% reduction in the snow water equivalent at best and 92% at worst.

**Keywords:** SWAT model; hydrological modelling; hydrological cycle; water balance alterations

## 1. Introduction

Climate change is a worldwide known phenomenon that is widely accepted by the scientific community [1]. This phenomenon is expected to alter precipitation and temperatures around the globe in various ways, making climates drier in some places and wetter in others. One of the main impacts will be on the hydrological cycle and water bodies on land, especially in streamflow regimes [2,3]. Rivers, lakes, aquifers, and their basins are strongly affected by changes in evapotranspiration, runoff processes, floods, and erosion [4–7]. Hence, changes in the temperature and precipitation patterns will alter these processes. Changes that affect snow processes—such as the snow accumulation pattern or glacier melt runoff—would also have a high impact [8,9]. All these variations will incur long-term negative consequences for ecosystems and human activities, especially in drainage basins. Serious detrimental alterations are currently occurring through droughts and floods [10]. The ecosystems that are most vulnerable to such alterations include those formed by long-living water-dependent vegetation, such as forests. Overall, water resource management could be seriously compromised by climate change. Water-dependent ecosystems would be particularly affected. The only way to prepare for the likely future scenario

is to foresee the effects of climate change on the hydrological cycle and make decisions accordingly. In recent years, multiple works have addressed these problems in different parts of the world [11–17].

Hydrologic circumstances vary by location. Therefore, the effects of climate change on local hydrological and ecosystem processes are expected to differ even under the same climate predictions. For example, in northern Europe, precipitation is expected to increase. In flat, humid areas with vegetation, this increase in precipitation may be linked to flooding and bogging down of the land. However, in a dry, sloping area, the increase in precipitation would lead to a very serious increase in soil erosion. In both cases, palliative measures to adapt to the increase in temperature must be different. When planning effective regional water resources, it is important to understand the regional conditions and to develop region-specific assessments of climate change [18].

In the case of Sweden, as in the rest of northern Europe, the average amount of precipitation is expected to increase in the future [19,20]. However, this does not necessarily imply an increase in water availability. On the contrary, the increase in seasonal precipitation is likely to be related to extreme events in terms of the daily rainfall [19,20]. This scenario could paradoxically lead to a reduction in water availability and to soil impoverishment [17]. These phenomena could seriously alter the forest ecosystems that depend on water resources in specific areas and the soil quality.

In the south of Sweden, as in any land areas towards the poles, snow is an important component of the climate and the hydrologic cycle [21]. All basins are partially covered by snow during the cold season. It should be noted that in snow-dominated basins, snow processes are of vital importance. Snowfall, snow accumulation, and snowmelt have a strong effect on the hydrological cycle [22]. Changes in the estimation of these water balance components can alter a hydrological simulation significantly [23]. Therefore, researchers should consider these components when modelling snow-covered basins [24].

The snow water equivalent (SWE) and snowmelt are the most essential snow statistics for hydrologists [25]. The SWE is described as a water column that forms as a result of the melting of unit cross-section snow samples with a height equal to the depth of the snowpack at the measurement point [26]. The SWE is the major parameter determining the magnitude of the snowmelt runoff volume. It is used as a variable in snow runoff analysis to estimate the distribution and quantity of snow [27].

The aim of this study is to model the Lake Erken basin and use the model to predict how climate change is likely to affect the hydrological cycle in this area and their ecosystems. To achieve this aim, the Soil and Water Assessment Tool+ (SWAT+) [28] software was used to create the model. Although its predecessor, SWAT [29] has been widely used around the world, and to date, few published works have used SWAT+. Only three studies have used SWAT+ to analyse the impact of climate change on a watershed. Chawanda et al. [30] used mass balance calibration and reservoir representations to evaluate, at the regional scale, the climate change effects in Southern Africa. Senent-Aparicio et al. [31] analysed the impact of climate change on environmental flows in the northwest of Spain using a new post-processing tool for SWAT+ models. Kiprotich et al. [32] studied the surface runoff response to climate change and land-use change in Nairobi, Kenya. None of these studies used global climate models from the Coupled Model Intercomparison Project 6 [33] but instead used its predecessor, the Coupled Model Intercomparison Project 5.

Even though SWAT was not developed for flood modelling, there have been SWAT flood studies documented [34–38]. Tan et al. offer a review of some of these studies [39], highlighting the problems that SWAT presents when performing calibrations and validations based on extreme events and the need for improvements in SWAT to capture extreme events. Despite this, most extreme performance evaluation studies reviewed found satisfactory results, with a focus on peak flow comparisons. No studies using SWAT+ to simulate extreme events have yet been published.

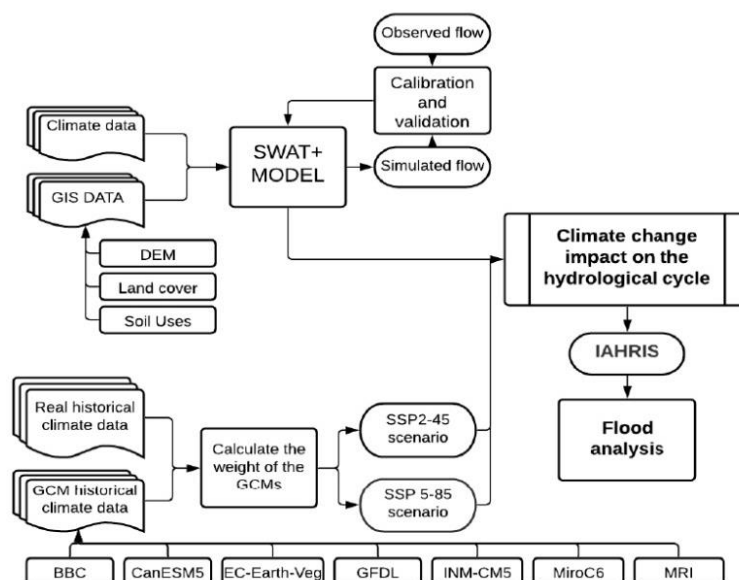
The most common data used to calibrate and validate SWAT models is the streamflow in the outpoint of a basin. Given the importance of the snow and snow parameters in the

Lake Erken basin, in this study, the SWE data have also been used in the calibration and validation of the model, in a complementary way. Finally, the temperature and precipitation data obtained from various climate change scenarios will be used to predict the evolution of the Lake Erken watershed in the coming decades.

## 2. Methodology

### 2.1. Conceptual Model

First, a SWAT+ model was developed, then calibrated and validated with observed streamflow and SWE satellite data. In addition, seven global climate models (GCMs) were weighted using real historical climate data as the reference. The future data were used under two climate change scenarios to simulate the water cycle of Lake Erken during a short-term period, a medium-term period and a long-term period. Finally, various parameters related to floods were calculated with Indicators of Hydrological Alteration in Rivers (IAHRIS) [40]. The aim of this step was to compare the historical floods in Lake Erken with the projected floods that would be altered because of the climate change effects. The methodology of this article is represented in Figure 1.

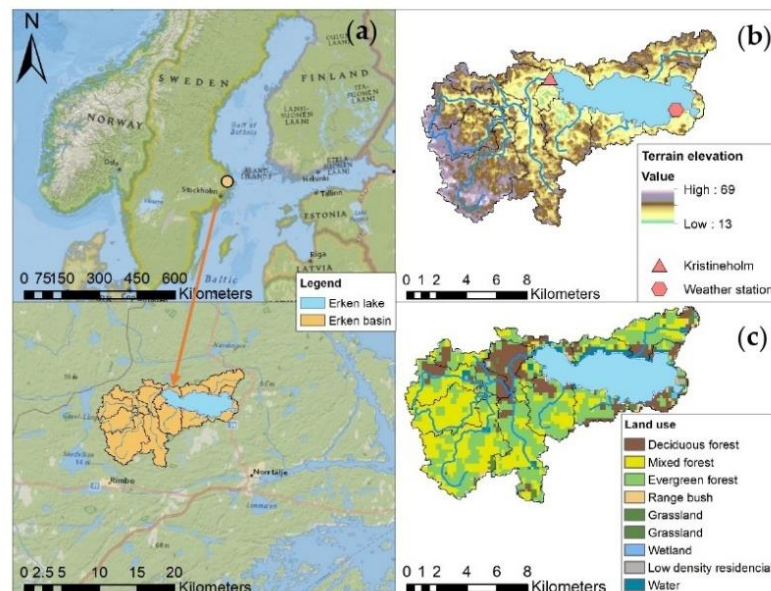


**Figure 1.** Flowchart of the approach underlying this investigation.

### 2.2. Description of the Study Area

Lake Erken is located in the eastern part of Sweden ( $59^{\circ}50'37''$  N,  $18^{\circ}35'38''$  E) at an altitude of 10 m above sea level (Figure 2). The surface area of the lake is approximately 24 km<sup>2</sup>. It is a shallow lake; the mean depth is around 9 m, and the deepest point is 21 m underwater. The lake has a residence time of 7.4 years. It can be described as a moderately eutrophic lake with an intermediate level of productivity. Its surface is usually ice-covered during winter, whereas during the summer, the water is stratified [41,42]. Both of these phenomena have been largely studied in Lake Erken [43–45].





**Figure 2.** Map of the study area: (a) localisation of Lake Erken and its basin in the Scandinavian Peninsula; (b) digital elevation map of the Lake Erken basin and location of Kristineholm and the weather station; (c) land uses in the Lake Erken basin.

The Erken basin is oriented toward the east and does not present significant slopes. It is a relatively small drainage basin ( $141 \text{ km}^2$ ) that is covered by forest, without any significant anthropic activity [46]. In the basin, there are exclusive areas of both deciduous forest and evergreen forest; in most of the basin, both types of vegetation share the space, forming a mixed forest that dominates the watershed (Figure 2c). This forest plays a vital role in the water cycle. Forests regulate processes such as evapotranspiration, runoff, and water retention in forested basins [47–51]. The main large water inflow point to the lake is Kristineholm (Figure 2b). This input is where the water discharge for calibration and validation is measured.

In the south of Sweden, the climate is humid and continental, with a warm summer ( $17.3^\circ\text{C}$  average in July and August) and a weak winter—despite the country's high latitude. The length of daylight varies from 18 h in June to 6 h in December. According to the historical data used in this study for 1990–2014, in the Erken basin the average temperature in July and August was  $17.3^\circ\text{C}$  and in February it was  $-4^\circ\text{C}$ . Precipitation does not change much during the year but is slightly higher during autumn; the annual average is 519 mm. Precipitation in the form of snowfall occurs between December and March, and the basin is covered by snow for 75 to 100 days a year.

### 2.3. SWAT+ Model

The Soil and Water Assessment Tool (SWAT) [29] software provides a hydrological model that is used worldwide. It has been successfully used in a range of scenarios with different climatic conditions, land management practices, and temporal and spatial scales. During the last 20 years, SWAT has been implemented periodically to meet the diverse requirements of the scientific community around the world. However, the current framework has reached the limit of its potential development. The most recent version, SWAT+, improves the runoff routing capabilities while preserving the model's computational efficiency and ease of use [28].

Water dynamics are represented by fluctuations in the hydrologic response units (HRUs) in both the SWAT and SWAT+ models. Each HRU is a unique combination of land-use, slope, soil, and management activities, which are connected by a geographic information system (GIS) interface. Using this GIS interface, in both models, the modelled basin is divided into various sub-basins, which are further sub-divided into HRUs [52]. The concept of water balance, represented by Equation (1), is applied in the model as the watershed's primary driver of all hydrology.

$$SW_i = SW_o + \sum (V_i - Q_i - E_i - P_i - QR_i) \times \Delta t \quad (1)$$

where  $SW_i$  and  $SW_o$  represent the final and initial soil water content (mm/day);  $V_i$  represents the precipitation (mm/day);  $Q_i$  represents the surface runoff (mm/day);  $E_i$  represents the evapotranspiration (mm/day);  $P_i$  represents the percolation (mm/day);  $QR_i$  represents the return flow (mm/day); and  $\Delta t$  represents the time interval (day). The  $i$  term refers to the index.

Despite using the same equations, in SWAT+ the elements of the watershed—such as aquifers, land-use units, HRUs, ponds, and reservoirs—are defined as spatial objects. This feature enhances the flexibility of the configuration and discretisation of the basin compared with the earlier SWAT [28].

#### 2.4. Model Setup

The use of a hydrological model with SWAT+ requires specific geographical information about the area of interest. The data required include a digital elevation map (DEM), a land cover map, and a soil map. The model also requires meteorological input data. For this study, the DEM was obtained from the Shuttle Radar Topography Mission (SRTM). The SRTM uses a single-pass space-borne interferometric SAR system, which operates in both the C-band (5.6-cm) and the X-band (3-cm) frequencies to collect data about the earth's surface elevation [53]. The land cover map was obtained from Glob Cover 2015, which provides a 300-m resolution [54]. The soil data were gathered from the Food and Agriculture Organisation of the United Nations' Harmonised World Soil Data. This collection contains information for 16,000 map units with two soil layers, namely 0–30 and 30–100 cm deep [55].

For the meteorological input data, daily precipitation and temperature data were obtained from the Erken Laboratory meteorological station (59°51'30.7080" N, 18°24'17.5536" E), situated on the Malma islet (Figure 2b). This station provides automated measurements daily temperature and precipitation data and other information. The Hargreaves method was used to determine potential evapotranspiration [56]; this method requires only the precipitation and temperature data. According to Oudin et al. [57], hydrological models that employ parsimonious temperature-based methods perform similarly to models that use more data-demanding methods.

The calibration and validation of the simulated streamflow required discharge data. The discharge data available has been measured daily at Kristineholm, the largest input of Lake Erken, since mid-2006. In this study, the SWE was also calibrated. The SWE data from the Copernicus Global Land Service were used. It offers a 0.05° spatial resolution, calculated by integrating passive microwave radiometer brightness temperature readings from the Special Sensor Microwave Imager/Sounder with synoptic weather station network snow-depth data [58].

#### 2.5. Calibration and Validation of the SWAT Model

To locate the most influential parameters for the streamflow, we performed a sensitivity analysis. Then, the sensitive parameters were adjusted with a daily automatic calibration for the 2007–2015 period. Both analyses were performed in Toolbox [59], a free software designed to perform SWAT+ model sensitivity analysis, calibrations, and more. Afterwards, we used the 2016–2020 daily data to validate the SWAT+ model.

For the sensitivity analysis, Toolbox uses the Sobol method [60]. Within an ensemble, it divides the overall output variance into the variation produced by each parameter. For automatic calibration, Toolbox uses a dynamically dimensioned search (DDS) [60]. The Nash–Sutcliffe efficiency coefficient was applied as the target function in this investigation. The goodness of fit was determined using Moriasi’s four recommended statistics. In addition, for both calibration and validation, the performance was evaluated using Moriasi’s four recommended statistics [61]. These are the coefficient of determination ( $R^2$ ) (Equation (2)), the Nash–Sutcliffe efficiency (NSE) (Equation (3)), the standard deviation of measured data (RSR) (Equation (4)), and the per cent bias (PBIAS) (Equation (5)). The criteria proposed by Moriasi [61] were applied. Both calibration and validation have been performed on a daily scale.

$$R^2 = \left[ \frac{\sum_{i=1}^n (O_i - \bar{O}) (S_i - \bar{S})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (S_i - \bar{S})^2}} \right]^2 \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (3)$$

$$RSR = \frac{\sqrt{\sum_{i=1}^n (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (4)$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - S_i)}{\sum_{i=1}^n O_i} \times 100 \quad (5)$$

In Equations (2)–(5), the observed and simulated water flow data are  $O_i$  and  $S_i$ ; the average observed and simulated water flow values are  $\bar{O}$  and  $\bar{S}$ ; and  $n$  refers to the total dataset.

To enhance the model, we performed a manual calibration of the SWE with the snow-related parameters. Since Toolbox does not allow for calibrating the SWE, we performed the calibration manually in SWAT+ Editor, which is a tool for editing, running, and saving changes to a SWAT model. Then, we validated each test in a spreadsheet by applying Equations (2)–(5) to the SWE.

## 2.6. Global Climate Models and Climate Change Scenarios

To make predictions for the Erken watershed, future climate models that simulate the temperature and precipitation in the coming years are required [62]. Historical data from seven GCMs were downloaded from the Coupled Model Intercomparison Project (CMIP6) website (<https://esgf-node.llnl.gov/search/cmip6/>, accessed on 26 November 2021) [33]. The downloaded data were compared with the real historical data for precipitation and temperature in the Erken watershed. Based on the analysis of McSweeney et al. [63], seven GCMs whose performance for Europe had been identified as satisfactory were selected: BBC, CanESM5, EC-Earth-Veg, GFDL, INM-CM5, MiroC6, and MRI. These seven GCMs were compared and assessed in this study. We used the methodology proposed by Pulido-Velazquez et al. [55]. The Id indicator (Equation (6)) was calculated by summing the increases in the mean and variance of the control series over the historical series for the period 1985–2014, as follows:

$$Id_i = \sum_{n,m=1}^2 Id_i(V_n S_m); \quad (6)$$

$$Id_i(V_n S_m) = \sum_{j=1}^{12} \frac{(V_n S_m)_i^j - (V_n S_m)_{Hist}^j}{(V_n S_m)_{Hist}^j}$$

where subscript  $i$  is a subindex for a particular GCM,  $V_1$  is the rainfall variable,  $V_2$  is the temperature variable,  $S_1$  is the mean monthly value,  $S_2$  is the monthly standard deviation, and superscript  $j$  is the number of months in a year. This indicator allows a ranking of



GCMs to be established in terms of goodness of fit to the observed time series, so that an ensemble of predictions can be proposed, which gives more weight to the best scoring (lower Id index values). Then, the total Id indicator was rescaled by defining the Id\* index, so that the sum of the values obtained for all models is equal to 1. Finally, the Ib indices were obtained, which are the complementary values of the Id\* indicator, i.e.,  $(1 - Id^*)$ , rescaled to 1. These Ib indicators were used as weights applied to the series obtained with each model to create an ensemble of predictions.

The historical data of each GCM were bias-corrected using the five statistical transformations available in the “qmap” package for R software. These were the robust empirical quantiles (RQUANT), distribution derived transformations (DIST), empirical quantiles (QUANT), parametric transformations (PTF), and smoothing spline (SSPLIN) [64]. These methods try to align the distribution of simulated data with that of observed climate data and are commonly used in hydrological and climatic studies [65–67].

The performance of the various methods was measured using the mean absolute error (MAE) between the observed and corrected data. This procedure is recommended by Gudmundsson et al. [64]. The method that best fitted the observed historical data was selected for the correction of future climate change scenarios.

Lastly, the climate projection was analysed under two different shared socioeconomic pathway (SSP) scenarios [68]. These were the SSP 2-45 and the SSP 5-85 scenarios. In the SSP 2, global emissions are predicted to follow current patterns. This implies significant obstacles for reduction and adaptation, but neither is particularly severe. On the other hand, the SSP 5 illustrates a scenario in which economic development takes precedence over environmental impacts. As a result, the challenges posed by climate change are difficult to meet [69]. The SSP 2-45 and SSP 5-85 are, respectively, the equivalents of the RCP4.5 and RCP8.5 of the CMIP 5, updated with socioeconomic reasons [70]. These two scenarios have been widely used in climate change studies because they allow a comparison between a more positive outlook (SSP 2-45) in which greenhouse gas emissions are intermediate and the effects of climate change are not as severe, and a more extreme outlook (SSP5-85) in which the challenges of climate change are greater.

### 2.7. IAHRIS Software

Indicators of Hydrologic Alteration (IHA) are commonly used to compare the variations in hydrological regimes between a base scenario and an altered scenario [71]. IAHRIS is a software program created by the Centre for Public Works Studies and Experimentation (CEDEX) [40]. It calculates various hydrological parameters of the flow and uses them to calculate various IHA. IAHRIS is particularly suited for evaluating flood events, since the indicators are divided into ordinary values, maximum extreme values (floods), and minimum extreme values (droughts). In addition, there are recent examples of previous studies that use IAHRIS and SWAT with satisfactory results [72,73]. In this work, IAHRIS was used to compare historical floods in Lake Erken with the projected floods that were altered in the future because of climate change effects. To study extreme peak flow events (floods) IAHRIS offers 8 parameters (Qc, Ql, Qconnec, Q5%, CV (Qc), CV (Q5%), consecutive days of flooding and flood days per month), which are described as follows. To analyse the magnitude and frequency of the floods, we used:

- Qc: the mean of the maximum annual daily flow.
- Ql: bed generation flow; this parameter represents the flow that performs most of the work of material relocation and is responsible for the geomorphology of the channel.
- Qconnec: the maximum flow that ensures the river channel–floodplain connection is represented by the connectivity flow.
- Q5%: this parameter is the flow corresponding to the average flow curve classified at the 5% exceedance percentile.

To analyse the variability of the floods, we used:

- CV (Qc): coefficient of variation of the series of maximum annual daily flow rates.
- CV (Q5%): coefficient of variation of the series of usual floods.

To study the duration of the floods, we used the maximum number of consecutive days with an average daily flow rate greater than the Q5%. Lastly, IAHRIS offers the flood days per month to analyse the seasonality of the floods.

More information about these parameters appears in the IAHRIS methodological reference manual [74].

### 3. Results and Discussion

#### 3.1. Calibration and Validation of the Model

The sensitivity analysis found the following parameters to be sensible: cn2, alpha, esco, perco, revap\_co, epco, awc, flo\_min, revap\_min, surlag, and k (see Table 1). For the SWE, we manually calibrated two parameters, the snomelt\_tmp and snomelt\_lag, which were modified. Table 1 shows the description of all modified parameters along with their range and the final value after calibration.

**Table 1.** Description, range, and adjusted value for all modified parameters after calibration.

| Parameter   | Description                                                                                                           | Range      | Adjusted Value |
|-------------|-----------------------------------------------------------------------------------------------------------------------|------------|----------------|
| Cn2         | The curve number relates to the soil permeability                                                                     | −20–20%    | −18%           |
| Alpha       | The baseflow recession constant measures the reaction of groundwater flow to recharge variations                      | 0–1        | 0.35           |
| Esco        | Soil evaporation compensation factor                                                                                  | 0–1        | 0.50           |
| Perco       | Percolation coefficient (it depends on the soil moisture)                                                             | −0.05–0.05 | 0.001          |
| Revap_co    | Groundwater re-evaporation coefficient                                                                                | 0–1        | 0.05           |
| Epco        | Compensation factor for plant uptake                                                                                  | 0.01–1     | 0.50           |
| Awc         | The soil layer's available water capacity                                                                             | −20–20%    | −0.5%          |
| Flo_min     | Minimum aquifer storage to allow return flow                                                                          | 0–5000     | 230.08         |
| Revap_min   | Threshold depth of water in the shallow aquifer needed for re-evaporation or percolation to the deep aquifer to occur | 0–5000     | 1313.18        |
| Surlag      | Surface runoff lag coefficient                                                                                        | 1–24       | 1.20           |
| K           | Saturated hydraulic conductivity                                                                                      | 1–100      | 99.77          |
| Snomelt_tmp | Snowmelt base temperature (°C)                                                                                        | −3–2.5     | 0.00           |
| Snomelt_lag | Snowpack temperature lag factor                                                                                       | 0–1        | 0.20           |

Most of the parameters that Cibin [75] identified as having a major impact on the streamflow simulation were sensible parameters in our model. The parameters related to the slope were not sensible, since this basin presents no significant changes in altitude, nor were the parameters related to the lateral flow. In this area, the most important parameters seem to be related to the groundwater and aquifers (alpha, revap\_co, flo\_min, and revap\_min) and to the soil (cn2, esco, perco, awc, and k). Some soil qualities influence groundwater opposition, which warrants the inclusion of soil parameters as useful. These parameters have commonly been used in various works [76].

Most of the parameters fell within the expected range for a watershed in the Scandinavian peninsula. In addition, the parameters cn2, esco, perco, and snomelt\_tmp were the best fitted to the expected values [77]. With the adjusted values for the parameters, the model performed well for the streamflow in the calibration period of 2007–2015 according to Moriasi's standards [78]. The NSE was greater than 0.6, the PBIAS was close to 0, and the RSE approached 0.7 (Table 2). To validate the model, we used the adjusted values of the parameters for 2016–2020 and applied the statistical evaluation indices to the daily streamflow. The results were also rather good, except for PBIAS.

**Table 2.** Calibration and validation of the streamflow statistical daily values.

|                                | NSE    | PBIAS     | RSR    | R <sup>2</sup> |
|--------------------------------|--------|-----------|--------|----------------|
| Calibration period (2007–2015) | 0.7073 | 0.6192%   | 0.5410 | 0.7143         |
| Validation period (2016–2020)  | 0.7704 | −19.3319% | 0.4791 | 0.7945         |

During the validation period, the precipitation was low compared to the calibration period, which meant the streamflow was also rather low in those years (Figure 3). During the calibration period (2007–2015), the average annual precipitation is over 600 mm, while during the validation period (2016–2020), the average annual precipitation is below 550 mm. The decrease in PBIAS during the validation period suggests that the simulated



flow was exaggerated, although it remained within acceptable limits. Because the calibration period was wetter than the validation period, the model overestimated the flow during dry periods. Despite this, the statistics are still acceptable, and the model is valid for both dry and wet periods. According to the statistical evaluation indices shown in Table 2, the SWAT+ model responded adequately to this alteration.

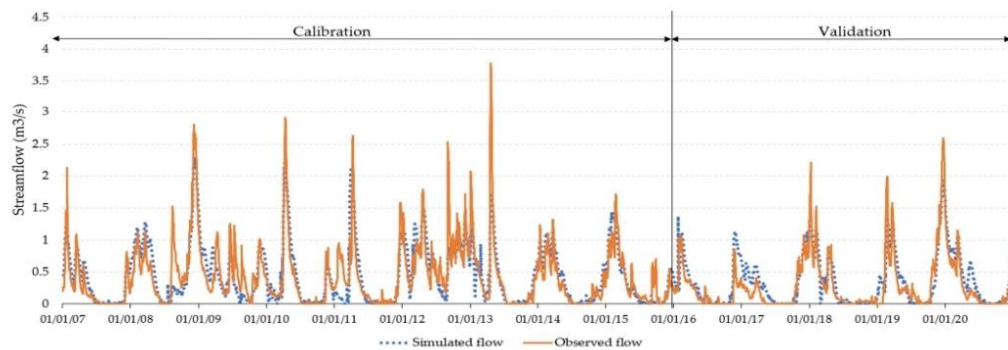


Figure 3. Calibration and validation of the SWAT+ model streamflow (daily values).

### 3.2. Assessment of the GCMs and the bias Correction Method

After determining the indicator  $I_d$  (Equation (6)), the weights ( $I_b$  indices) for the creation of the ensemble of predictions of all models were calculated. The  $I_d$  index represents the sum of the relative difference between the historical series of the model and the control scenario for the precipitation and temperature data. The  $I_b$  indicators were used as weights applied to the series obtained with each model to create an ensemble of predictions. Both indices can be seen in Table 3.

Table 3.  $I_d$  indicator for each GCM.

| GCMs         | Monthly Series |         |             |         | Id    | Ib   |
|--------------|----------------|---------|-------------|---------|-------|------|
|              | Precipitation  |         | Temperature |         |       |      |
|              | Id (Δx)        | Id (Δσ) | Id (Δx)     | Id (Δσ) |       |      |
| BCC          | 1.63           | 2.82    | 27.70       | 3.64    | 35.79 | 0.13 |
| CanESM5      | 3.13           | 2.83    | −1.12       | 3.07    | 7.91  | 0.16 |
| EC-Earth-Veg | 2.72           | 2.52    | 11.56       | 3.06    | 19.87 | 0.14 |
| GFDL         | 3.27           | 2.31    | 27.30       | 2.92    | 35.80 | 0.13 |
| INM-CM5      | 3.57           | 4.34    | 1.21        | 3.70    | 12.82 | 0.15 |
| MiroC6       | 3.62           | 2.52    | 10.71       | 2.10    | 18.96 | 0.14 |
| MRI          | 4.28           | 4.23    | 4.17        | 3.61    | 16.29 | 0.15 |

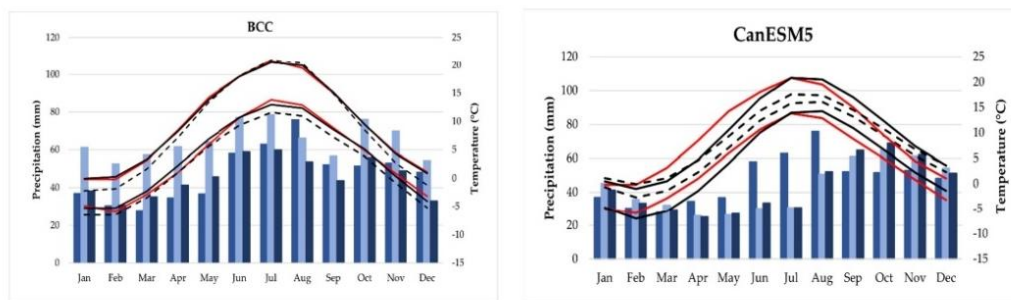
Note:  $\Delta x$  is the increase in the average and  $\Delta \sigma$  the increase in the variance.

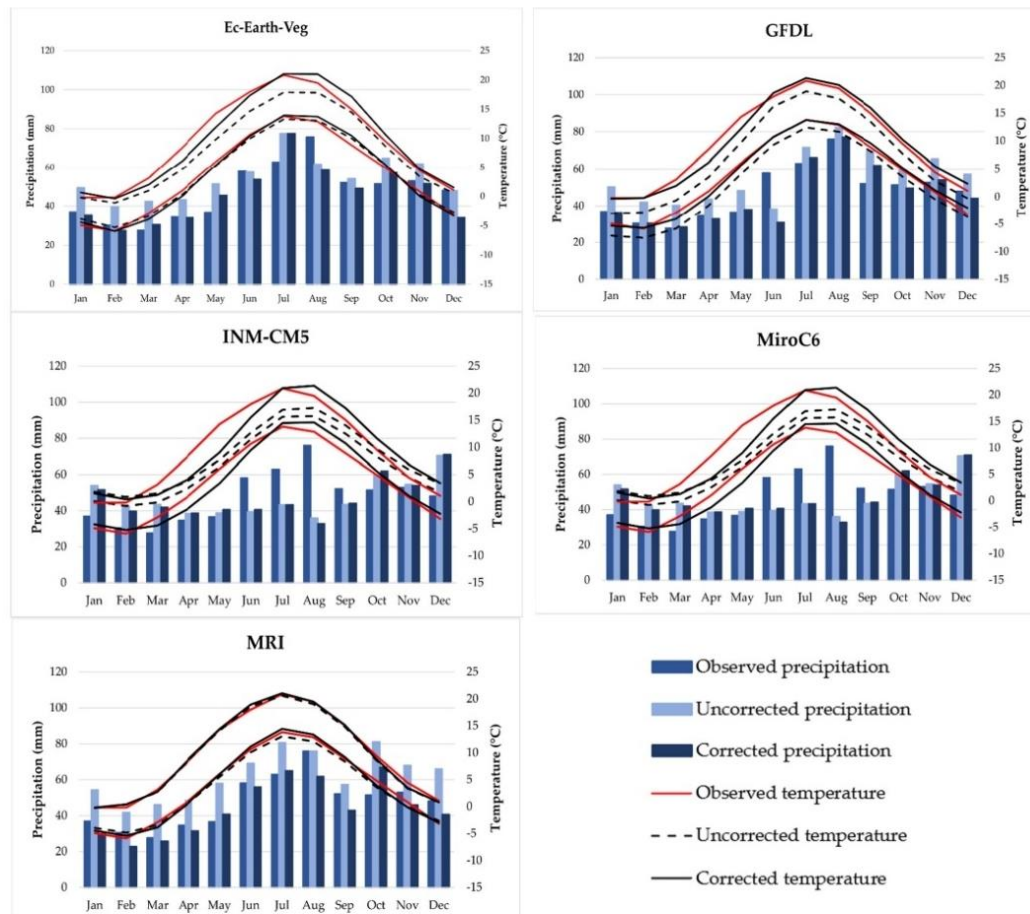
The five bias-correction methods of the “qmap” R package were applied to correct the historical data; the results are shown in Table 4. The PTF was found to be the best method for bias correction as it presented the lowest MAE for the three climate variables (daily precipitation, minimum temperature, and maximum temperature) in the majority of GCMs. Other studies have also shown that the PTF method provides the optimal correction [65]. Therefore, we applied the PTF method—which uses a parametric transformation of the quantile–quantile relation of observed and modelled values—to all the climate data of the seven GCMs for climate change forecasting.

**Table 4.** MAE of five bias-correction methods for observed versus corrected daily data (1985–2014).

| GCMs         | Variables     | DIST | PFT  | QUANT | RQUANT | SSPLIN |
|--------------|---------------|------|------|-------|--------|--------|
| BCC          | Precipitation | 2.53 | 2.50 | 2.56  | 2.55   | 2.55   |
|              | Min. temp.    | 4.59 | 4.47 | 4.43  | 4.43   | 4.38   |
|              | Max. temp.    | 4.30 | 4.11 | 4.07  | 4.07   | 3.98   |
| Can_ESM5     | Precipitation | 2.51 | 2.46 | 2.57  | 2.53   | 2.54   |
|              | Min. temp.    | 4.33 | 3.71 | 3.81  | 3.81   | 3.73   |
|              | Max. temp.    | 4.29 | 4.10 | 4.18  | 4.18   | 4.16   |
| EC-Earth-Veg | Precipitation | 2.53 | 2.51 | 2.58  | 2.55   | 2.56   |
|              | Min. temp.    | 4.16 | 3.83 | 3.90  | 3.90   | 3.90   |
|              | Max. temp.    | 3.86 | 3.82 | 3.87  | 3.87   | 3.87   |
| GFDL         | Precipitation | 2.58 | 2.49 | 2.56  | 2.54   | 2.53   |
|              | Min. temp.    | 4.39 | 4.20 | 4.22  | 4.22   | 4.23   |
|              | Max. temp.    | 4.01 | 4.03 | 4.03  | 4.04   | 4.04   |
| INM-CM5      | Precipitation | 2.55 | 2.51 | 2.55  | 2.53   | 2.55   |
|              | Min. temp.    | 4.32 | 3.51 | 3.64  | 3.64   | 3.64   |
|              | Max. temp.    | 4.25 | 3.84 | 4.04  | 4.04   | 4.05   |
| MiroC6       | Precipitation | 2.53 | 2.50 | 2.56  | 2.55   | 2.60   |
|              | Min. temp.    | 3.89 | 3.68 | 3.80  | 3.80   | 3.80   |
|              | Max. temp.    | 3.91 | 3.63 | 3.71  | 3.71   | 3.71   |
| MRI          | Precipitation | 2.51 | 2.47 | 2.54  | 2.52   | 2.52   |
|              | Min. temp.    | 4.46 | 4.01 | 4.09  | 4.09   | 4.01   |
|              | Max. temp.    | 4.09 | 3.91 | 3.99  | 3.99   | 3.99   |

The corrected data series of each model have been graphically compared with the uncorrected series and the real data in Figure 4. As can be seen in the graphs, both simulated temperature and precipitation improve considerably in most models when correcting the data, achieving results very similar to the observed values. This is especially noticeable in temperature, as there is a very appreciable improvement in all models, as can be seen in the graphs. Regarding precipitation, although in all the GCMs the corrected values are closer to the real values, the CanESM5, INM and MiroC6 models tend to underestimate precipitation during the summer months (June, July and August).

**Figure 4.** Cont.



**Figure 4.** Comparison of bias-corrected baseline data of each GCM compared with observed monthly average precipitation, maximum and minimum temperature in the Lake Erken basin in the historical period (1985–2014).

### 3.3. Climate Change Prevision

After the future temperature and precipitation data were corrected, the established periods were compared with the historical data (Table 5). An increase or decrease in temperature and precipitation values was estimated for the coming years, for the near future (2026–2050), the medium term (2051–2075) and the long term (2076–2100).

There is considerable variability among the climate models, but the general trends are similar (Table 5). The INM-CM5 model is the only one that predicts a general decrease in temperatures in the short term, and a decrease in precipitation in the short and long term. The general trend of the rest of the models in both climate change scenarios is, temperature would experience a significant increase with respect to the historical period. In the intermediate scenario (SSP 2-45), the average temperature would increase to around 1 to 4 °C, and in a high emission scenario (SSP 5-85) the increase could be from 4 to 6 °C, depending on the GCMs. In the near future, the rising of temperature would be milder, but still concerning, around 2 °C in both scenarios. In most of these cases, in the far future

period, the increase would be large enough to alter the hydrological cycle. One of the consequences will be increased stratification. The stratification in Lake Erken has been increasing for several decades [44] and other studies predict an intensification of this trend with serious implications [45].

**Table 5.** Historical and projected annual average precipitation and temperature data for the Erken basin for each GCM.

| Model        | Scenario | Periods   | Temperature (°C) | Precipitation (mm) |
|--------------|----------|-----------|------------------|--------------------|
| BCC          | Historic | 1990–2014 | 6.65             | 553.45             |
|              |          | 2026–2050 | 6.66 (+0.01 °C)  | 492.36 (−11%)      |
|              | SSP 2–45 | 2051–2075 | 7.25 (+0.6 °C)   | 551.00 (0%)        |
|              |          | 2076–2100 | 7.61 (+0.9 °C)   | 520.79 (−6%)       |
|              |          | 2026–2050 | 7.01 (+0.4 °C)   | 570.37 (+3%)       |
|              |          | 2051–2075 | 8.14 (+1.5 °C)   | 549.62 (−1%)       |
| CanESM5      | Historic | 1990–2014 | 6.63             | 517.14             |
|              |          | 2026–2050 | 8.79 (+2.2 °C)   | 591.74 (+14%)      |
|              | SSP 2–45 | 2051–2075 | 10.55 (+3.9 °C)  | 638.93 (+24%)      |
|              |          | 2076–2100 | 10.94 (+4.3 °C)  | 653.29 (+26%)      |
|              |          | 2026–2050 | 9.22 (+2.6 °C)   | 587.27 (+14%)      |
|              |          | 2051–2075 | 11.25 (+4.6 °C)  | 698.50 (+35%)      |
| EC-Earth-Veg | Historic | 1990–2014 | 6.74             | 574.70             |
|              |          | 2026–2050 | 9.29 (+2.5 °C)   | 571.38 (−1%)       |
|              | SSP 2–45 | 2051–2075 | 9.46 (+2.7 °C)   | 575.15 (0%)        |
|              |          | 2076–2100 | 10.35 (+3.6 °C)  | 588.11 (+2%)       |
|              |          | 2026–2050 | 9.08 (+2.3 °C)   | 563.15 (−2%)       |
|              |          | 2051–2075 | 10.41 (+3.7 °C)  | 611.52 (+6%)       |
| GFDL         | Historic | 1990–2014 | 6.61             | 553.09             |
|              |          | 2026–2050 | 8.29 (+1.7 °C)   | 569.19 (+3%)       |
|              | SSP 2–45 | 2051–2075 | 8.41 (+1.8 °C)   | 628.55 (+14%)      |
|              |          | 2076–2100 | 8.84 (+2.2 °C)   | 597.79 (+21%)      |
|              |          | 2026–2050 | 7.89 (+1.3 °C)   | 592.12 (+7%)       |
|              |          | 2051–2075 | 9.41 (+2.8 °C)   | 630.93 (+14%)      |
| INM-CM5      | Historic | 1990–2014 | 6.78             | 568.92             |
|              |          | 2026–2050 | 5.68 (−1.1 °C)   | 520.74 (−8%)       |
|              | SSP 2–45 | 2051–2075 | 5.89 (−0.9 °C)   | 532.45 (−6%)       |
|              |          | 2076–2100 | 7.31 (+0.5 °C)   | 528.20 (−7%)       |
|              |          | 2026–2050 | 6.14 (−0.6 °C)   | 500.27 (−12%)      |
|              |          | 2051–2075 | 7.40 (+0.6 °C)   | 551.00 (−3%)       |
| MiroC6       | Historic | 1990–2014 | 6.78             | 541.29             |
|              |          | 2026–2050 | 7.77 (+1 °C)     | 568.86 (+5%)       |
|              | SSP 2–45 | 2051–2075 | 8.47 (+1.7 °C)   | 564.86 (+4%)       |
|              |          | 2076–2100 | 8.88 (+2.1 °C)   | 591.92 (+9%)       |
|              |          | 2026–2050 | 7.74 (+1 °C)     | 608.62 (+12%)      |
|              |          | 2051–2075 | 9.17 (+2.4 °C)   | 649.97 (+20%)      |
| MRI          | Historic | 1990–2014 | 6.64             | 537.19             |
|              |          | 2026–2050 | 8.34 (+1.7 °C)   | 511.49 (−5%)       |
|              | SSP 2–45 | 2051–2075 | 8.80 (+2.2 °C)   | 527.29 (−2%)       |
|              |          | 2076–2100 | 8.61 (+2 °C)     | 570.44 (+6%)       |
|              |          | 2026–2050 | 8.94 (+2.3 °C)   | 561.42 (+5%)       |
|              |          | 2051–2075 | 9.49 (+2.9 °C)   | 566.88 (+6%)       |
|              | SSP 5–85 | 2026–2050 | 10.04 (+3.4 °C)  | 609.89 (+14%)      |
|              |          | 2076–2100 | 10.04 (+3.4 °C)  | 609.89 (+14%)      |

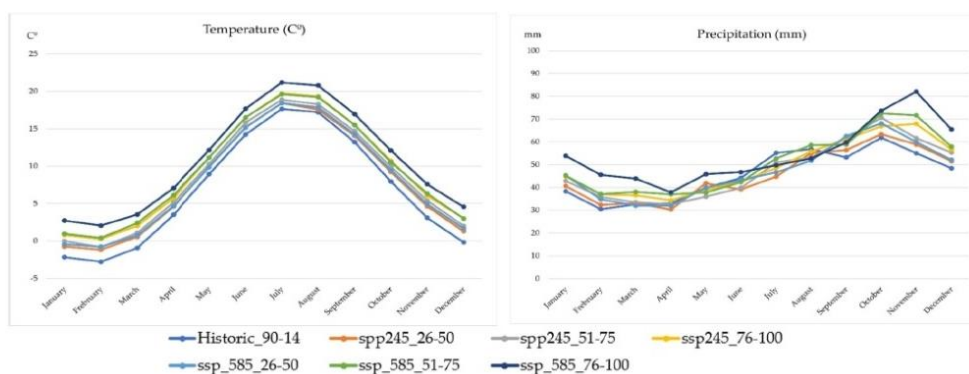
Note: Values in parentheses show the increase in precipitation or temperature compared to the historical period.

Regarding precipitation, the variability among the GCMs is greater. Similarly, the general trend is that average annual precipitation would increase in a high-emission scenario. The INM-CM5 model shows a decrease in precipitation in both scenarios in the far future. The BCC and EC-Earth-Veg models show a decrease or a very slight increase in precipita-



tion for the near and medium future, but an increase between 11 and 19% in the far future for the worst-case scenario (SSP 5-85). The MRI model shows a slight decrease in the near and medium future in the SSP 2-45 ( $-2$ ,  $-5\%$ ), but a gradual increase in the SSP 5-85 (up to  $14\%$ ). The GFDL model shows a gradual increase very similar for both scenarios up to  $21\%$ . Lastly, the MiroC6 and CanESM5 models show a gradual increase in precipitation for both scenarios, being higher in the SSP5 scenario. These results are congruent with those of other meteorological studies in Sweden. An increase in temperature and rainfall is expected in the north of Europe as a consequence of climate change [19,20,79–81].

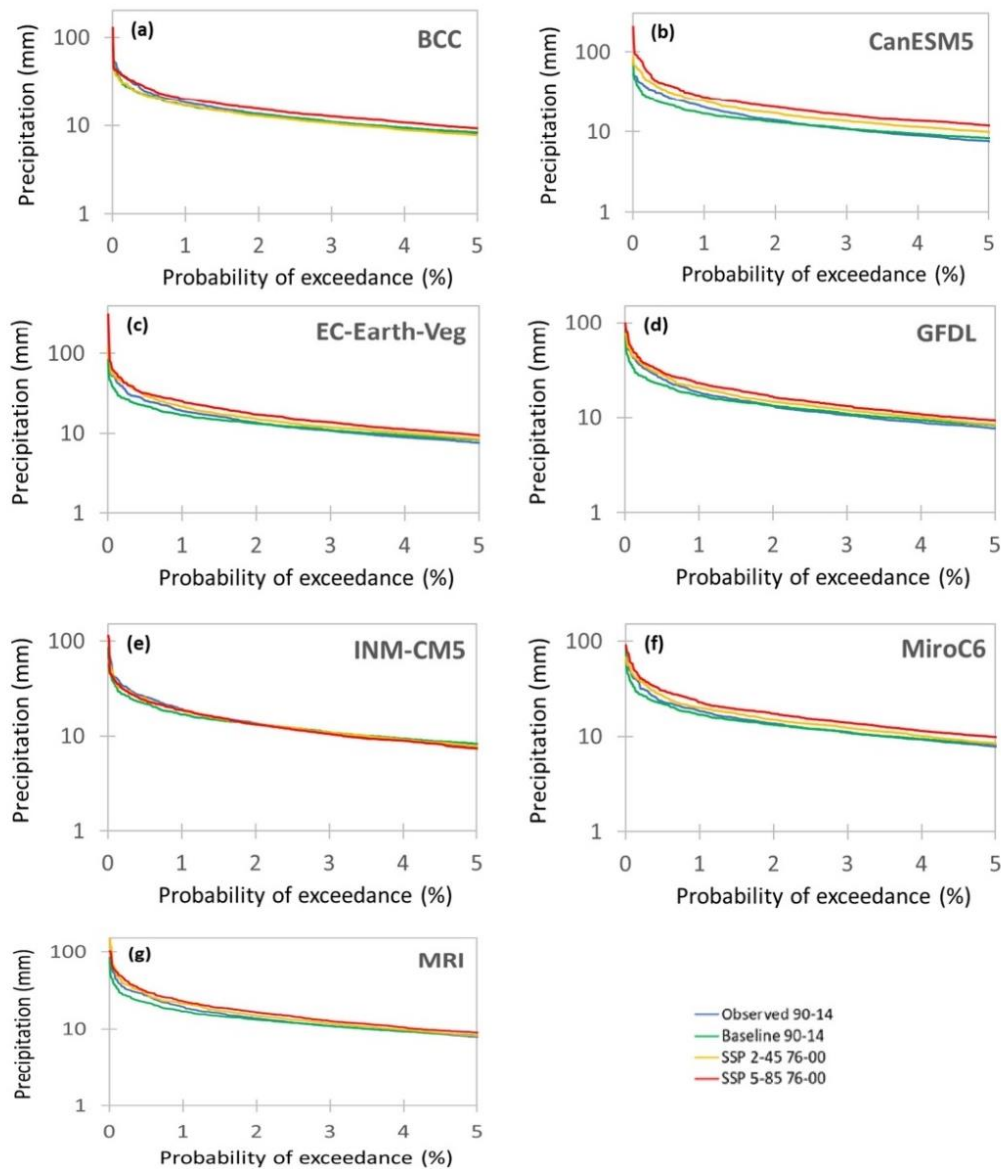
The monthly distributions of the average temperature and precipitation were analysed in each period for both scenarios (Figure 5). In this figure, the ensemble precipitation and temperature data for the seven GCMs studied have been plotted. These analyses help in understanding the climate alterations in a general overview. Precipitation was found to increase in every scenario during the cold season (October, November, December, January and February). By contrast, during summer (June, July, and August) in some cases the precipitation was found to be lower, even though the average annual rainfall was higher according to most GCMs than during the historic period. The increase in temperature was similar in both scenarios for the near future but was more pronounced in the high-emission scenario (SSP5-85) for the far future. The annual distribution was unaltered because it increased uniformly during the whole year. However, the increase was slightly larger during summer and winter, especially in December, January and February.



**Figure 5.** Comparison of monthly average precipitation and temperature in the Lake Erken basin for the periods and scenarios studied.

Forecasts of seasonal patterns in precipitation and temperature in Sweden by other studies have been highly similar to our results [79–82]. Notably, the greatest temperature rise is expected to occur throughout the coldest months. As a result of this rise during December, January, February, and March, the hydrology could be altered, especially the processes related to snowfall and snow accumulation. This is because in all scenarios, the monthly average temperature for those months will rise above  $0\text{ }^{\circ}\text{C}$  in the far future (Figure 5). This would prevent snow accumulation in the basin. On the other hand, the increase in temperature in summer would increase the stratification in the lake [45].

The 5% probability exceedance distribution for precipitation was plotted to analyse the extreme meteorological events in the far future (Figure 6), using the ensemble data of the seven GCMS. The graphs show how the torrential precipitation is expected to increase in the period 2076–2100 in both the SSP 2-45 and SSP 5-85 scenarios. The increase is higher in the high emission scenario (SSP 5-85). This could imply that the increase in the annual average precipitation in the future (Table 5) would be related to an increase in the torrential events of precipitations.



**Figure 6.** Exceedance probability distribution of daily precipitation for observed, baseline and projected data. Each subfigure represents a different GCMs: (a) BCC, (b) CanESM5, (c) EC-Earth-Veg, (d) GFDL, (e) INM-CM5, (f) MiroC6, (g) MRI.

### 3.4. Alterations on the Hydrological Cycle

The expected changes in precipitation and temperature will alter the hydrological cycle. To address these changes, we used the SWAT+ model for Lake Erken to simulate the future hydrological cycle for both scenarios, using the GCMs' temperature and precipitation data. After simulating every GCMs model under the SSP 2-45 and SSP 5-85 scenario,

we ensemble the hydrological components with the weighted average. The results show how the water balance is likely to be altered by climate change (Table 6).

**Table 6.** Annual average of the water cycle components in the Erken basin. Ensemble of the GCMs.

| Scenario | Periods   | Discharge (m <sup>3</sup> /s) | Water Yield (mm) | Evapotrans. (mm) | SWE (mm)    |
|----------|-----------|-------------------------------|------------------|------------------|-------------|
| Historic | 1990–2014 | 0.36                          | 50.27            | 354.44           | 4.51        |
| SSP 2–45 | 2026–2050 | 0.37 (+3%)                    | 46.68 (−7%)      | 352.36 (−1%)     | 2.77 (−38%) |
|          | 2051–2075 | 0.41 (+14%)                   | 52.40 (+4%)      | 357.34 (+1%)     | 2.52 (−44%) |
|          | 2076–2100 | 0.43 (+18%)                   | 52.74 (+5%)      | 358.34 (+1%)     | 1.58 (−65%) |
| SSP 5–85 | 2026–2050 | 0.43 (+20%)                   | 52.44 (+4%)      | 363.12 (+2%)     | 2.32 (−49%) |
|          | 2051–2075 | 0.48 (+33%)                   | 59.46 (+18%)     | 371.84 (+5%)     | 1.10 (−76%) |
|          | 2076–2100 | 0.53 (+49%)                   | 66.05 (+31%)     | 379.36 (+7%)     | 0.38 (−92%) |

Note: Values in parentheses show the increase in the component relative to the historical period.

In Table 6, “discharge” represents the water that enters Lake Erken through the different channels of the basin. “Water yield” represents the sum of the surface runoff, lateral soil flow, and tile flow; that is, the amount of water contributing to the flow rate. The SWE was defined in the introduction of this paper.

A gradual increase in the water discharge and water yield is the principal long-term pattern (Table 6). This effect of climate change is related to the increase in precipitation and torrential rainfall expected for the long-term scenario [18,19] (Figure 6). In the intermediate scenario, the increase in discharge could reach around 18% in the far future and 49% in the high-emission scenario. In this scenario, the water yield would also increase to around 31%. Such a sharp increase in discharge and runoff could imply a reduced availability of water resources since it would result in less water retention in the basin as well as soil degradation and erosion [16]. It is important to consider that forests buffer these effects and others caused by extreme torrential rainfall events [50]. Degradation of the watershed forest in future years could lead to even greater discharge, water yield, and soil degradation than those predicted in this study, with even heavier consequences for the ecosystem.

Regarding the SWE, even in the lowest-emission scenario, SWE was reduced by between 38 and 61% from 2026 to 2100. In the worst-case scenario, the reduction could reach 92% in the far future period. This is the expected result related to the temperature rise due to climate change. The increase in temperatures during December, January and February would reduce the snowfall and snow accumulation in the Lake Erken basin. As a consequence, in a high-emission scenario, the SWE would be reduced by nearly 95%. In other words, there would be almost no snow accumulation in the Erken basin during the cold season. The absence of snow accumulation could further favour runoff processes, as water would not be retained in the basin in the form of snow during the cold months.

Finally, a slight general increase in evapotranspiration in the basin is expected, especially in the high-emission scenario, where it could increase by 7% in the far future period. The increase in evapotranspiration is explained by the higher temperatures due to climate change.

### 3.5. Alterations on the Floods

Eight hydrological parameters related to floods were obtained from IAHRIS for each GCMs. The weighted average of the indicators is in Table 7. We compared their values to observe how floods might be altered by climate change in future years. Their magnitude, frequency, variability, and duration were analysed for the different scenarios proposed.



**Table 7.** Ensemble of the hydrological parameters related to floods of each GCMS (data obtained from IAHRIS).

| Scenario | Periods   | Qc (m <sup>3</sup> /s) | QL (m <sup>3</sup> /s) | Qconnec (m <sup>3</sup> /s) | Q5% (m <sup>3</sup> /s) | CV (Qc) (m <sup>3</sup> /s) | CV (Q5%) (m <sup>3</sup> /s) | Duration (days) |
|----------|-----------|------------------------|------------------------|-----------------------------|-------------------------|-----------------------------|------------------------------|-----------------|
| Historic | 1990–2014 | 1.69                   | 1.67                   | 2.22                        | 1.21                    | 0.49                        | 0.37                         | 16.08           |
| SSP 2–45 | 2026–2050 | 1.73                   | 1.77                   | 2.38                        | 1.18                    | 0.53                        | 0.32                         | 17.15           |
|          | 2051–2075 | 1.92                   | 2.04                   | 2.79                        | 1.32                    | 0.57                        | 0.30                         | 22.11           |
|          | 2076–2100 | 1.97                   | 2.13                   | 2.94                        | 1.36                    | 0.62                        | 0.33                         | 22.81           |
| SSP 5–85 | 2026–2050 | 1.80                   | 1.76                   | 2.31                        | 1.30                    | 0.46                        | 0.27                         | 24.65           |
|          | 2051–2075 | 2.18                   | 2.47                   | 3.48                        | 1.47                    | 0.64                        | 0.30                         | 29.82           |
|          | 2076–2100 | 2.39                   | 2.95                   | 4.29                        | 1.54                    | 0.75                        | 0.25                         | 34.57           |

According to the four parameters related to the magnitude of floods (Qc, QL, Qconnec and Q5%), in the Lake Erken basin floods would become progressively higher over time. This increase in magnitude will be greater in the SSP 5–85 scenario. The most affected parameter was Qconnec. This finding implies that the flood plain will flood more frequently, will increase in area, and will receive more water as heavy rainfall events increase in the basin. This pattern could change the ecosystem of the flood plain and its surroundings, altering the succession processes of the riparian forest and affecting the maintenance of the diversity and functionality of macroinvertebrate communities [83–85].

The variability of the floods was analysed with two parameters coefficient of variation. On the one hand, the variation of the mean of the maximum annual daily flow (CV (Qc)) would rise. This would imply that the magnitude of the floods would change depending on the year. Some years the magnitude of the floods would be higher, others would be lower, although the tendency would be to increase (Qc). On the other hand, the variation of the series of usual floods would decrease in future periods, although there is no clear trend of progressive decrease. This implies that the flow corresponding to the average flow curve classified at the 5% exceedance percentile will maintain similar values every year in the studied periods. In other words, some years there will be much more abundant floods than others, but the number of floods will be similar in most years.

The duration of the floods also showed extreme increases in the long term for the worst scenario. The increase in the flood duration or flood period could, in turn, raise the death rate of the most vulnerable plant species, as it causes anoxic stress [86]. The increase in floods may be related to the increase in precipitation and the increase in events of torrential precipitation (Figure 6).

Finally, we analysed the seasonality; the results are shown in Table 8. Changes in the natural seasonal patterns of floods can produce strong distortions in the riparian ecosystem. Loss of synchrony with the life cycles of the affected species is the main reason for such distortions, in addition to many accumulating effects from other environmental variables. Some of these effects could include alteration in biomass production [87]; loss of synchrony with the phenology of multiple plant species, altering dispersal and germination processes [84,87]; and progression of generalist foreign plant species, with a resulting decrease in diversity and an impact on riparian forest productivity [84].

**Table 8.** Ensemble of the number of days in a month having a daily average flow rate greater than the Q5% (exceedance percentile) of each GCM.

| Scenario | Periods   | Jan   | Feb   | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec   |
|----------|-----------|-------|-------|------|------|------|------|------|------|------|------|------|-------|
| Historic | 1990–2014 | 3.13  | 1.43  | 1.75 | 4.22 | 1.92 | 0.39 | 0.19 | 0.02 | 0.18 | 1.57 | 3.10 | 3.82  |
| SSP 2–45 | 2026–2050 | 4.29  | 2.45  | 2.80 | 3.07 | 1.95 | 0.94 | 0.03 | 0.14 | 0.32 | 0.85 | 3.24 | 4.85  |
|          | 2051–2075 | 6.52  | 3.71  | 2.99 | 2.82 | 1.48 | 0.28 | 0.06 | 0.03 | 0.18 | 1.68 | 4.28 | 6.50  |
|          | 2076–2100 | 7.58  | 3.73  | 4.45 | 3.71 | 0.98 | 0.41 | 0.11 | 0.21 | 0.37 | 1.10 | 3.82 | 7.08  |
| SSP 5–85 | 2026–2050 | 7.78  | 5.65  | 4.95 | 3.97 | 2.05 | 0.64 | 0.18 | 0.11 | 0.25 | 1.22 | 4.05 | 6.92  |
|          | 2051–2075 | 9.65  | 6.06  | 5.14 | 2.84 | 1.20 | 0.33 | 0.15 | 0.24 | 0.54 | 1.68 | 5.15 | 9.76  |
|          | 2076–2100 | 14.29 | 10.63 | 7.13 | 2.80 | 0.92 | 0.36 | 0.05 | 0.17 | 0.20 | 1.29 | 5.56 | 12.10 |

An increase in seasonality is observed in Table 8. During the warm months (April to October), the days with floods are expected to remain similar to the historical period or even to decrease. The greater decrease would be in spring, during the month of April, where there would be 1 or 2 days less of floods in the far future. In the cold months,



the days with floods would increase significantly, especially during December, January, and February. The increase in winter floods could be related to increased precipitation and a lack of solid snow in the Erken basin. The snow precipitation that accumulates until the thawing months in these scenarios would contribute directly to the watercourse [88].

#### 4. Conclusions

In this work, we analysed the impact of climate change on the hydrological cycle of the Lake Erken basin under both an intermediate and a high-emission scenario. We also developed a SWAT+ model of the watershed and used precipitation and temperature data obtained from seven GCMs (BCC, CanESM5 GCM, EC-Earth-Veg, GFDL, INM-CM5, MiroC6, MRI). The main conclusions drawn from this study are as follows:

- After calibration and validation, the SWAT+ model of Lake Erken performed notably well regarding the examined statistics. Although SWAT+ is a new tool and has not been as widely used compared to its predecessor (SWAT), our results demonstrated its validity and effectiveness. We conclude that the SWAT+ can be used effectively to create hydrological models in lake basins. Furthermore, observing the concordance of the results obtained with SWAT+ and IAHRIS, it seems to respond acceptably to flood and peak flow events.
- Precipitation and temperature are expected to increase in Sweden in the future because of climate change. The results of this study are in concordance with that forecast. In a high-emission scenario (SSP 5-85), the temperature could increase from 4 to 6 °C in the distant future (2076–2100), especially during winter. Precipitation would increase by around 20%.
- An increase in precipitation linked to torrential events would affect the hydrological cycle of the Lake Erken basin. In the distant future, the discharge can be expected to increase by almost 50% and runoff by 30% in a high-emission scenario. This dynamic could intensify soil erosion and degradation processes, which could damage the watershed's forests. As the duration of water retention in the watershed decreases, the availability of water resources for vegetation may also decrease.
- The increase in temperature during the winter months would affect the snow-related processes of the basin. The accumulation of snow in the basin would be severely altered in both scenarios. In the intermediate scenario, it would be reduced by 65%, and in the high-emission scenario, by 92%. This would imply the near disappearance of the snowpack that usually covers the basin in the winter months. Such a change would drastically affect all forest ecosystems in the basin.
- In the worst scenario (SSP5-85), the magnitude, frequency and variability of floods are expected to increase. The duration of floods would also increase from 16 days to 23 or 35, depending on the scenario. Regarding the seasonality of floods, the number of days in a month having a daily average flow rate greater than the exceedance percentile would increase in winter, especially in February (from 1 to 10 days), January (from 3 to 14 days) and December (from 4 to 12 days), while in the warmer months they would decrease. These changes may cause damage to the ecosystems of the Lake Erken basin and cause a degradation of its soil due to erosion.

#### 5. Limitations

- The present study has several limitations, some of them due to data availability, others due to the methodology of the study itself or the tools used. In any case, these limitations should be considered: The SWAT program has been widely used, but its most recent version, SWAT+, does not have as many studies to support its use. In addition, many SWAT studies have been conducted simulating peaks or flood flows and although acceptable, SWAT models tend to underestimate these peak flows, as explained in the introduction of this study. There are not enough studies with SWAT+ to know if peak simulation is also underestimated by this version.

- Only one meteorological station has been used in this study, even though a single station is acceptable due to the small size of the basin, according to the World Meteorological Organisation [89].
- The inflow data for Lake Erken at Kristineholm did not start to be collected until mid-2006. In order to calibrate and validate the SWAT+ model, daily observed discharged data of full years are required. As a consequence, our calibration and validation period go from 2007 to 2020 and is considerably shorter than the historical period, for which observed precipitation and temperature data are available.
- CMIP6 includes over 100 global climate models from more than 50 modelling centers. In this study, we have used seven of these models. This allows us to decrease the uncertainty of the results but not to reduce it to zero.

**Author Contributions:** I.C.J.-N. and J.S.-A. conceived and developed the study; I.C.J.-N. and A.L.-B. developed the SWAT+ model; I.C.J.-N. and J.P.-S. analyzed the input data; I.C.J.-N., A.L.-B. and J.P.-S. analyzed the output data; I.C.J.-N. wrote the paper; J.S.-A., J.P.-S. and P.J.-S. revised the paper. All authors have read and agreed to the published version of the manuscript.

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5.2. RESEARCH PAPER 2: APPLICATION OF AN INTEGRATED CATCHMENT-LAKE MODEL APPROACH FOR SIMULATING EFFECTS OF CLIMATE CHANGE ON LAKE INPUTS AND BIOGEOCHEMISTRY

Jiménez-Navarro, I. C., Mesman, J. P., Pierson, D., Trolle, D., Nielsen, A., & Senent-Aparicio, J. (2023). Application of an integrated catchment-lake model approach for simulating effects of climate change on lake inputs and biogeochemistry. *Science of the Total Environment*, 885, 163946.

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## Application of an integrated catchment-lake model approach for simulating effects of climate change on lake inputs and biogeochemistry



Inmaculada C. Jiménez-Navarro<sup>a,\*</sup>, Jorrit P. Mesman<sup>b</sup>, Don Pierson<sup>b</sup>, Dennis Trolle<sup>c</sup>, Anders Nielsen<sup>c</sup>, Javier Senent-Aparicio<sup>a</sup>

<sup>a</sup> Department of Civil Engineering, Catholic University of San Antonio, Campus de Los Jerónimos s/n, 30107, Guadalupe, Murcia, Spain

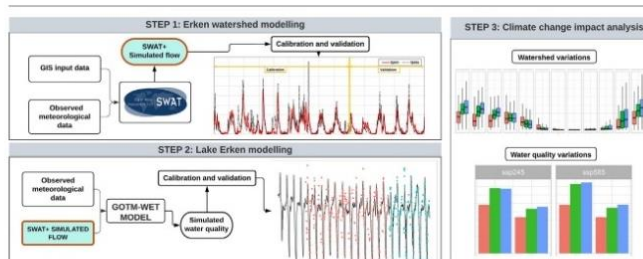
<sup>b</sup> Department of Ecology and Genetics, Limnology, Uppsala Universitet, Norbyvägen 18 D, 752, 36, Uppsala, Sweden.

<sup>c</sup> WaterTech, Døjssøvej 1, 8660 Skanderborg, Denmark

### HIGHLIGHTS

- The models GOTM-WET and SWAT+ are used to develop a coupled catchment-lake model.
- Climate change impacts on the catchment and water body of Lake Erken (Sweden).
- Several climate change models and scenarios are used to obtain a range of outcomes.
- More inflow from the catchment is expected and changes in the lake biogeochemistry.

### GRAPHICAL ABSTRACT



### ARTICLE INFO

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### ABSTRACT

Climate change is simultaneously affecting lakes and their catchments, resulting in altered runoff patterns in the catchment and modified mixing and biogeochemical dynamics in lakes. The effects of climate change in a catchment will eventually have an impact on the dynamics of a downstream water body as well. An integrated model would allow considering how changes in the watershed affect the lake, but coupled modelling studies are rare. In this study we integrate a catchment model (SWAT+) and a lake model (GOTM-WET) to obtain holistic predictions for Lake Erken, Sweden. Using five different global climate models, projections of climate, catchment loads and lake water quality for the mid and end of the 21st century have been obtained under two future scenarios (SSP 2-45 and SSP 5-85). Temperature, precipitation and evapotranspiration will increase in the future, overall resulting in an increase in water inflow to the lake. An increasing importance of surface runoff will also have consequences on the catchment soil, hydrologic flow paths, and the input of nutrients to the lake. In the lake, water temperatures will rise, leading to increased stratification and a drop in oxygen levels. Nitrate levels are predicted to remain unchanged, while phosphate and ammonium levels increase. A coupled catchment-lake configuration such as that illustrated here allows prediction of future biogeochemical conditions of a lake, including linking land use changes to changing lake conditions, as well as eutrophication and browning studies. Since climate affects both the lake and the catchment, simulations of climate change should ideally take into account both systems.

\* Corresponding author.  
E-mail address: [icjimenez@ucam.es](mailto:icjimenez@ucam.es) (I.C. Jiménez-Navarro).

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## 1. Introduction

We are currently experiencing a period of climatic change and instability in most parts of the planet. The consequences of climate change are already being felt and this is affecting our ecosystems, the services they provide and our lives in general (Wehner et al., 2017; Wuebbles et al., 2017). In the coming years, increasingly severe alterations are expected due to this anthropogenic phenomenon (López-Ballesteros et al., 2020; Pulido-Velazquez et al., 2021). One of the areas most affected by climatic alterations is hydrology (Kiesel et al., 2019). The hydrological cycle is a process directly dependent on various climatic conditions, such as precipitation and temperature, among many others (Blanco-Gómez et al., 2019). For example, alteration in precipitation can lead to changes in catchment flows and surface runoff, and alterations in temperature can affect snowmelt and evapotranspiration (Akter et al., 2018; Javadinejad et al., 2020).

Lakes and reservoirs are sensitive ecosystems whose dynamics can be easily altered by external changes. In addition, their environmental and socio-economic value is high, as they act as a water supply, provide potential flood mitigation, a source of fish as well as being an important recreational and tourist attraction (Reynaud and Lanzanova, 2017). Climate change can affect lakes in several ways, for example, an increase in temperatures could lead to changes in thermal water stratification and alter a variety of ecosystem dynamics (Woolway et al., 2021). In addition, all the changes that occur in the catchment due to climate change will eventually have an impact on the lake and its dynamics, causing further alterations in the ecosystem (Nielsen et al., 2012). For example, increasing winter temperatures can increase streamflow and nutrient loads due to increased snowmelt, thereby altering lake ecosystem processes and seasonality (Hryciuk et al., 2021). Therefore, to achieve holistic climate change predictions of the water quality of a lake, it is necessary to consider not only the alterations in the catchment and the lake, but also the interaction between these two systems. Our main objective is to develop an integrated catchment-lake model, taking into account both the changes in the catchment and in the water body, and to apply this to better understand how the lake will respond to a future climate.

Models have been used for decades to assist in the management and planning of water resources throughout the world. Both catchment and lake models have the ability to simulate climatic, geographic and human impacts, if sufficient data are available. This allows for local management of water resources, which is indispensable for the implementation of appropriate measures (Brekke et al., 2004). In a similar way, there are several studies during the last decade that use an integration of a hydrological and hydrodynamic model in different regions of the world, since this approach improves the simulation of the spatial and temporal variability of hydrodynamic processes, as well as the basin-water body response (Munar et al., 2018). Most of these are based only on physical models. For example, Inoue et al. (2008) uses such approach to simulate the changes in the salinity of the Barataria Basin, in Louisiana (U.S.A.); and Wu et al. (2017) combined a model of the Hongfeng Reservoir and its basin, in Guizhou Province (China), to analyze the water exchange processes. Lopes et al. (2018) proposes an approach in which they use a model where hydrology and hydrodynamics are integrally coupled, in the Patos Lagoon (Brazil-Uruguay). This model allowed them to efficiently simulate the hydrograph, water level and flooding areas of the lagoon and the basin. There are also several previous studies that uses the first version of the SWAT model to simulate the catchment of the water body. One of them is Dargahi and Setegn (2011) which combine SWAT with the GEMSS model to simulate the water level in a three-dimensional format, in Lake Tana (Ethiopia), in order to achieve a sustainable use of the water resource. Zhang et al. (2017) combine SWAT with the Delft3D model to obtain a holistic model of the ungauged Poyang Lake (China), calibrating the SWAT model with a gauging in the watershed part of the basin. Senent-Aparicio et al. (2021a) conducted a study in the Mar Menor (Spain) combining the SWAT model with QWET, a version of the GOTM-WET model used from the QGIS software. Less abundant are the studies that, by integrating these models, also combine physical and ecological models to study the

variation of nutrients and other biogeochemical variables, as in our case. An example of this is the study conducted by Coppens et al. (2020) in Lake Mogan (Turkey), in which the model is also used to make climate change forecasts.

In this study, we integrated physical and chemical models in this study. The Soil and Water Assessment Tool + (SWAT+, Bieger et al., 2017) was used to simulate the catchment dynamics of a lake in Sweden. In addition, the General Ocean Turbulence Model (GOTM, Umlauf et al., 2005) coupled to the Water Ecosystems Tool (WET, Schnedler-Meyer et al., 2022) model was then used to obtain predictions of the physical and chemical processes occurring in the water body. The coupling of the models was carried out so that the predictions obtained by the SWAT+ model served as input data for the GOTM-WET model for future climate simulations. In this study the SWAT model update known as SWAT+ has been used, which, to our knowledge, has not yet been used to perform a basin-lake model application. Finally, this coupling will be applied to obtain predictions of water discharge and nutrient dynamics in the lake under climate change scenarios. The limitations of this study are discussed in Section 4.5, since it should be considered that this study has several, mainly due to the limited data available.

This methodology could enable decision-makers to make more conscious decisions about water management in specific areas. It will be especially relevant in areas facing abrupt changes in land use in the basin, or extreme changes in climatology due to climate change. One of the virtues of the methodology is that it allows for both long-term and short-term simulation, and that it is applicable to any water body and its basin with sufficient input data.

## 2. Study area

Lake Erken is a mesotrophic lake, with a surface area of 24 km<sup>2</sup> and an average depth of 9 m. At its deepest point it reaches 21 m. It is located in the east of Sweden, to the north of Stockholm (59°50'37"N, 18°35'38"E) (Fig. 1(a)). In this region the climate is humid continental, so summers are mild and warm, but short, and winters are cold. Precipitation occurs throughout the year in similar amounts, occurring in winter mostly in the form of snow. For this reason, Lake Erken has two very different seasonal characteristics: it is stratified between June and August and ice-covered from December till April (Blenckner et al., 2006; Persson and Jones, 2008) and both of these phases have been studied in Lake Erken (Ayala et al., 2020; Moras et al., 2019; Pierson et al., 2011). Lake Erken has several inflow channels, the main one being the Kristineholm stream (Fig. 1(c)), which drains roughly half of the catchment area. The gauging station is located here (59°51'18"N, 18°28'42"E), where discharge flowing into the lake is measured daily.

The Lake Erken catchment covers an area of 141 km<sup>2</sup>. It is a low relief drainage catchment, without steep slopes (Fig. 1(b)). Most of the catchment is occupied by evergreen forest, with small areas of deciduous forest and mixed forest (Fig. 1(c)). There are areas of pastureland that are used for grazing farm animals. In general, farming activities in the catchment are not intensive. The main human activities in the catchment are agriculture and forestry, but also some low intensity development.

## 3. Methodology

The methodology of the present study was divided into a series of steps that are described in Fig. 2. The first step was to develop, calibrate and validate a SWAT+ model to obtain data on water discharge flowing into Lake Erken as well as different hydrological components of the catchment area. Next, the LOAD ESTimator (LOADEST) (Runkel et al., 2004) approach was used to estimate the nutrient load entering the Lake Erken. The LOADEST approach is data-driven, and allows good estimates of nutrient dynamics in inflows without the need to account for detailed land use management (e.g. agricultural management). The third step was the development of a GOTM-WET model of the water body, which simulated the physics and water quality of the lake. For this model, the input data for calibration and validation were observed meteorology, observation-derived



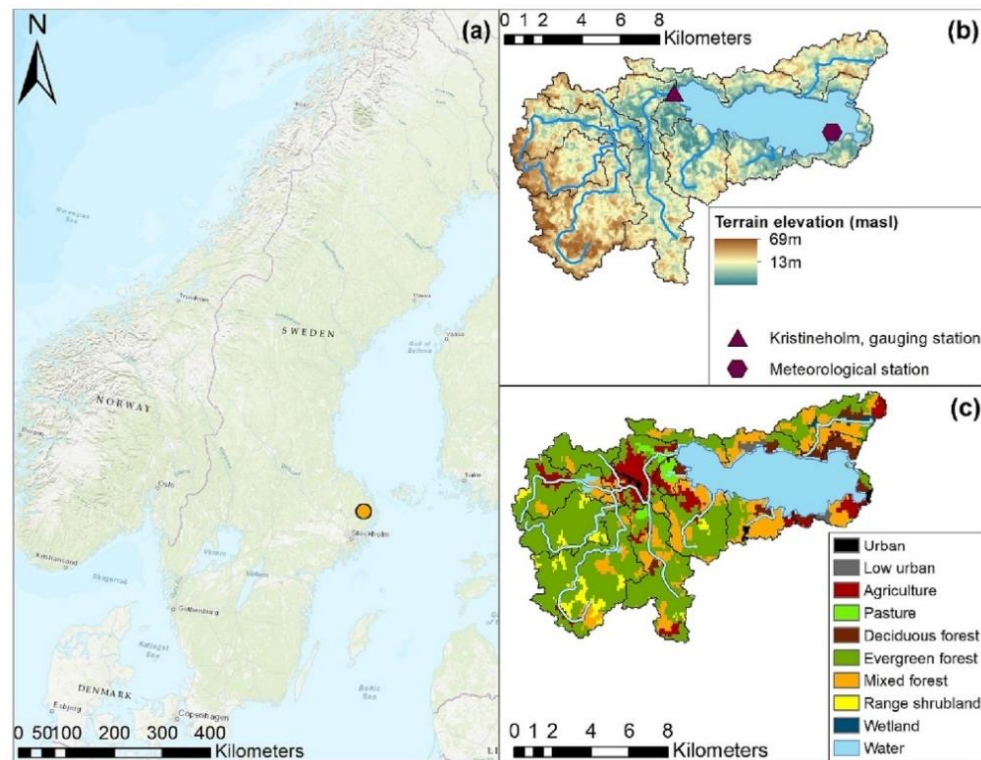


Fig. 1. Map of the study area: (a) location of Lake Erken and its catchment in the Scandinavian Peninsula; (b) digital elevation map of the Lake Erken catchment and location of Kristineholm (gauging station) and the meteorological station; (c) land uses in the Lake Erken catchment.

flows, plus measured inflow nutrients and temperature. For the future simulation, we used *LOADEST* and *air2stream* to feed the model with inflow nutrients and temperature. In the remainder of this section, we describe the individual models and their inputs in more detail.

The next step was to obtain future meteorological input data for the coupled models and for this purpose, Global Climate Models (GCMs) were used. Five climate models (BCC-CSM2-MR, CanESM5, INM-CM5-0, MiroC6 and MRI-ESM2-0) were selected, and meteorological data were extracted from these under a low greenhouse gas emission scenario (SSP 2-45) and a high emission scenario (SSP 5-85) (O'Neill et al., 2014). The data extracted from these models were then subjected to bias-correction before being fed to the respective models. Finally, the results obtained have been analyzed. Predictions on the meteorology, hydrological components of the catchment and water quality of Lake Erken were developed.

### 3.1. Catchment modelling

The first part of this study consisted of developing a model of the Lake Erken catchment, in order to simulate the hydrology of the catchment. This model allows us to estimate how much water drains into the lake distributed into several flow components of the hydrological cycle. To achieve this, the Soil and Water Assessment Tool + (SWAT+) was used. In this section, a description of the model as well as the model development process and its subsequent calibration and validation are detailed. *LOADEST* was used to obtain the nutrients loads data, and to simulate the temperature of the stream flows, *air2stream* has been used.

#### 3.1.1. Description of SWAT+ model

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012) is a model that simulates the hydrology and water quality of catchments. The model has been used globally for the last 20 years in many different scenarios, conditions and scales. Since its creation, SWAT has been implemented on a regular basis to meet the needs of the scientific community, allowing increasingly flexible and reliable modelling. This was the case until the limit of the framework that allowed the SWAT model to continue to improve was reached, and new foundations for the model were needed. In 2017, a new SWAT model (SWAT+) (Bieger et al., 2017) was released, which was intended to be more flexible and realistic. The new SWAT+ treats catchment elements -including aquifers, landscape units, hydrologic response units (HRUs), ponds, and reservoirs- as spatial objects. In comparison to the older SWAT, this feature improves the flexibility of the catchment's configuration and discretization (Bieger et al., 2017).

Water dynamics are represented by fluctuations in the HRUs in both the SWAT and SWAT+ models. Each HRU is a unique combination of land-use, slope, soil, and management activities, which are connected by a geographic information system (GIS) interface. As a consequence, SWAT and SWAT+ are "semi-distributed" models, where it is considered that the same combination of land-use, slope, soil and management activities will cause the same hydrological response (Mohammed et al., 2018). These subdivisions allow the model to reflect differences in evapotranspiration for different crops and soils (Neitsch et al., 2011).

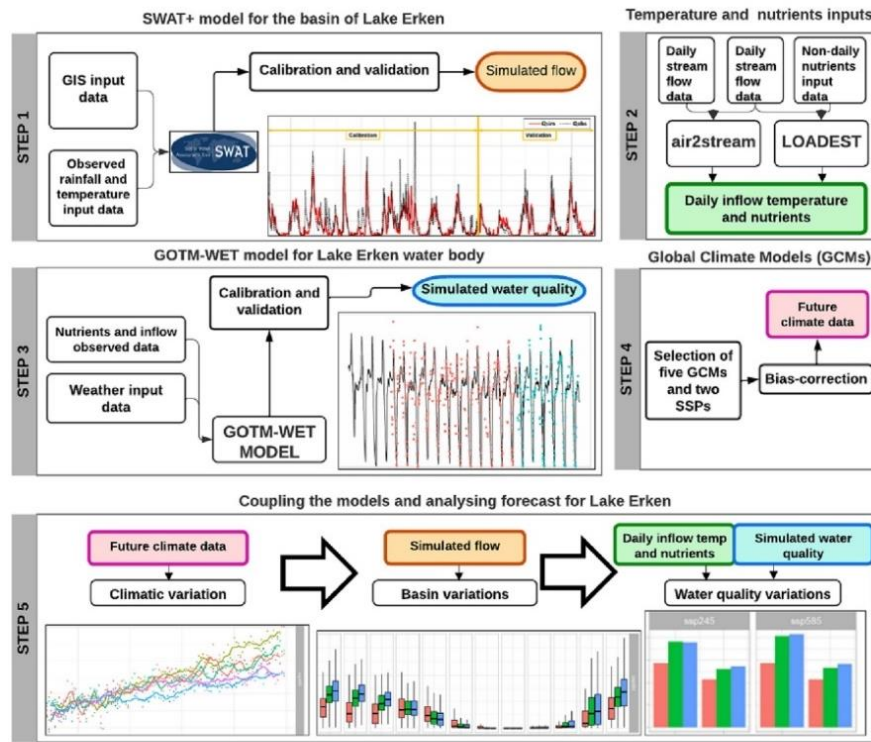


Fig. 2. Flow chart of the methodology developed in this study.

### 3.1.2. SWAT+ model setup

The SWAT+ model presented in this study was developed based on a previous study of the area by some of the authors (Jiménez-Navarro et al., 2021). The methodology followed was very similar.

In order for SWAT+ to establish the HRUs of a catchment, it needs several inputs (Table 1). The necessary information for the HRUs creation and the implementation of the model is: spatial data (a digital elevation map (DEM), a land cover map and a soil map). In addition, meteorological data (daily precipitation and temperature) is needed as forcing data. In order to calibrate and validate the model, it is also necessary to have observed data from the elements of the water cycle, in this case the water discharge to the lake through the main channel.

**Table 1**  
Inputs of the SWAT+ model setup.

| Input                                                      | Resolution | Source                                                                              |
|------------------------------------------------------------|------------|-------------------------------------------------------------------------------------|
| Meteorology (air pressure, air temperature, precipitation) | Daily      | Erken Laboratory meteorological station (Fig. 1(b))                                 |
| Inflow discharge                                           | Daily      | Gauging station at Kristineholm (Fig. 1(b))                                         |
| Digital elevation map                                      | 30 m       | Shuttle Radar Topography Mission (SRTM) (Farr and Kobrick, 2000)                    |
| Harmonised World Soil Date                                 | 1 km       | Food and Agriculture Organization of the United Nations (Nachtergaele et al., 2010) |
| Corine land cover                                          | 100 m      | Copernicus Land Monitoring Service (CLC, 2018)                                      |

As in the previous study, the DEM was obtained from the Shuttle Radar Topography Mission (SRTM) (Farr and Kobrick, 2000). The soil data were gathered from the Food and Agriculture Organization of the United Nations' Harmonised World Soil Date (Nachtergaele et al., 2010), as in the previous study. This collection contains information for 16,000 map units with two soil layers, namely 0–30 and 30–100 cm deep.

A more accurate and updated land use map has been used than the one used in the previous study. The Corine land cover dataset has been used for this work; it was obtained from Copernicus Land Monitoring Service. It consists of an inventory of 44 land cover classes, and comes in a raster resolution of 100 m (CLC, 2018).

Observed meteorological data from the period 2000–2021 have been obtained largely from meteorological measurements made on a small island 500 m off shore of the Erken laboratory (Fig. 1(b)). Here it was beneficial to obtain measurements that were particularly sensitive to the lake location. In some cases where data was not available, we also obtained data from the Swedish Meteorological Institute Svanberga station located 425 m from the lake shore at the Erken laboratory. When data was missing from either of these stations, missing values were replaced using data from other SMHI stations using machine learning models developed by Moras et al. (2019). Stream water discharge and temperature data to the lake were automatically measured at Kristineholm (Fig. 1(b)). In this study, daily average values of all variables were used.

### 3.1.3. Calibration and validation

In a SWAT+ model, there are a multitude of parameters that can potentially be calibrated. To avoid over-parameterization and identify the most sensitive parameters in the hydrological process of our study area, a



sensitivity analysis was executed before the calibration. The sensitivity analysis, the calibration and the validation were carried out in SWAT + Toolbox (Chawanda, 2021) a free software specially designed to calibrate and perform various analyses and changes to SWAT + models.

Applying the sensitivity analysis methodology proposed by Sobol' (2001), the overall output variance was divided into the variation produced by each parameter, within an ensemble. Based on this, ten parameters were found to be sensitive for water discharge in our model. Subsequently, an automatic calibration of these parameters was performed for the period 2007–2015 on a daily scale, using the discharge into the lake trough the Kristineholm as the observed data. For automatic calibration, Toolbox uses the dynamically dimensioned search (DDS) algorithm (Yen et al., 2019). The Nash–Sutcliffe efficiency coefficient (NSE) was applied as the objective function in this investigation. For the validation, the period from 2016 till 2021 was simulated with the parameters achieved from the calibration. A two-year warm-up period was established for each simulation carried out.

The goodness of fit for both the calibration and validation was calculated. Five different statistics recommended by Moriasi et al. (2007, 2015) were used for this purpose. These statistics are the coefficient of determination ( $R^2$ ) (Eq. (A.1)), the Nash–Sutcliffe efficiency (NSE) (Eq. (A.2)), the root mean square error (RMSE) (Eq. (A.3)), the standard deviation of measured data (RSR) (Eq. (A.4)), and the percent bias (PBIAS) (Eq. (A.5)). The equations used to obtain these statistics are in Appendix A.

### 3.1.4. Nutrients loads and water temperature estimation

In order to estimate nutrients entering Lake Erken via the Kristineholm stream, the program LOAD ESTimator (LOADEST) (Runkel et al., 2004) was used, in the form of the *loadest* package (Runkel and De Cicco, 2017). This program is commonly used in hydrological studies that require daily nutrient and/or sediment input data, but only coarser data are available (Jha and Jha, 2013). LOADEST estimates the loads and concentrations of various constituents of stream flows by fitting several regression models and selecting the most optimal one in terms of Akaike Information Criterion (AIC). As input data it requires observed flow data and the concentration of each constituent. For the flow we used the data of discharge at Kristineholm, and for the concentration nutrients we used the available data collected also from the Kristineholm stream. This measurement is not automated, so it is not periodical. The data was collected in bi-weekly to monthly intervals, from 1999 to 2021.

In this study, LOADEST was used to estimate the following constituents: phosphate (PO4-P), nitrate (NO3-P), ammonium (NH4-N), dissolved organic phosphorus (DOP), particulate organic phosphorus (POP), dissolved organic nitrogen (DON), particulate organic nitrogen (PON), and silicate (Si). To obtain the equation for each component, 2004–2015 was used as the training period, and 2016–2020 as the testing period; with the exception of Si for which 2014–2019 and 2020–2021 were used for training and testing, respectively, due to a shortage in data availability. Since the aim was to apply the LOADEST equations to future climate scenarios, regression models that included a linear time component were not used, only models that used discharge and optionally a seasonality parameter. It is thus assumed that the relationship between flow and nutrient loading that LOADEST models simulates will not undergo large changes in the future. For the estimation of future stream temperatures, *air2stream* was used, a hybrid process-based and data-driven model (Toffolon and Piccolroaz, 2015; Piccolroaz et al., 2016).

### 3.2. Lake modelling

In the second part of this study the focus was on developing a model of the Lake Erken itself, in order to simulate the water temperature and concentrations of oxygen, nitrate, ammonium, phosphate, and chlorophyll-a. This model will allow us to estimate changes in the water quality of the lake in the future scenarios. To achieve this, the GOTM model and the WET model were used. In this section, a description of the model as well

as the model development process and its subsequent calibration and validation are detailed.

#### 3.2.1. Description of the GOTM-WET model

The General Ocean Turbulence Model (GOTM) is a one-dimension water column model for lakes and oceans, employing a vertical-grid structure and solving turbulence closure equations to simulate vertical mixing dynamics (Umlauf et al., 2005). It has been applied to a variety of cases, including near-sediment mixing dynamics (Umlauf et al., 2015), climatic changes in lake thermal structure (Ayala et al., 2020), and transport of tracers and biogeochemical substances (Jung et al., 2019). This physical model can be coupled to biogeochemical models through the Framework for Aquatic Biogeochemical Models (FABM, Bruggeman and Bolding, 2014). In this setup, GOTM turbulence calculations regulate mixing of substances between layers, and the biogeochemical equations are applied to each layer at every time step. In addition, GOTM diffusion is included in the calculation of vertical movement rates of inorganic particles and phytoplankton. In this case, we coupled GOTM to the Water Ecosystems Tool (WET), a modularized aquatic ecosystem model that is capable of simulating dynamics of biogeochemistry (e.g. oxygen, phosphorus, nitrogen) and organisms (e.g. phytoplankton, zooplankton, and fish) in both water column and sediment (Schneider-Meyer et al., 2022).

#### 3.2.2. GOTM-WET model setup

The inputs used for the GOTM-WET model are described in Table 2. The model was driven by daily-averaged meteorological data (wind speed, air pressure, air temperature, relative humidity, cloud cover, shortwave radiation, precipitation). These observed data were obtained in the same way as for the catchment model, described in Section 3.1.2. For the purpose of calibrating GOTM-WET, we used inflow values that were based on measured water levels, measured inflow discharges, and output from the HYPE model for the ungauged areas (Hydrological Predictions for the Environment, Lindström et al., 2010), from 2004 onwards, and the first four years were recycled for the years 2000–2003. SWAT+ and GOTM-WET were therefore integrated only after calibration. Nutrient concentrations and temperature in the inflow were measured at the main inflow (Fig. 1 (b)). Si concentrations in the inflow were available only from 2014 onwards, and earlier values were therefore created by extrapolation based on seasonal decomposition of the existing data using the *stl* function in R (Cleveland et al., 1990). Two years of spin-up were used by recycling years 2000 and 2001. A model integration time step of 1 h was used and 42 layers of 0.5 m depth was used in the vertical discretization of the GOTM model.

The food web used in the WET model consisted of four phytoplankton groups (diatoms, cyanobacteria, green algae, and flagellates), one macrophyte group, and one zooplankton group. The model parameters associated with the four phytoplankton groups were initially set to representative each of the groups that are common in Lake Erken, being *Aulacoseira* (diatoms), *Dolichospermum* (cyanobacteria), *Closterium* (green algae), and *Cryptomonas* (flagellates). Other initial variable and parameter values in the

**Table 2**  
Inputs of the GOTM-WET model setup.

| Input                                                                                                                       | Resolution       | Source                                              |
|-----------------------------------------------------------------------------------------------------------------------------|------------------|-----------------------------------------------------|
| Meteorology (wind speed, air pressure, air temperature, relative humidity, cloud cover, shortwave radiation, precipitation) | Daily            | Erken Laboratory meteorological station (Fig. 1(b)) |
| Inflow discharge                                                                                                            | Daily            | Gauging station at Kristineholm (Fig. 1 (b))        |
| Components of the inflow discharged (NO3, PO4, NH4, DOP, POP, DON, PON, Si) <sup>a</sup>                                    | Biweekly-monthly | Erken Laboratory meteorological station (Fig. 1(b)) |
| Hypsograph of Lake Erken                                                                                                    | 2 m              | (Hakanson, 1978)                                    |

<sup>a</sup> Note: at the beginning, D stands for dissolved and P for particulate; O for organic; and in the end, N for nitrogen, and P for phosphorus.

biogeochemistry were also based on literature where possible (see Appendix B, Table B.1). Default values provided for the Lake Ravn WET case study were used otherwise (WET, 2022). However, the parameters were still included in the calibration if the sensitivity analysis (see Table B.1, appendix B) showed that they were sensitive, but we ensured that they did not deviate too strongly from the literature-based values. In the climate change scenario simulations, the calibrated parameter values were used, but the forcing files were changed accordingly.

### 3.2.3. Calibration and validation

The *ParSAC* software (Bruggeman and Bolding, 2020) was used to perform a sensitivity analysis and calibration of the GOTM-WET model, using 2000–2015 as calibration period, and 2016–2021 for validation. Sensitivity and optimal fit were assessed for the output variables water temperature and concentrations of phosphate, nitrate, ammonium, oxygen, silicate, total phosphorus, and chlorophyll (total and group-specific). For both the sensitivity analysis and calibration, initial ranges of 20 % around the initial values (see Table B.1, appendix B) were used, with the exception of Arrhenius temperature parameters (5 % range, as a larger range led to cause instability due to their use in exponential equations) and accounting for minimum and maximum values (e.g., not letting fractions exceed 100 %).

The purpose of the sensitivity analysis was to reduce the number of parameters to calibrate. All 275 model parameters of our model setup were included in the sensitivity analysis, and a dummy variable, having no effect on model output, was added to this list. Borgonovo's delta-sensitivity method (Borgonovo, 2007; Andersen et al., 2021) was used on 55,000 parameter sets, and a 95 % confidence interval was calculated from 100 resamples using bootstrapping (Plischke et al., 2013). If a parameter's sensitivity fell within the 95 % confidence interval of the dummy variable for all output variables, this parameter was excluded from calibration. This resulted in 165 parameters being used in the calibration (Appendix B).

*ParSAC* uses a differential evolution method to maximize a natural-log-transformed likelihood objective function of the 12 output variables. A stepwise calibration approach was used, where each calibration round consisted of 30,000–70,000 iterations and the goodness-of-fit distribution of all parameters were plotted. After visual inspection of the plots, assessment of the parameter bounds (to ensure that parameters were not set to unrealistic values), and changes made during previous calibration rounds, the parameter ranges were adjusted or parameter values were fixed, after which a new calibration round was started. The calibration was stopped when the improvement in model fit became trivial. The same statistics used in the model SWAT+ were used to assess the goodness-of-fit, for the calibration and validation periods (see Section 3.1.3).

### 3.3. Global climate models

In order to apply the developed models and simulate the hydrology and the water quality of Lake Erken in the future, we needed meteorological data from the future period. For this purpose, Global Climate Models (GCMs) have been used. The data were extracted from the Coupled Model Intercomparison Project (CMIP6) website (WCRP CIMP, 2022). More information about the phase 6 of CMIP can be found in their overview paper (Eyring et al., 2016).

Five GCMs were selected, which had satisfactory results for this study area in previous articles (Jiménez-Navarro et al., 2021) with the methodology proposed by McSweeney et al. (2015), and which provided all the meteorological variables required for this study. The five GCMs were BCC-CSM2-MR, CanESM5, INM-CM5-0, MiroC6 and MRI-ESM2-0. From each GCM we obtained wind speed, atmospheric pressure, solar radiation, cloud cover, relative humidity, mean temperature, maximum and minimum temperature, and precipitation data.

First, historical data were extracted for each GCM in order to perform a bias-correction for each one, using real historical data as a reference (Appendix E, Table E.1). The parametric transformations (PTF) statistical transformation of the *qmap* package for R software was used. This method was proven in a previous study to provide the optimal correction in this area

(Jiménez-Navarro et al., 2021) and tries to align the distribution of simulated data with that of observed meteorological data (Gudmundsson et al., 2012).

After this, future data was extracted and bias corrected. In order to assess the uncertainty of the predictions, data from two different climate change scenarios were downloaded. Different Shared Socioeconomic Pathways (SSPs) were used for this purpose. The SSPs are defined as “reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies” (O'Neill et al., 2014). The two scenarios used were SSP 2-45 and SSP 5-85. According to the SSP 2, global emissions shall keep the current trends. This implies substantial, although not exceptionally severe, barriers to both reduction and adaptation to climate change. The SSP 5 presents a scenario, in contrast, in which economic growth takes priority above environmental consequences. Therefore, the problems brought on by climate change are complex to overcome (Dellink et al., 2017). In CMIP5, the RCP4.5 and RCP8.5 scenarios correspond to the SSP 2-45 and SSP 5-85 scenarios of CMIP6, with the difference that in CMIP6 it also takes economic factors into consideration (DKRZ, 2022). These are two of the most widely used climate change scenarios in projection studies, as they allow us to compare a more optimistic 100-year future, in which carbon emissions, although not halted, only reach intermediate levels (SSP 2-45), with a more extreme future, in which climate change has greater consequences (SSP 5-85). In order to make predictions comparable to the historical period (1985–2014), two future periods of the same length (30 years) were established. In this way, medium-term (2040–2069) and long-term (2070–2099) predictions were obtained.

To assess whether lake variables showed a linear temporal trend in response to the climate forcing, we used Mann-Kendall trend tests using the *modifiedmk* R package (Patakamuri and O'Brien, 2021) was used to calculate the Sen's slope.

## 4. Results and discussion

### 4.1. SWAT+ calibration and validation

We performed a sensitivity analysis with 18 parameters related to the discharge in order to calibrate only the more sensitive ones. The parameters that were found sensitive can be seen in Table 3, along with a brief description of each parameter.

These ten parameters are mostly parameters that are normally calibrated in hydrological studies with SWAT (Cibin et al., 2010; Nossent and Bauwens, 2012; Leta et al., 2015; Khorashadi Zadeh et al., 2017; Pérez-Sánchez et al., 2020; Senent-Aparicio et al., 2021b; Sánchez-Gómez et al., 2022). The exception is the parameter *cn3.swf*, whose default value in SWAT+ seems to be different than in SWAT and therefore now requires calibration, and the parameter *latq.co*, which seems to be more sensitive in the study catchment, since it is a forested catchment and this parameter is linked to the ET of the vegetation in the area. In the automatic calibration, the optimum range and value of these ten parameters were established. This is also shown in Table 3.

Once the values of the selected parameters were adjusted, the optimal fit of the model was established for both time periods: calibration and validation, using different statistics (Table 4). The statistics are satisfactory: NSE and  $R^2$  above 0.6 and RSR below 0.7. The RMSE also showed a good performance, being close to 0. The PBIAS was very good, as the calibrated value stayed close to 0. Potentially because there are fewer extreme events during the validation period, the RSR, NSE and  $R^2$  statistics show a slight improvement (Table 4).

As can be seen in Fig. 3, the model realistically simulates the flow in most situations. Extreme events where the flow is abruptly increased are simulated with a larger margin of error, but still within acceptable limits and correct timing. The model tends to underestimate abrupt increases in flow. This tendency to underestimate peak flows was common in SWAT. In fact, there are studies on the difficulties of SWAT in simulating extreme events (Tan et al., 2020). Although there are still few SWAT+ studies, some



**Table 3**  
Description, range, and adjusted value for all modified parameters after calibration for the SWAT+ model.

| Parameter                     | Description                                                                                  | Range       | Change     | Adjusted value |
|-------------------------------|----------------------------------------------------------------------------------------------|-------------|------------|----------------|
| Curve number (cn2)            | Related to soil permeability                                                                 | ~ 20–20 %   | Percentage | –19.44         |
| Baseflow Alpha factor (alpha) | Response of groundwater flow to changes in recharge                                          | 0–1         | Absolute   | 0.18           |
| Latq_co                       | ET coefficient to calculate the retention coefficient; dependent on plant evapotranspiration | 0.5–2       | Absolute   | 0.72           |
| Perco                         | Fraction that recharges the deep aquifer in the zone                                         | – 0.08–0.09 | Relative   | – 0.06         |
| Cn3_swf                       | Coefficient of water evaporating from the pond                                               | 0.2–0.9     | Absolute   | 0.57           |
| Awc                           | Water capacity at ground level                                                               | – 20–20 %   | Percentage | –17.31         |
| Flo_min                       | Threshold of the depth of water required in the shallow aquifer for water return to occur    | – 500–1000  | Relative   | 420.18         |
| Revap_min                     | Threshold of water depth in the shallow aquifer for revap or percolation to the deep aquifer | – 500–250   | Relative   | 31.02          |
| Latt_time                     | Number of days on which the lateral flow path occurs                                         | 0–100       | Absolute   | 9.26           |
| Revap_co                      | Coefficient of water flowing from the shallow aquifer to the overlying unsaturated zone      | 0.02–0.2    | Absolute   | 0.20           |

Note: The absolute change indicates that the parameter value was replaced by the adjusted value, the relative change indicates that the parameter value was modified by adding or subtracting the adjusted value, and the percentage change indicates that the parameter value was modified by the percentage indicated by the adjusted value.

of them seem to also reflect this problem of peak flow underestimation (Bailey et al., 2020; Pulighe et al., 2021; Llanos-Paez et al., 2022). Despite these problems, most of the extreme yield assessment studies reviewed by Tan et al., 2020 found satisfactory results, just as in the SWAT+ studies.

#### 4.2. Loadest and air2stream results

The LOADEST-derived loadings fitted the observations well, with  $R^2$  values between 0.5 and 1.0 for the different constituents (Appendix C, Fig. C.1 and Table C.1). Variation in discharge rather than concentration dictated the largest variations in loading (Appendix C), which increases the reliability of future load estimations based on SWAT+ hydrologic output. Concurrent with discharge data, loadings therefore peaked in winter/spring and was negligible in summer in most years.

The air2stream model reproduced well the seasonal cycles in stream temperature ( $R^2 = 0.98$  and  $RMSE = 0.83$  °C for the calibration,  $R^2 = 0.98$  and  $RMSE = 0.87$  °C for the validation).

#### 4.3. GOTM-WET calibration and validation

The GOTM-WET model performed reasonably well for the variables water temperature, oxygen, nitrate, phosphate, and chlorophyll (Table 5, Fig. 4). Nutrient values in winter tended to be underestimated by the model, but the timing and magnitude of summer hypolimnetic oxygen depletion and the spring chlorophyll peak (with concurrent uptake of nutrients) were generally reproduced adequately. For the nutrients and chlorophyll, goodness-of-fit decreased in the validation period (Table 5). This seemed to have been primarily caused by an intense summer phytoplankton bloom in 2019 that was not reproduced by the model and mismatches of 2–3 weeks in the timing of the spring phytoplankton bloom during the validation period. The summer of 2019 in Lake Erken may be considered anomalous and the bloom contained large amounts of *Gloeotrichia*.

**Table 5**

Model performance of the GOTM-WET model for the calibration (2000–2015) and validation (2016–2021) periods. For the full list of goodness-of-fit metrics, variables, and depths, see Appendix D, Table D.1.

| Variable                           | Depth (m) | Calibration |       | Validation |       |
|------------------------------------|-----------|-------------|-------|------------|-------|
|                                    |           | RMSE        | $R^2$ | RMSE       | $R^2$ |
| Water temperature (°C)             | 3         | 0.80        | 0.99  | 0.69       | 0.99  |
| Oxygen (mg/l)                      | 15        | 2.07        | 0.77  | 2.08       | 0.79  |
| Nitrate (mg/l)                     | 3         | 0.04        | 0.64  | 0.05       | 0.48  |
| Phosphate (mg/l)                   | 3         | 0.01        | 0.41  | 0.01       | 0.29  |
| Chlorophyll-a (mg/m <sup>3</sup> ) | 3         | 4.89        | 0.35  | 6.81       | 0.16  |

**Table 4**  
Performance of the simulated discharge ( $m^3/s$ ) from the SWAT+ model during the calibration and validation periods, on a daily and monthly basis.

| Period  |                         | NSE  | RSR  | RMSE | PBIAS  | $R^2$ |
|---------|-------------------------|------|------|------|--------|-------|
| Daily   | Calibration (2007–2015) | 0.61 | 0.63 | 0.31 | 7.63   | 0.63  |
|         | Validation (2016–2021)  | 0.71 | 0.54 | 0.31 | –10.96 | 0.72  |
| Monthly | Calibration (2007–2015) | 0.65 | 0.59 | 0.25 | 2.17   | 0.69  |
|         | Validation (2016–2021)  | 0.84 | 0.40 | 0.15 | –16.53 | 0.86  |

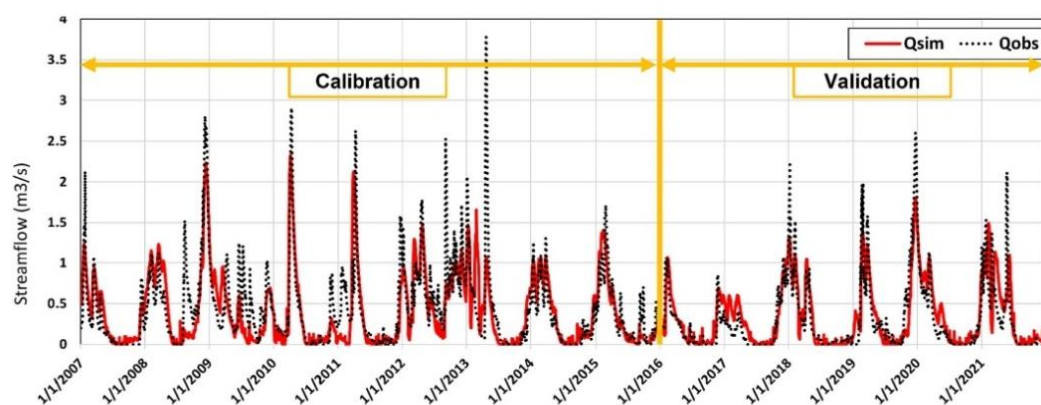


Fig. 3. Observed (Qobs) and simulated (Qsim) daily discharge inflow in Lake Erken for the calibration and validation periods.

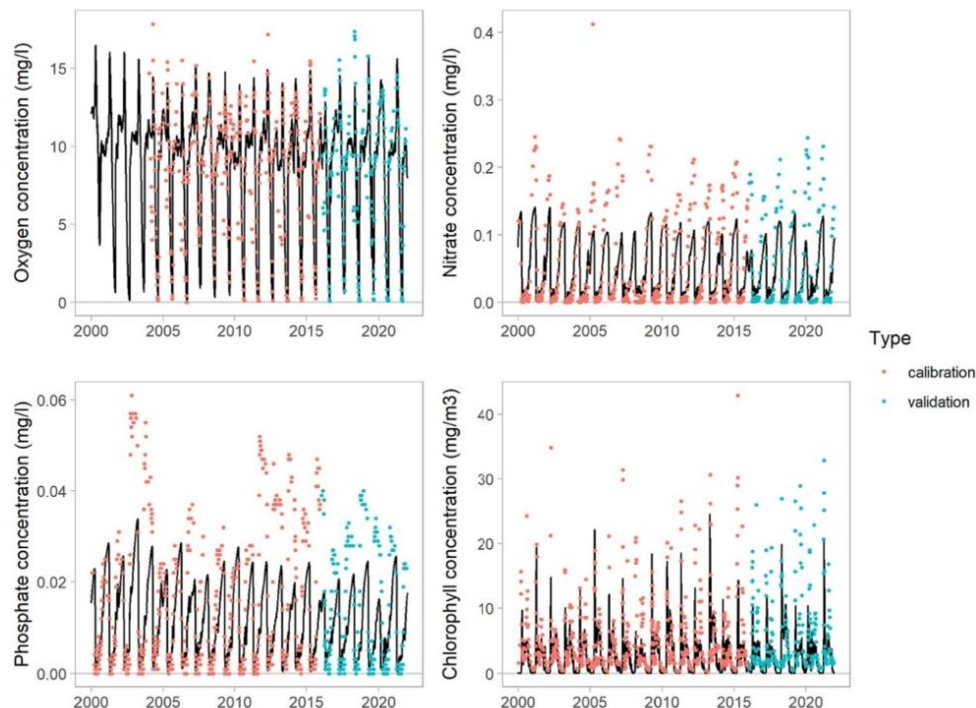


Fig. 4. Concentrations of oxygen (mg/l, at 15 m depth), nitrate (mg/l, at 3 m depth), phosphate (mg/l, at 3 m depth), and chlorophyll (mg/m<sup>3</sup>, at 3 m depth) simulated by GOTM-WET (black line) compared to observations (dots). Red dots indicate the calibration period and blue dots the validation period.

*echinulata* that depend to a large extent on resting stages (Karlsson-Elfgren et al., 2003), which cannot be simulated by the GOTM-WET model. A recent machine learning study in Lake Erken also encountered problems in simulating this event (Lin et al., 2023). Moreover, a mismatch in timing, especially in time series with considerable peaks such as the Lake Erken chlorophyll observations, is known to be strongly penalizing in terms of goodness-of-fit statistics, despite the model still producing useful results in terms of seasonal phytoplankton succession (Elliott et al., 2000). We therefore consider these simulations to provide a reasonably good fit for the physical and biogeochemical conditions in Lake Erken, despite the reduction of performance in the validation period.

During the calibration process, most parameters tended to stay close to the initial value (56 % of the parameters were within 25 % of the initial value, 79 % were within 50 %, Appendix B). Some notable exceptions were a >200 % increase in the background extinction  $k_d$ -folding depth, which is most likely explained by the biological components taking over light absorption, and a 99 % decrease in the light half-saturation constant for diatom growth, which points towards difficulties in reproducing the spring peak during fully-mixed conditions, similar to an earlier study in Lake Erken with a different model (Mesman et al., 2022). The use of a lower light half-saturation may partially compensate for an incomplete process description in the code, but this is an issue that could be addressed in a future study. The wind speed scaling factor was restrained to 1.5 times the original values, and most likely it tended to high values due to the underestimation of mixing as a result of using daily averaged wind speeds, as wind energy flux scales with wind speed cubed (Wüest et al., 2000).

#### 4.4. Analysis of the climate change impact

The statistical improvement of the GCMs data after the bias-corrections can be seen in Table E.1. (Appendix E). The different climate change predictions obtained with the methodologies proposed in this study will be discussed in this section below. First, a brief analysis will be made of the climatic variations expected in the study area, according to the five GCMs used. Then, the evolution of the components of the hydrological cycle in the Lake Erken catchment will be analyzed with the results obtained in SWAT+. Finally, the expected variation of water quality in Lake Erken will be analyzed.

##### 4.4.1. Climatic variation

Once the climatic data was corrected, we compared the historical period data with the future data obtained from the different models. Table 6 shows the average of different climatic conditions in the study area for different periods. This was calculated for the five GCMs used. In order to obtain an estimation of how these conditions will vary, the mean of the five GCMs was calculated (Table 6).

The climatic conditions that will change the most in the future will be precipitation and temperature. Atmospheric pressure, percent cloud cover and relative humidity will remain fairly stable according to the projections. Wind speed will not change much either. Solar radiation will show a slight increase in the future, both in the medium and long term, compared to the historical period. However, it is precipitation and temperature that show a clear tendency to increase progressively in the future. The increase will be steeper in the SSP 5-85 scenario, which foresees a more aggressive increase in greenhouse gasses.



**Table 6**

Ensemble of the average meteorological data of the five GCMs in the study area for the historical period (1985–2014), and the future mid-century (2040–2069) and end-century (2070–2099) periods.

|          |             | Prec (mm) | Temp (°C) | Wind speed (m/s) | Sol. Rad. (W/m <sup>2</sup> ) | Atmosph. Pres. (Pa) | Cloud cover (%) | Humid. Relat. (%) |
|----------|-------------|-----------|-----------|------------------|-------------------------------|---------------------|-----------------|-------------------|
| Hist     | Historical  | 564.9     | 6.6       | 3.9              | 111.4                         | 101,324.2           | 65.5            | 80.2              |
| SSP 2-45 | Mid-century | 618.0     | 9.1       | 4.0              | 114.8                         | 101,352.3           | 64.5            | 79.8              |
|          | End-century | 637.6     | 9.7       | 4.1              | 114.2                         | 101,324.5           | 65.0            | 80.0              |
| SSP 5-85 | Mid-century | 657.9     | 9.5       | 4.0              | 113.6                         | 101,318.0           | 64.9            | 80.3              |
|          | End-century | 700.0     | 11.2      | 4.0              | 112.9                         | 101,296.6           | 64.6            | 80.3              |

For precipitation we can see a pattern of increase, especially in the last half century (Fig. 5(a)). The five GCMs do not show large differences in their predictions, although they are a bit more variable in the SSP 5-85 scenario. In addition to this increase, an alteration in the seasonality of precipitation can be seen as well (Fig. 5(b)). While from March to August there will not be large changes in the amount of precipitation, from September to February the increase will be considerable, especially in October, November, December and January.

For air temperature, the increase is much more pronounced (Fig. 6(a)). In this case, all GCMs show an increase, but there is more discrepancy among them, especially at the end of the century. Also, the increase in temperatures seems slightly more pronounced in the cold months, including November and December (Fig. 6(b)). The CanESM5 model, from 2050 onwards, shows a markedly higher temperature than the rest of the GCMs. On the other hand, the MIROC6 model tends to show a lower temperature than the rest of the models, especially in the SSP 5-85 scenario. Despite these differences, the general trend is an increase between 2.5 and 4 °C by the end of the century (Table 6). As for seasonality, it seems that it will not be altered markedly, as the coldest and warmest months will remain the same throughout the century. However, there will be a general rise in temperatures throughout the year. This increase is especially alarming in the cold months, where the present-day average temperature is close to 0 °C. In this context, an average temperature increase of between 3 and 5 °C (as shown in Fig. 6(b) for December, January and February) may have consequences on the hydrological cycle due to the role of snow and ice in this catchment (Jiménez-Navarro et al., 2021).

The projected temperature increase is in agreement with the conclusions obtained in other climate change studies at the global level (Wuebbles et al., 2017) and at the national level (Lind and Kjellström, 2008). Similarly, the increase in precipitation is an expected consequence of climate change in northern Europe (Jacob et al., 2014; Strandberg et al., 2015).

#### 4.4.2. Variations in the catchment water balance

As a consequence of the changes in the meteorology, the Erken hydrological cycle will also suffer alterations. These changes were addressed and analyzed with the SWAT+ model (Table 7). The components that have been analyzed are discharge, water yield and evapotranspiration occurring in the catchment.

There are discrepancies among the GCMs analyzed (Table 7). On the one hand, CanESM5 is the model that presents the highest increase of the three components in both scenarios (SSP 2-45 and SSP 5-85). This increase is most pronounced in the SSP 5-85 scenario. The CanESM5 model is also the one that presented the largest increase in precipitation and temperature in the last half of the century (Figs. 5 and 6).

On the other hand, the MIROC6 and MRI-ESM2-0 GCMs also show the same increasing trend as the previous model, but with a less abrupt increase. The MIROC6 model is an exception to this trend by predicting a slight decrease in evapotranspiration at mid-century with respect to the historical period. The MRI-ESM2-0 model, on the other hand, shows a stabilization of evapotranspiration at the end of the century, with a slight decrease compared to mid-century. Both exceptions occur only in the SSP 2-45 scenario.

Finally, the GCMs BCC-CSM2-MR and INM-CM5-0 show an increasing trend in discharge and water yield during the mid-century period, and a subsequent decreasing rate of change to the end of the century. That is, the values increase with respect to the historical period until 2069; but in

the last period of the century (2070–2100) the values decrease slightly, implying some stability in the hydrological cycle. For the GCM BCC-CSM2-MR this pattern of change is only shown in the SSP 2-45 scenario, while the SSP 5-85 shows a progressive increase similar to the other GCMs. INM-CM5-0 shows continued increases in both scenarios.

Considering the five GCMs analyzed, the general trend is an increase in discharge, water yield and evapotranspiration, as we can see in the average section of Table 7. This increase would be more gradual in the SSP 2-45 scenario, which is less aggressive, and more pronounced in the SSP 5-85 scenario, allowing less flexibility to mitigate its effects. In both cases, the increase would be significant enough to affect the human activities in the lake catchment. Such a significant increase in water yield implies increased surface runoff and possible loss of soil dissolved and particulate nutrients from the catchment (Geng et al., 2015; López-Ballesteros et al., 2020). Both of these processes are related to the increase in precipitation and its seasonality. On top of that, the trend in ET is lower than expected given the clear trend in increasing air temperature (Table 7). Therefore, the increasing trend in water yield is also a result of relatively small increases in ET. In addition, higher evapotranspiration means a potential water loss from the lake and the soil, due to the higher temperatures and to the slight increase in solar radiation (Table 6) (Abtew and Melesse, 2013).

As a consequence of climate change, the seasonality of water discharge will increase significantly in Lake Erken (Fig. 7). Although the general trend is for the annual water discharge to increase (Table 7), in the warm months (May to August) the trend is for the discharge to remain the same as in the historical period or even show a decrease in May and June. However, during the rest of the months the discharge will increase significantly, especially in December, January and February. This may be linked not only to the increase in precipitation in the study area, but also to the increase in temperature in those months. As the average temperature rises above 0 °C, water from precipitation would no longer be retained in the catchment in the form of snow, and would further increase the surface runoff process and the inflow of water into the lake throughout the winter period.

#### 4.4.3. Future Lake water quality conditions

Water temperatures increased markedly in future scenarios, with differences as high as 6 °C for surface temperatures between historical and end-of-century periods, and 2.5 °C for deep-water temperatures (Appendix G). Concurrently, the duration and strength of stratification increased, although mixed layer depth did not show a clear trend. Ice cover decreased in duration as well, and tended to disappear at the end of the century in the SSP 5-85 scenario in three of the five GCM simulations. The average rates of temperature increase found in the present study (Sen's slope of 0.26–0.43 °C/decade for surface water, 0.19–0.31 °C/decade for bottom water for SSP245 - 585, Appendix G) are in line with those found in previous studies (O'Reilly et al., 2015; Pilla et al., 2020).

Oxygen in the surface waters decreased (Fig. 8, Sen's slope 0.07–0.09 mg/l/decade), most likely due to lower solubility at higher temperatures. It decreased markedly faster at 15 m (Sen's slope 0.14–0.21 mg/l/decade), due to longer periods of stratification, which led to hypolimnetic anoxia becoming more prevalent in the future scenarios. Whereas the decline in hypolimnetic oxygen was linear, there appeared to be a rather sudden decrease in surface-level oxygen in the last two or three decades of the century, occurring in multiple GCMs (Appendix Fig. F.1). Inspection of the data suggested this was due to the stronger development of anoxia during stratification, which caused decreases in epilimnetic oxygen after complete

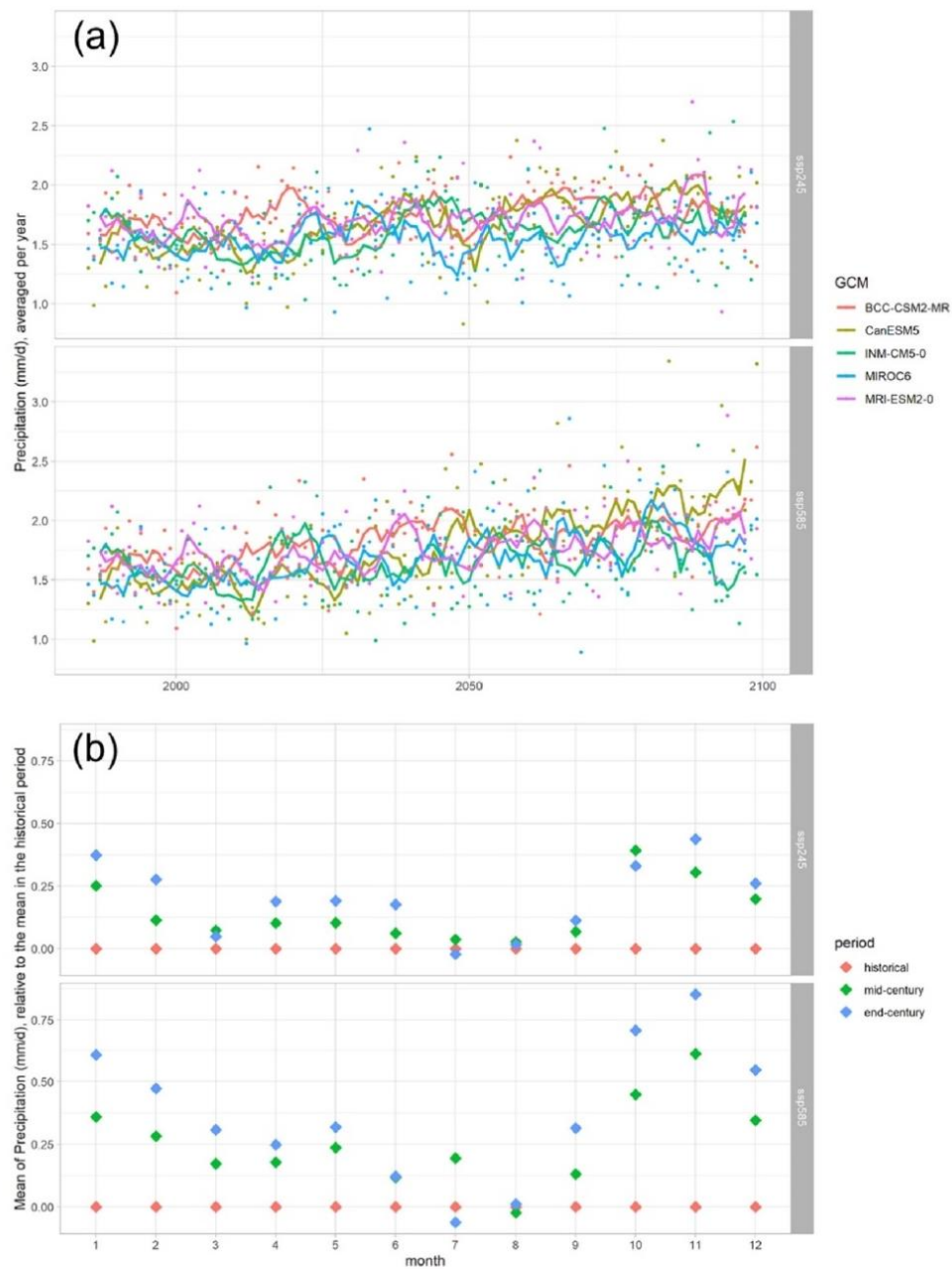


Fig. 5. Evolution of the precipitation in the area of study for the historical period (1985–2014), and the future mid-century (2040–2069) and end century (2070–2099) periods: (a) linear evolution for each GCM. Dots indicate the value per year and the lines are the 5-year moving average; (b) annual distribution for future period, relative to the historical period.



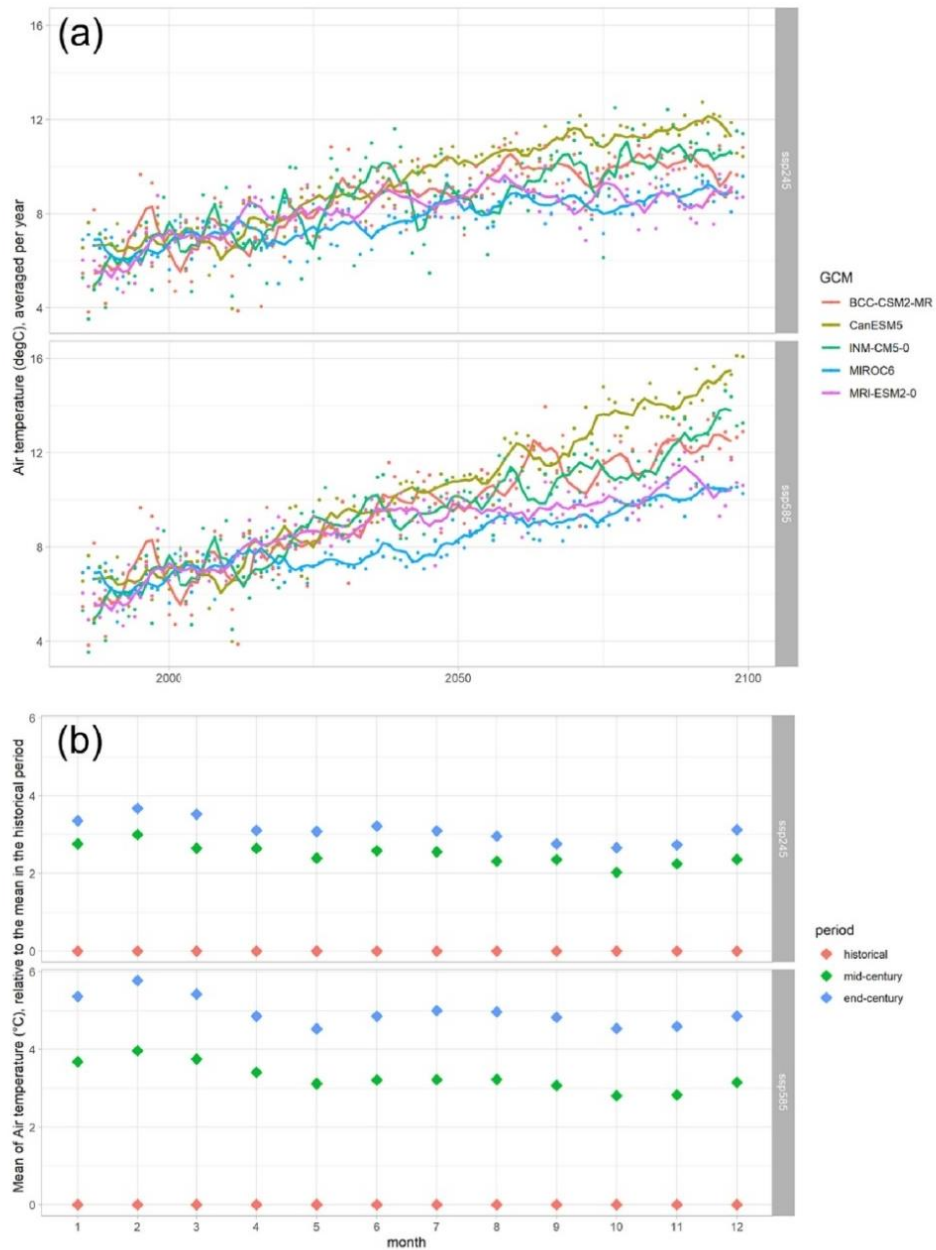


Fig. 6. Evolution of the temperature in the area of study for the historical period (1985–2014), and the future mid-century (2040–2069) and end century (2070–2099) periods: (a) linear evolution for each GCM. Dots indicate the value per year and the lines are the 5-year moving average; (b) annual distribution for future period, relative to the historical period.

**Table 7**

Variation of the components of the hydrological cycle in Erken catchment in the future in different GCMs and in the average of the five GCMs for the historical period (1985–2014), and the future mid-century (2040–2069) and end century (2070–2099) periods. For each component the table shows the absolute value of the variation and the increase in percentage compared to the historical period ( $\Delta x$ ).

| GCM         | Scenario | Period      | Discharge ( $\text{m}^3/\text{s}$ ) |            | Water yield (mm) |            | Evapotransp. (mm) |            |
|-------------|----------|-------------|-------------------------------------|------------|------------------|------------|-------------------|------------|
|             |          |             | Abs. Value                          | $\Delta x$ | Abs. Value       | $\Delta x$ | Abs. Value        | $\Delta x$ |
| BCC-CSM2-MR | Hist     | 1985–2014   | 0.46                                |            | 80.85            |            | 355.93            |            |
|             | SSP 2-45 | Mid-century | 0.57                                | 24 %       | 98.27            | 22 %       | 363.52            | 2 %        |
|             |          | End-century | 0.56                                | 21 %       | 96.09            | 19 %       | 361.25            | 1 %        |
|             | SSP 5-85 | Mid-century | 0.62                                | 33 %       | 105.25           | 30 %       | 379.25            | 7 %        |
|             |          | End-century | 0.69                                | 49 %       | 117.46           | 45 %       | 371.36            | 4 %        |
| CanESM5     | Hist     | 1985–2014   | 0.38                                |            | 68.58            |            | 329.26            |            |
|             | SSP 2-45 | Mid-century | 0.56                                | 46 %       | 95.21            | 39 %       | 354.12            | 8 %        |
|             |          | End-century | 0.60                                | 56 %       | 102.03           | 49 %       | 371.90            | 13 %       |
|             | SSP 5-85 | Mid-century | 0.65                                | 69 %       | 110.12           | 61 %       | 359.77            | 9 %        |
|             |          | End-century | 0.77                                | 101 %      | 132.93           | 94 %       | 406.64            | 24 %       |
| INM-CM5-0   | Hist     | 1985–2014   | 0.43                                |            | 75.37            |            | 336.38            |            |
|             | SSP 2-45 | Mid-century | 0.56                                | 31 %       | 97.18            | 29 %       | 341.26            | 1 %        |
|             |          | End-century | 0.53                                | 25 %       | 92.60            | 23 %       | 349.02            | 4 %        |
|             | SSP 5-85 | Mid-century | 0.55                                | 29 %       | 95.40            | 27 %       | 341.71            | 2 %        |
|             |          | End-century | 0.54                                | 26 %       | 93.29            | 24 %       | 346.03            | 3 %        |
| MiroC6      | Hist     | 1985–2014   | 0.37                                |            | 65.49            |            | 349.22            |            |
|             | SSP 2-45 | Mid-century | 0.38                                | 2 %        | 65.95            | 1 %        | 342.73            | –2 %       |
|             |          | End-century | 0.48                                | 27 %       | 81.25            | 24 %       | 352.00            | 1 %        |
|             | SSP 5-85 | Mid-century | 0.54                                | 45 %       | 92.95            | 42 %       | 363.34            | 4 %        |
|             |          | End-century | 0.59                                | 58 %       | 100.98           | 54 %       | 377.02            | 8 %        |
| MRI-ESM2-0  | Hist     | 1985–2014   | 0.44                                |            | 77.35            |            | 368.86            |            |
|             | SSP 2-45 | Mid-century | 0.51                                | 17 %       | 87.34            | 13 %       | 372.28            | 1 %        |
|             |          | End-century | 0.55                                | 25 %       | 93.88            | 21 %       | 371.63            | 1 %        |
|             | SSP 5-85 | Mid-century | 0.54                                | 24 %       | 92.92            | 20 %       | 375.90            | 2 %        |
|             |          | End-century | 0.57                                | 30 %       | 97.81            | 26 %       | 389.41            | 6 %        |
| VERAGE      | Hist     | 1985–2014   | 0.42                                |            | 73.53            |            | 347.93            |            |
|             | SSP 2-45 | Mid-century | 0.52                                | 24 %       | 88.79            | 21 %       | 354.78            | 2 %        |
|             |          | End-century | 0.54                                | 31 %       | 88.79            | 27 %       | 361.6             | 4 %        |
|             | SSP 5-85 | Mid-century | 0.58                                | 40 %       | 99.33            | 36 %       | 363.99            | 5 %        |
|             |          | End-century | 0.63                                | 53 %       | 108.49           | 49 %       | 378.09            | 9 %        |

mixing occurred. Regardless, this pattern was unexpected and we could not identify the exact drivers of this sudden change. Exacerbation of oxygen conditions under warming atmospheric conditions has been found in other studies as well (Schwefel et al., 2016; Jane et al., 2021),

pointing towards more frequent anoxia as lakes warm and stratify longer.

Nitrate concentrations tended to remain constant, whereas ammonium and phosphate concentrations increased, although near the end of the

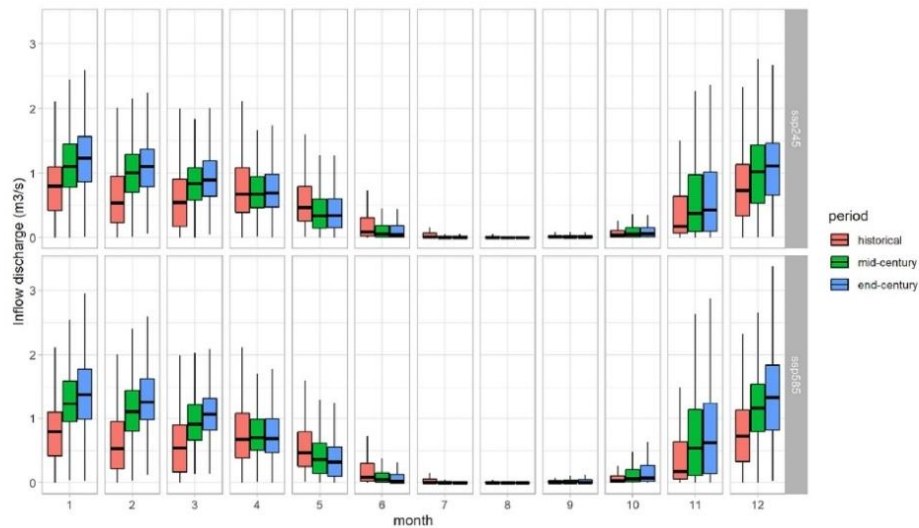


Fig. 7. Monthly distribution of the inflow discharge into Lake Erken for the historical period (1985–2014), and the future mid-century (2040–2069) and end century (2070–2099) periods.

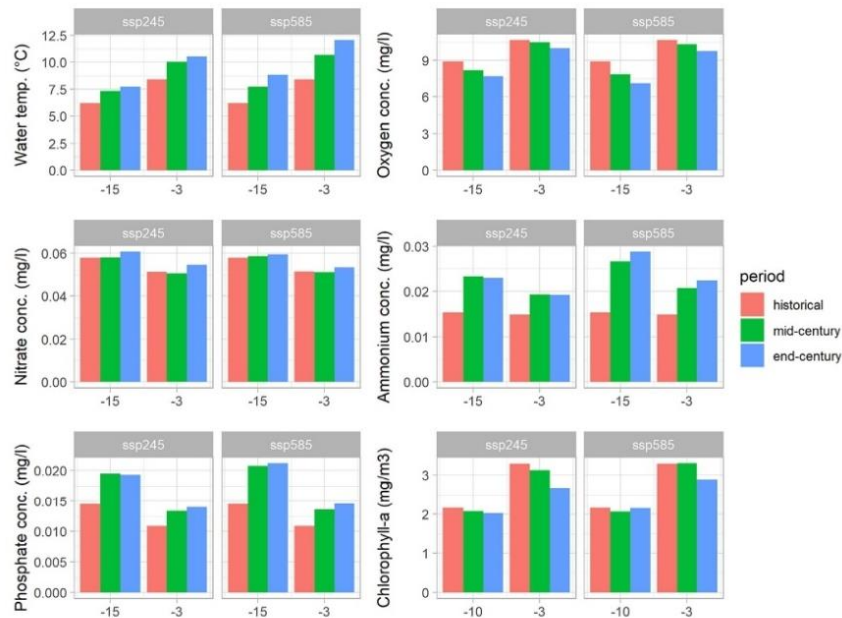


Fig. 8. Average values of water temperature and concentrations of oxygen, nitrate (NO<sub>3</sub>-N), ammonium (NH<sub>4</sub>-N), phosphate (PO<sub>4</sub>-P), and chlorophyll-a for different depths, scenarios, and periods (historical 1985–2014, mid-century 2040–2069, end-century 2070–2099), averaged over all GCMs.

century, nitrate started to increase and ammonium and phosphate stagnated or decreased (Appendix F, Fig. F.1). Although concentrations at 15 m depth tended to be higher than those at 3 m depth, these trends could be found irrespective of depth. The increase in nutrients may be partially caused by increased nutrient loading or relate to the longer stratification period. As chlorophyll did not show a clear linear trend during most of the study period, the increased availability of nutrients did not lead to increased biomass. Some of the clearest increases in surface-level nutrients were indeed seen during the winter months, when light limitation regulates growth, although summer hypolimnetic nutrients increased as well. As nutrient concentrations in a lake are highly dependent on boundary conditions (and the time scale of the lake response depends on depth and residence time), future predictions of nutrient concentrations in lakes are bound to diverge based on catchment land use and lake characteristics. In a previous study in Lake Erken, using an unchanged nutrient loading in a warming scenario, deep-water nutrient concentrations increased due to a longer stratification period (Mesman et al., 2022). Our choice of using a constant discharge-nutrient concentration relationship while precipitation is increasing led to higher nutrient loading, which will have influenced our future nutrient concentrations. Combined effects of climate and land use change in the Erken catchment will determine nutrient loading into the lake, and this may diverge from the scenario we used.

Until 2070, the concentration of chlorophyll remained largely constant in future scenarios, with a slight increase under the SSP 5-85 scenario (Appendix F Fig. F.2). The shorter ice cover and longer stratification period may stimulate phytoplankton growth earlier in the season, but nutrient limitation in the epilimnion sets in earlier as well, balancing positive and negative effects against each other. Responses of chlorophyll to warming are often dependent on the trophic state of the lake, as eutrophic lakes may show increases and nutrient-poor lakes decreases in chlorophyll (Kraemer et al., 2017). A constant or mildly increasing chlorophyll level in the mesotrophic Lake Erken therefore follows this pattern, and corresponds with the small increase with warming found in another study in this lake (Mesman

et al., 2022). After 2070, however, chlorophyll at 3 m decreased in most GCMs, with the SSP 5-85 scenario slightly preceding the changes in the SSP 2-45 scenario (Appendix F, Fig. F.1). The chlorophyll at 10 m depth did not show such a decrease and a deep chlorophyll maximum seemed to have formed during part of the summer. The longer the stratification period, the more the supply of nutrients from the hypolimnion becomes an essential source of nutrients for the summer bloom (at least in a non-eutrophic lake with a long residence time, such as Lake Erken), and a deep chlorophyll maximum would be a strategy to exploit such a source efficiently, given a sufficiently stable water column. A deep chlorophyll maximum is currently not observed in Lake Erken, but that multiple ensemble members predicted this, could point to the emergence of this phenomenon in the future. Lake Erken occasionally experiences large seiche movement in response to wind, which are not reproduced in a 1D model. These may disrupt DCM formation, and as such, this could be an important discrepancy between the simulations and reality.

#### 4.5. Limitations of the study

This study has several limitations, which should be taken into account when evaluating these results and drawing conclusions. These limitations have been addressed in several ways in order to obtain reliable conclusions. Because nutrient calibration was not yet reliable in the SWAT + model, LOADEST has been used. This implies that it has been assumed that the discharge-component relationship will remain constant in future simulations. This is especially relevant considering that an increase in the flow entering the lake is expected in the future. Possible future changes in the landuse of the basin have also not been taken into account, although these are not expected in the basin of Lake Erken.

Other small issues that may be considered limiting in this study are as follows. Only bimonthly or monthly measurements of nutrients in the main in flow are available in the Erken data. This has allowed us to obtain a continuous and daily series of flow components as input data for the



GOTM-WET model, but adds some uncertainty, as sudden peaks may be missed. Only one weather station has been used in this study. Although this is a limitation, according to the WMO (2008) in lowland areas, such as the catchment area draining the Erken lake, one station is sufficient for a basin of the size of our case study (141 km<sup>2</sup>).

## 5. Conclusions

After developing the SWAT+ and GOTM-WET models in the Lake Erken catchment, predictions of climate, lake catchment and water quality for the mid-21st century and for the end of the century have been obtained, using five different GCMs (BCC-CSM2-MR, CanESM5, INM-CM5-0, MiroC6 and MRI-ESM2-0). The following conclusions are drawn from this study:

- We described a coupled setup of the SWAT+ catchment model, the GOTM physical water column model, and the WET biogeochemical lake model in the Swedish Lake Erken. Both models perform well for both calibration and validation.
- Temperature and precipitation showed a clear tendency to gradually increase in the study area. This increase was significant enough to affect catchment conditions and the hydrological cycle. In addition, precipitation will vary more across seasons, increasing in October, November, December, January and February.
- Due to increased precipitation, the flow of water entering the Erken lake will increase in the future. Likewise, runoff will also increase, which may have consequences on the catchment soil and the input of components into the lake. In addition, seasonality will increase, with less flow in the summer months, and more in the other months, especially in winter.
- An increase in lake water temperature is expected, which will cause an increase in the length and stability of stratification and a decrease in oxygen. Nitrate is predicted to remain constant, while phosphate and ammonium increase. Finally, chlorophyll concentrations will decrease slightly, most likely due to increasingly stringent nutrient limitation in the more strongly stratified lake.
- All of the above changes will occur in both the strong-mitigation scenario (SSP 2-45) and the weak-mitigation scenario (SSP 5-85). In general, similar changes will occur in both scenarios, but more intensely in SSP 5-85.
- The results obtained in this study are both realistic and reasonable, and the methodology used here could be applied to other areas for study. A coupled catchment-lake configuration allows prediction of future lake biogeochemical conditions, including linking changes in land use to changing lake conditions, as well as studies of eutrophication and browning. Since climate affects both the lake and the catchment, simulations of climate changes should ideally take into account both systems, as the lake is intrinsically linked to its catchment. This manuscript can be considered a first step in this direction, and demonstrates a powerful methodology that allows many new research questions to be answered. On a practical level, this methodology can be applied in lakes whose watershed is particularly relevant. Some specific examples would be: watersheds where there have been strong changes in land use that must be taken into account, highly anthropized watersheds where the discharge of components to the lake is substantial, or watersheds in areas especially vulnerable to climate change where large alterations in climatology and precipitation regime are expected. The methodology would allow to better establish water plans and in general to foresee which measures can be more effective to guarantee the highest possible water quality in the water bodies.

## CRedit authorship contribution statement

**Inmaculada C. Jiménez Navarro:** Conceptualization, developed of the methodology and study, SWAT+ model development, coupling of the model, analysis of results, discussion, conclusions and writing of the manuscript. **Jorrit P. Mesman:** Conceptualization, developed of the methodology and study, GOTM-WET model development, coupling of the model, analysis of results, discussion, conclusions and writing of the manuscript.

**Don Pierson:** Conceptualization, GOTM-WET model supervision, review & editing of the manuscript. **Dennis Trolle:** SWAT+ model supervision, review & editing of the manuscript. **Anders Nielsen:** SWAT+ model supervision, review & editing of the manuscript. **Javier Senent-Aparicio:** Conceptualization, SWAT+ model supervision, review & editing of the manuscript.

## Data availability

The CMIP6 climate forcing data used for this study are publicly available and were downloaded from the DKRZ ESGF-CoG Node. Lake Erken meteorological, inflow and lake data can be retrieved from the SITES data portal (<https://data.fieldsites.se/portal/>). For access and documentation on the models used, please visit <https://swat.tamu.edu/software/plus/> for SWAT+ and refer to <https://projects.au.dk/wet> for GOTM-WET.

## 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2023.163946>.

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5.3. RESEARCH PAPER 3: THE IMPLICATIONS OF THE USE OF ET REMOTE SENSING DATA FOR CALIBRATING HYDROLOGICAL MODELS: A COMPARISON OF SINGLE AND MULTI-CRITERIA CALIBRATION IN SWAT+

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# The Implications of the Use of ET Remote Sensing Data for Calibrating Hydrological Models: A Comparison of Single and Multi-criteria Calibration in SWAT +

Inmaculada C. Jiménez-Navarro<sup>1</sup> · Don Pierson<sup>2</sup> · Javier Senent-Aparicio<sup>1</sup>

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## Abstract

The availability of remotely sensed data has opened new possibilities for research and development of hydrological models. Satellite-derived evapotranspiration (ET) data are useful for improving calibration in ungauged catchments and for performing multi-criteria calibrations in gauged catchments. In this study, SWAT + has been used to analyze different calibration strategies in the watershed of Lake Erken Sweden. Two sensitivity analyses were carried out to detect flow-sensitive and ET-sensitive parameters. A calibration has been performed with observed discharge data (Q scenario), with ET data obtained from the Amsterdam Global Terrestrial Evaporation Model (ET scenario), and a multi-criteria calibration using both data (Q-ET scenario). The calibrations were performed using the SWAT Toolbox software. Results show that all three simulations are statistically acceptable for flow and ET (NSE = 0.773 for Q and NSE = 0.765 for ET in the Q scenario; NSE = 0.712 for Q and NSE = 0.779 for ET in the ET scenario; NSE = 0.764 for Q and NSE = 0.771 for ET in the Q-ET scenario). In the single calibrations, we observed an improved result for the calibrated variable but a reduced fit for the other. The combined calibration approach, however, produces intermediate values for both streamflow and ET, demonstrating its utility. Notably, calibrating with ET alone exhibits some limitations in simulating lateral flow and soil water retention but shows promise as a robust calibration method in ungauged basins. Our study suggests that a mixed calibration, prioritizing streamflow while using ET data to further refine relevant parameters, offers a realistic and effective approach to improve calibration of hydrologic models.

**Keywords** Evapotranspiration · GLEAM · Lake Erken · Multi-variable calibration · SWAT +

## 1 Introduction

Hydrological models have long served as indispensable tools within the scientific community for the examination and sustainable management of Earth's water resources, as evidenced by numerous examples (Devia et al. 2015; Jodar-Abellán et al. 2019; Pandi et al. 2021). One of the most widely used hydrological models in recent decades has been the Soil and Water Assessment Tool (SWAT), a

semi-distributed model that has been applied effectively in different parts of the world (Bressiani et al. 2015; Tan et al. 2019; Akoko et al. 2021). These models are designed to replicate the processes of the hydrological cycle, requiring rigorous calibration and validation procedures to ensure their reliability. Ideally to accomplish this, a discernible hydrological cycle component that can be accurately measured or estimated is carefully chosen. Subsequently, the observed data for this selected component are meticulously compared to the model-simulated counterparts (Salvadore et al. 2015). Often however, this component is stream discharge at the outlet of the watershed, which is affected by multiple processes.

One of the predominant applications of hydrological models is to facilitate the management of surface water resources. In such scenarios, the conventional practice involves calibration against historical records derived from gauged basins. However, there are instances where

✉ Inmaculada C. Jiménez-Navarro  
icjimenez@ucam.edu

<sup>1</sup> Department of Civil Engineering, Catholic University of San Antonio, Campus de Los Jerónimos S/N, 30107 Guadalupe, Murcia, Spain

<sup>2</sup> Department of Ecology and Genetics, Limnology, Uppsala Universitet, Norbyvägen 18 D, 752, 36, Uppsala, Sweden



data on water discharge may not be readily available. In such scenarios, an alternative calibration method often involves resorting to evapotranspiration as an alternative source of data for comparative purposes (Aznarez et al. 2021; López-Ballesteros et al. 2023). Among the integral components of the hydrological cycle, precipitation and evapotranspiration stand out as two of the most pivotal, alongside runoff and infiltration. These components exhibit close interconnections, with approximately 60% of the moisture stemming from precipitation being returned to the atmosphere through evapotranspiration. Additionally, it is noteworthy that roughly half of the solar energy absorbed at the Earth's surface is expended in evapotranspiration processes (Hunt et al. 1986; Kiehl and Trenberth 1997). Obtaining evapotranspiration (ET) data has become increasingly convenient and accessible with the advancement of remote sensing technology (Powell et al. 2013). The use of remote sensing technologies has not only been used in the last decade, but also have various uses nowadays. For instance, they can be used to study the impact of surface temperature in urban areas (Zeren Cetin et al. 2023a, b) or to analyze land cover changes in a specific area (Cetin 2019; Cetin et al. 2021; Aksoy et al. 2022; Sahin et al. 2022) among others. Another major use of remote sensing techniques is that these technologies facilitate the development of global-scale atmospheric data models by leveraging satellite capabilities. A noteworthy example is the Global Land Evaporation Amsterdam Model (GLEAM) (Miralles et al. 2011), which integrates remote sensing data, meteorological observations, and sophisticated algorithms for the comprehensive computation of global-scale evapotranspiration.

The accessibility of these databases significantly facilitates the development of hydrological models by providing a larger dataset for calibration and validation purposes. This proves particularly advantageous in two distinct scenarios. Firstly, it permits the use of this dataset in regions lacking streamflow gauge records (Alemayehu et al. 2022). Secondly, it enables the implementation of multi-criteria calibration techniques in regions where continuous data series of stream discharge are available. In recent years, there has been a discernible trend toward employing multi-factor calibration methodologies to attain superior outcomes in hydrological model development. Multi-criteria calibration confers numerous advantages, foremost among them being the enhancement of model accuracy through its capacity to accommodate greater spatial and temporal variability. Additionally, the incorporation of data from diverse facets of the hydrological cycle serves to constrain the model, considering a broader spectrum of hydrological dynamics (Immerzeel and Droogers 2008; Parajuli et al. 2018; Sirisena et al. 2020). Multi-criteria calibration offers another valuable advantage by addressing the issue

of equifinality. Equifinality refers to the phenomenon where different combinations of model parameters can yield acceptable representations of the processes affecting stream discharge, even though not all equally approximate reality. This problem is particularly prevalent in semi-distributed parameter rich hydrological models like SWAT. To mitigate equifinality, various strategies can be employed. One approach involves reducing the number of calibrated parameters (Fu et al. 2015). Another effective method is to incorporate multiple variables into the model calibration process, thereby expanding the pool of observations (Rajib et al. 2018; Her and Seong 2018; Shah et al. 2021). Integrating calibration data from remote sensing datasets has proven effective in reducing the likelihood of model equifinality, as shown in previous studies (Xie and Zhang 2010; Lettenmaier et al. 2015).

Previous studies have examined the calibration of ET and streamflow using the initial version of the SWAT model. For instance, in the study conducted by Odusanya et al. (2021), two calibrations were performed using streamflow data and ET data. In this paper a large basin served as the study area and the findings indicate that calibration against streamflow better replicates flow dynamics but performs less accurately for ET. Conversely, ET based calibration while more accurate for ET exhibited poorer performance simulating flow dynamics. Nevertheless, in the absence of measured discharge, the sole reliance on ET adequately captured temporal runoff dynamics. Other prior investigations have implemented various multi-calibration strategies for SWAT across different geographical regions. Franco et al. (2020) compared multi-site calibration of a large Brazilian basin with a multi-criteria calibration involving streamflow and ET data extracted from the METRIC model. This study determined that multi-variable calibration did not yield a significant enhancement in model performance but did reduce uncertainty. Tobin and Bennett (2017) employed satellite-derived ET data to refine the SWAT parameters in an Oklahoma basin. The findings of this study underscore the utility of evapotranspiration in combination with streamflow for model constraint, emphasizing the need for further calibration strategies. Additionally, various studies have explored the efficacy of calibrating solely with evapotranspiration or streamflow. The study conducted by Parajuli et al. (2018) concludes that calibration exclusively with ET produces favorable results, while the study by Sirisena et al. (2020) reaches the opposite conclusion. Furthermore, some studies propose the use of remote sensing-derived ET as a viable strategy for basins with limited data (Koltsida and Kallioras 2022). The SUFI-2 method is used for both calibrations and sensitivity assessments in all the investigations mentioned above. The analyses are carried out using the outdated version of SWAT and the SWAT-CUP software (Abbaspour

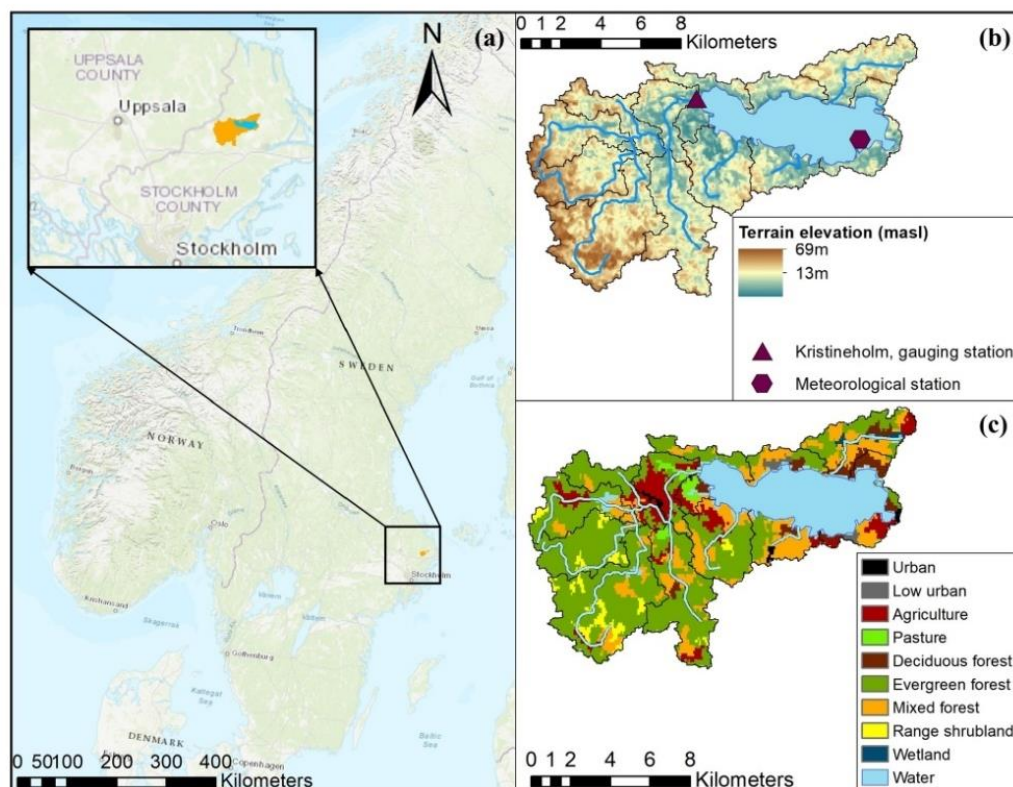
2015). In this study, we suggest a novel method that employs a SWAT+ model and the Toolbox software for the sensibility analysis and calibrations. different statistical techniques are also proposed and used; they are explained in the methodology section and include the dynamically dimensioned search method for calibration and the Sobol analysis for sensitivity analysis.

In this study, we investigate multi-criteria calibration techniques in the Erken Lake basin located in Sweden. We use the latest version of the SWAT hydrological model, SWAT+ (Bieger et al. 2017), and incorporate observed streamflow data and evapotranspiration data obtained through remote sensing from the GLEAM model (Miralles et al. 2011). Our research encompasses various single-variable and multi-variable calibration strategies to assess how SWAT+ performs under different conditions. The primary objectives of this study are to compare the performance of the SWAT+ model under each calibration strategy, identify the sensitive parameters for each

calibration, and analyze their implications. Additionally, we aim to evaluate the model's performance through validation to determine if satisfactory flow simulation results can be achieved using ET data exclusively. Furthermore, our study seeks to analyze and compare different components of the hydrologic cycle under each calibration scenario and assess whether the inclusion of ET data in the calibration process effectively constrains a model initially calibrated solely with streamflow data.

## 2 Study Area

Lake Erken is a shallow, mesotrophic lake located in the eastern part of Sweden ( $59^{\circ}50'37''\text{N}$ ,  $18^{\circ}35'38''\text{E}$ ), at an altitude of 10 m above sea level (Fig. 1). The region is defined by a humid continental climate, characterized by brief yet pleasant summers and cold winters. The amount of precipitation is relatively constant throughout the year, with



**Fig. 1** Map of the study area: (a) location of Lake Erken and its catchment in the Scandinavian Peninsula; (b) digital elevation map of the Lake Erken catchment and location of Kristineholm (gauging station) and the meteorological station; (c) land uses in the Lake Erken catchment



a predominant presence of snow during the winter season. Based on the meteorological data collected for this study (2007–2021), the average annual maximum temperature in the Erken basin was 10.1 °C and the minimum 4.3 °C, and the yearly average precipitation is 581 mm. The draining area to Erken Lake covers an area of 141 km<sup>2</sup> and is east-westward oriented. This basin is characterized by its predominantly flat topography, lacking significant slopes or rugged terrain features (Fig. 1b). The majority of the watershed is covered by evergreen forest, interspersed with pockets of deciduous and mixed forests. Additionally, the region comprises expanses of grasslands designated for grazing, as the watershed accommodates non-intensive agricultural and farming practices (Fig. 1c). Due to its conditions and the limited activities that take place around it, Erken Lake has been used as a hydrological and limnological study site for many years (Weyhenmeyer et al. 1995; Pierson et al. 2011; Yang et al. 2016; Mesman et al. 2020; Jiménez-Navarro et al. 2023).

The watershed is settled over late-orogenic granite-pegmatite intrusive rocks, whose combination of fracturing, chemical alteration, and dissolution processes creates favorable conditions for the formation of aquifers (Johansson 2019). The importance of the aquifer in the study area was verified by applying the baseflow filter (Arnold and Allen 1999) to the daily observed flow data, which showed an average baseflow close to 65% in the Lake Erken basin.

### 3 Methodology

The research methodology employed in this study is visually represented in Fig. 2. In the following paragraph we provide a summary of the workflow used in this study, describing Fig. 2.

The initial phase of the study was a comprehensive and detailed process that involved the development and implementation of a SWAT+ model specifically designed for the Lake Erken drainage basin, using an extensive array

of all necessary and relevant data to ensure accuracy and reliability in the model's outputs.

In the second step of the study, using the model developed for the study area, two distinct sensitivity analyses were performed separately to evaluate and identify the parameters that are independently sensitive to streamflow discharge and ET, ensuring a comprehensive understanding of each parameter's impact.

After the sensibility analyses, the model was calibrated during step 3 using three different approaches: (a) a calibration of simulated discharge against observed discharge data using all parameters sensitive to streamflow; (b) a calibration of simulated ET against ET data obtained from GLEAM using all parameters sensitive to evapotranspiration; and (c) a mixed calibration approach using ET data to calibrate parameters that naturally influence evapotranspiration while calibrating the remaining sensitive parameters against streamflow data.

As a result, four separate scenarios were obtained according to the calibration performed on the model. These scenarios are: (a) the default scenario uncalibrated, (b) the Q scenario, calibrated using streamflow data, (c) the ET scenario, calibrated using ET data, (d) the Q-ET scenario, with a multi-calibration approach. For the step 4, all these scenarios were analyzed in different ways:

- The basin's characterization was completed by analyzing the fixed values of crucial parameters in each calibration.
- A validation period was established to evaluate the robustness of each simulation, and the calibration and validation procedures were rigorously assessed using graphical and statistical methods.
- Lastly, the data generated from each calibration scenario were used to graphically analyze and compare the various components of the hydrological cycle.

All these processes are described in detail below, in the following subsections of the methodology.

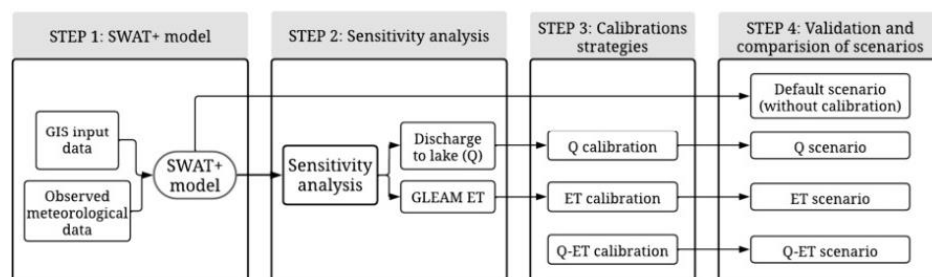


Fig. 2 Flowchart of the methodology

### 3.1 SWAT + Model

The Soil and Water Assessment Tool (SWAT) (Arnold et al. 2012) is a widely used hydrological modeling software for watersheds. This model has been used over the last 20 years in many parts of the world with a wide range of climatic and geographic conditions, as well as various temporal and spatial scales. Within this model, the drainage basin is subdivided into discrete sub-basins, which are subsequently partitioned into Hydrologic Response Units (HRUs). Each HRU is a unique combination of land-use, slope, soil and management activities, connected through a geographic information system interface. The variations between the HRUs enable the model's representation of spatial variations in water dynamics. This model adopts a semi-distributed approach, under the assumption that identical HRUs with combinations of land-use, slope, soil properties, and management practices will engender consistent hydrological responses (Mohammed et al. 2018). The water balance equation (Eq. 1) is the main driver of the model's hydrology, expressed as follows:

$$W_i = SW_o + \sum (V_i - Q_i - E_i - P_i - QR_i) \times \Delta t \quad (1)$$

In Eq. 1,  $SW_i$  and  $SW_o$  represent the final and initial soil water content;  $V_i$  represents the precipitation;  $Q_i$  represents the surface runoff;  $E_i$  represents the evapotranspiration;  $P_i$  represents the percolation and  $QR_i$  represents the return streamflow. All these components are expressed in millimeters per day.  $\Delta t$  represents the time interval in days. The  $i$  term denotes the index.

In 2017, the SWAT model underwent a significant evolution, leading to the introduction of SWAT+ (Bieger et al. 2017). This development emerged in response to the increasing demands from the scientific community, as further enhancements to the original SWAT model had reached their limits. In this updated model, elements of the watershed, including aquifers, land use units, HRUs, ponds, and reservoirs, are defined as spatial objects. This distinctive feature substantially augments the configurational and discretization capabilities of the watershed, in contrast to the earlier version of SWAT.

The SWAT+ models have more than 150 parameters that can be evaluated from the Toolbox software (Chawanda 2021). In this study, mainly 16 of these parameters have been used. A short definition of these 16 parameters is given in Table 1 for reference.

### 3.2 Model Setup

To develop a robust SWAT+ model, three categories of data are imperative: comprehensive geographic information pertaining to the study region, meteorological input data corresponding to the targeted simulation period; and independent estimates of data characterizing the simulated model hydrological state variables, essential for model calibration and validation. In this Sect. 3.2., we provide a comprehensive account of the specific data sets employed in our model, along with their respective sources and acquisition methodologies. All data used are described in Table 2.

To establish the HRUs within a watershed, several geographic datasets are indispensable, including a Digital

**Table 1** Definition of the SWAT+ parameters involved in this study

| Parameter | Description                                                                                                   |
|-----------|---------------------------------------------------------------------------------------------------------------|
| lat_ttime | Lateral flow length in days                                                                                   |
| Epc       | Vegetative absorption compensation factor                                                                     |
| flo_min   | Threshold of the depth of water required in the shallow aquifer for water return to occur                     |
| cn3_swf   | Soil water factor for curve number condition III                                                              |
| cn2       | Curve number, relates to the soil permeability                                                                |
| revap_co  | Groundwater "reevap" coefficient                                                                              |
| Awc       | Available water capacity of the soil layer (m H <sub>2</sub> O/m soil)                                        |
| Bd        | Moisture bulk density                                                                                         |
| Chn       | Manning's "n" value for the main channel                                                                      |
| Canmx     | Maximum canopy storage (mm H <sub>2</sub> O)                                                                  |
| revap_min | Threshold depth of water in the shallow aquifer for "reevap" or percolation to the deep aquifer to occur (cm) |
| K         | Saturated hydraulic conductivity (mm/hr)                                                                      |
| latq_co   | Lateral flow coefficient                                                                                      |
| Alpha     | Base streamflow alpha factor (1/day)                                                                          |
| Esco      | Soil evaporation compensation factor                                                                          |
| Perco     | Shallow aquifer percolation fraction                                                                          |



**Table 2** Inputs of the SWAT+ model setup and data used for calibration

| Input                                    | Resolution                                         | Source                                                                             |
|------------------------------------------|----------------------------------------------------|------------------------------------------------------------------------------------|
| Digital elevation map                    | 30 m                                               | Shuttle Radar Topography Mission (SRTM) (Farr and Kobrick 2000)                    |
| Harmonized World Soil Data               | 1 km                                               | Food and Agriculture Organization of the United Nations (Nachtergaele et al. 2010) |
| Corine land cover                        | 100 m                                              | Copernicus Land Monitoring Service (CLC 2018)                                      |
| Meteorology (temperature, precipitation) | Daily                                              | Erken Laboratory and SMHI meteorological station (Fig. 2b)                         |
| Inflow discharge                         | Daily                                              | Gauging station at Kristineholm (Fig. 2b)                                          |
| GLEAM (v3.7b)                            | 0.25° latitude–longitude regular grid and at daily | Global Land Evaporation Amsterdam Model (Miralles et al. 2011)                     |

Elevation Map (DEM), a Land Cover Map, and a Soil Map. These datasets serve as the foundational inputs for the SWAT+ software, which, through the QGIS interface, facilitates the delineation of watercourses within the watershed and the subsequent partitioning of the area into subwatershed and HRUs. This process is done with the software QSWAT+. The DEM employed in our study was sourced from the Shuttle Radar Topography Mission (SRTM) dataset (Farr and Kobrick 2000). Soil data were acquired from the Food and Agriculture Organization of the United Nations Harmonized World Soil Database (Nachtergaele et al. 2010). The Land Use Map was extracted from the Copernicus Land Monitoring Service, and specifically the Corine Land Cover dataset was used, which consists of an inventory of 44 land cover classes (CLC 2018).

The input meteorological data used to force our model were obtained from daily temperature and precipitation measurements recorded at either the Erken Laboratory meteorological station (59°51'30.7080"N, 18°24'17.5536"E) or a station operated by SMHI (Sveriges meteorologiska och hydrologiska institut, n. d.) (59,83,232, 18,634,817) also at the Erken Laboratory. One meteorological station is strategically situated on a small island approximately 500 m offshore within Lake Erken (Fig. 2b), while the SMHI station is located on land approximately 425 m from the lake shore. Both stations collect automated daily measurements of various meteorological parameters, including atmospheric temperature and precipitation. These measurements serve as the primary input data for SWAT+ in the computation of potential evapotranspiration. SWAT+ offers several methods for estimating ET, such as Penman–Monteith, Priestley–Taylor and Hargreaves, with the choice of method contingent upon the availability of specific daily climatological data. For our study, we opted to utilize the Hargreaves method (Hargreaves 1994), a simplified approach reliant solely on precipitation and temperature data. Notably, the Hargreaves method aligns with our data availability, as it requires fewer inputs compared to other more data-intensive methods. This decision is substantiated by Oudin et al. (2005), who

reported that hydrological models employing temperature-based methods with reduced data requirements exhibit comparable performance to those reliant on more data-intensive alternatives. Furthermore, simplified data inputs would be compatible with the ET only calibration, which would be expected to be applied to data sparse areas.

To effectively calibrate and validate the SWAT+ model, primarily depends on utilizing key components of the hydrological cycle. Among the commonly used measured data, streamflow at a specific location within the basin is of paramount importance. In our study, we used stream discharge data measured at the Kristineholm monitoring station (Fig. 2b), situated along the primary inflow channel to Lake Erken. This dataset comprises daily records dating back to the middle of 2006. In addition to streamflow data, we tested different calibration strategies using ET data. For this purpose, we accessed ET data from GLEAM (Miralles et al. 2011), a remote sensing evapotranspiration dataset developed by the Vrije University of Amsterdam. GLEAM (v3.7b.) This dataset is the most recent version, offering comprehensive global coverage over a two-decade period, ranging from January 1, 2003, to December 31, 2022. GLEAM (v3.7b) is characterized by its robustness, being constructed through a fusion of remote sensing observations from multiple satellites and rigorously validated using eddy-covariance towers and in-situ sensors (Martens et al. 2017).

### 3.3 Calibration and Validation of the Model

After the model was developed, we conducted two distinct sensitivity analyses employing the Sobol method (Sobol' 2001). These sensitivity analyses aimed to discern the influential parameters within the model, to pinpoint those parameters that exert the most substantial influence on specific components of the hydrological cycle. Consequently, we executed a sensitivity analysis for flow and a separate one for ET, systematically investigating the parameters that exhibited sensitivity to each component. The Sobol method, chosen for its variance-based sensitivity analysis capability, dissects the total output variance into individual

contributions attributed to each model parameter within an ensemble. This method provides valuable insights into the relative importance of each parameter in shaping the model's behavior. A total of 1080 simulations were conducted for each sensitivity analysis.

Having identified the parameters that exhibit sensitivity to streamflow and ET, we established three distinct calibration strategies for the model. The first strategy involved the calibration of the 16 parameters sensitive to streamflow, using actual flow data for calibration. The second strategy focused on the calibration of the 10 parameters sensitive to ET, employing GLEAM data for calibration. Our third approach involved a mixed calibration scheme, where the five parameters that inherently impact evapotranspiration by definition were calibrated, while the remaining sensitive parameters were calibrated using streamflow data. These calibration strategies resulted in the creation of four unique scenarios for comparative analysis: (a) a default scenario without calibration, (b) a scenario calibrated based on streamflow data, (c) a scenario calibrated using ET data, and (d) a multi-calibration scenario. For the default scenario, the model was not calibrated, but the default values that SWAT attributes to each parameter were used.

All sensitivity analyses and model calibrations were executed using the SWAT+Toolbox software (Chawanda 2021), a freely available software designed to perform SWAT+ model sensitivity analysis, calibrations, and more. Calibration procedures were performed automatically and at a monthly temporal resolution, employing the dynamically dimensioned search method (Tolson and Shoemaker 2007). The Nash–Sutcliffe efficiency was employed as the objective function throughout the calibration processes. To ensure the model's simulation robustness, a validation period was established following each calibration exercise. For all four scenarios, the calibration phase encompassed the years from 2007 to 2016, while the subsequent validation phase spanned from 2017 to 2021. The temporal extent of this study was dictated by the availability of observed streamflow data, as elaborated in the preceding Sect. 3.1. Furthermore, a two-year warm-up period was established for each simulation prior to performance evaluation. For each calibration a total of 200 simulations were conducted.

After completing the calibration process, an analysis of the fixed parameter values obtained in each calibration was undertaken to discern the primary characteristics of the Erken Lake basin as simulated by SWAT+. To determine the goodness of fit for each scenario's calibration and validation, we assessed their respective performances using the four statistical metrics recommended by Moriasi et al. (2007, 2015). These metrics encompass the coefficient of determination ( $R^2$ ) (Eq. 2), the Nash–Sutcliffe efficiency (NSE) (Eq. 3), the standard deviation (RSR) (Eq. 4), and the percent bias (PBIAS) (Eq. 5).

$$R^2 = \left[ \frac{\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (S_i - \bar{S})^2}} \right]^2 \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (3)$$

$$RSR = \frac{\sqrt{\sum_{i=1}^n (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^n (O_i - \bar{S})^2}} \quad (4)$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - S_i)}{\sum_{i=1}^n O_i} \times 100 \quad (5)$$

In Eqs. 2, 3, 4 and 5,  $O_i$  and  $S_i$  are the observed and simulated data; the average observed and simulated values are  $\bar{O}$  and  $\bar{S}$ , and  $n$  refers to the total number of data points.

Finally, we examined variations in the hydrological cycle across each scenario. We used the R package SWATdoctR (Plunge et al. 2024) to extract the average precipitation, evapotranspiration, water yield and groundwater contribution from each simulated scenario. In addition, we analyzed the mean annual distribution of percolation, water yield, soil water and evapotranspiration simulated. A graphical comparison was used to clarify distinctions among the scenarios.

## 4 Results and Discussions

### 4.1 Parameter's Sensitivity

To determine the sensitivity of a parameter during the sensitivity analyses performed in this study toolbox applied several random changes to the parameter value within a given range to see how it affects the variable being analyzed (evapotranspiration or discharge). Both the alterations applied within the toolbox to each parameter and the established parameter ranges are shown in Table 3. Table 3 also shows the sensitivity of each parameter for both analyses. The closer the sensitivity of the parameter is to 0, the less it influences the variable. When the sensitivity equals zero the parameter is discarded for the calibration. After performing the analyses, we identified 16 parameters that exhibited a significant impact on streamflow. Notably, among these 16 parameters, 10 were also found to be sensitive to ET.



**Table 3** Type of change and range for parameters used in the sensitivity analysis, and the results of the streamflow discharge (Q) and evapotranspiration (ET) sensitivity analysis

| Parameter | Change   | Range used in sensitivity analysis | Q           |       | ET          |       |
|-----------|----------|------------------------------------|-------------|-------|-------------|-------|
|           |          |                                    | Sensitivity | Order | Sensitivity | Order |
| Perco     | Relative | – 0.5 to 0.5                       | 0.6980      | 1°    | – 0.0866    | 2°    |
| cn2       | Percent  | – 20 to 20                         | 0.1082      | 2°    | 0.0250      | 5°    |
| Epc       | Replace  | 0–1                                | 0.1078      | 3°    | 0.7855      | 1°    |
| flo_min   | Relative | – 25 to 50                         | 0.0608      | 4°    | 0.0000      | –     |
| revap_co  | Replace  | 0.02 to 0.2                        | 0.0476      | 5°    | 0.0000      | –     |
| cn3_swf   | Replace  | 0–1                                | 0.0344      | 6°    | 0.0604      | 4°    |
| revap_min | Relative | – 25 to 50                         | 0.0271      | 7°    | 0.0000      | –     |
| Bd        | Percent  | – 20 to 20                         | 0.0244      | 8°    | – 0.0182    | 6°    |
| lat_ttime | Replace  | 1–180                              | 0.0220      | 9°    | 0.0000      | –     |
| Awc       | Percent  | – 20 to 20                         | 0.0144      | 10°   | 0.0695      | 3°    |
| K         | Percent  | – 20 to 20                         | –0.0143     | 11°   | 0.0009      | 10°   |
| Chn       | Replace  | 0.01–0.3                           | 0.0120      | 12°   | 0.0000      | –     |
| Alpha     | Replace  | 0–1                                | 0.0099      | 13°   | 0.0000      | –     |
| latq_co   | Replace  | 0–1                                | 0.0017      | 14°   | 0.0111      | 7°    |
| Esco      | Replace  | 0–1                                | –0.0017     | 15°   | 0.0029      | 8°    |
| Canmx     | Percent  | – 20 to 20                         | –0.0011     | 16°   | – 0.0011    | 9°    |
| Surlag    | Replace  | 1–24                               | 0.0000      | –     | 0.0000      | –     |

Note: Empty boxes indicate non-sensitive parameters

Most of the parameters identified as sensitive to discharge represent commonly employed calibration parameters for streamflow adjustment in SWAT (Cibin et al. 2010; Nossent and Bauwens 2012; Leta et al. 2015; Khorashadi Zadeh et al. 2017; Senent-Aparicio et al. 2021; Sánchez-Gómez et al. 2022). However, two parameters, namely perco, cn3\_swf and latq\_co, stand out as exceptions. The percolation to the shallow aquifer (perco), the pothole evaporation coefficient (cn3\_swf) and the lateral flow coefficient (latq\_co) are not typically calibrated in studies employing previous versions of SWAT. Nonetheless, in SWAT+, these parameters deviate from the default value (set to zero) and consequently necessitates calibration. Notably, ten of the sensitive parameters were also found to exert a significant influence on watershed evapotranspiration, encompassing perco, cn3\_swf and latq\_co.

Among the parameters identified as most sensitive for simulating either streamflow (perco, cn2, epco and flo\_min) or ET (epco, perco, awc, cn3\_swf and cn2), there are three parameters that are common to both categories. In total, there are six parameters that collectively emerge as the most crucial contributors in the Erken Lake watershed (perco, epco, cn2, flo\_min, awc, cn3\_swf), underscoring their significance in the region. Most of these parameters are intricately linked to soil characteristics (perco, epco, cn2 and awc). Nevertheless, other pivotal parameters are directly associated with various hydrological cycle processes, including groundwater (flo\_min) and ET (cn3\_swf). Additionally, specific soil features strongly affect resistance to groundwater flow, highlighting the essential role of soil

parameters in the hydrological dynamics. Consequently, our analysis confirms the importance of considering not only parameters linked to surface runoff and groundwater but

**Table 4** Final values of the sensitive parameters that were determined by calibration

| Parameters | Change   | Final calibrated values |             |               |    |
|------------|----------|-------------------------|-------------|---------------|----|
|            |          | Q scenario              | ET scenario | Q-ET scenario |    |
| Epc        | Replace  | 0.820                   | 0.987       | 0.996         | ET |
| Esco       | Replace  | 0.843                   | 0.992       | 0.997         |    |
| cn3_swf    | Replace  | 0.627                   | 0.998       | 0.997         |    |
| Bd         | Percent  | 10.182                  | 19.766      | 18.5          |    |
| cn2        | Percent  | – 11.337                | – 16.101    | – 19.348      | Q  |
| Canmx      | Percent  | 19.378                  | 19.612      | 13.482        |    |
| Awc        | Percent  | – 18.818                | – 14.540    | 4.601         |    |
| K          | Percent  | 5.621                   | – 8.788     | – 0.616       |    |
| latq_co    | Replace  | 0.973                   | 0.222       | 0.839         |    |
| Perco      | Percent  | 19.165                  | – 19.163    | 18.539        |    |
| Lat_ttime  | Replace  | 10.071                  | –           | 6.029         |    |
| flo_min    | Relative | 0.133                   | –           | 3.939         |    |
| revap_min  | Relative | – 3.847                 | –           | 34.859        |    |
| Alpha      | Replace  | 0.296                   | –           | 0.983         |    |
| Chn        | Replace  | 0.168                   | –           | 0.193         |    |
| revap_co   | Replace  | 0.049                   | –           | 0.064         |    |

Empty boxes indicate parameters not calibrated due to their lack of sensitivity in previous analyses (Table 3)



also those related to soil and vegetation when conducting comprehensive hydrological assessments (Park et al. 2014).

#### 4.2 Calibrations and Basin Characterization

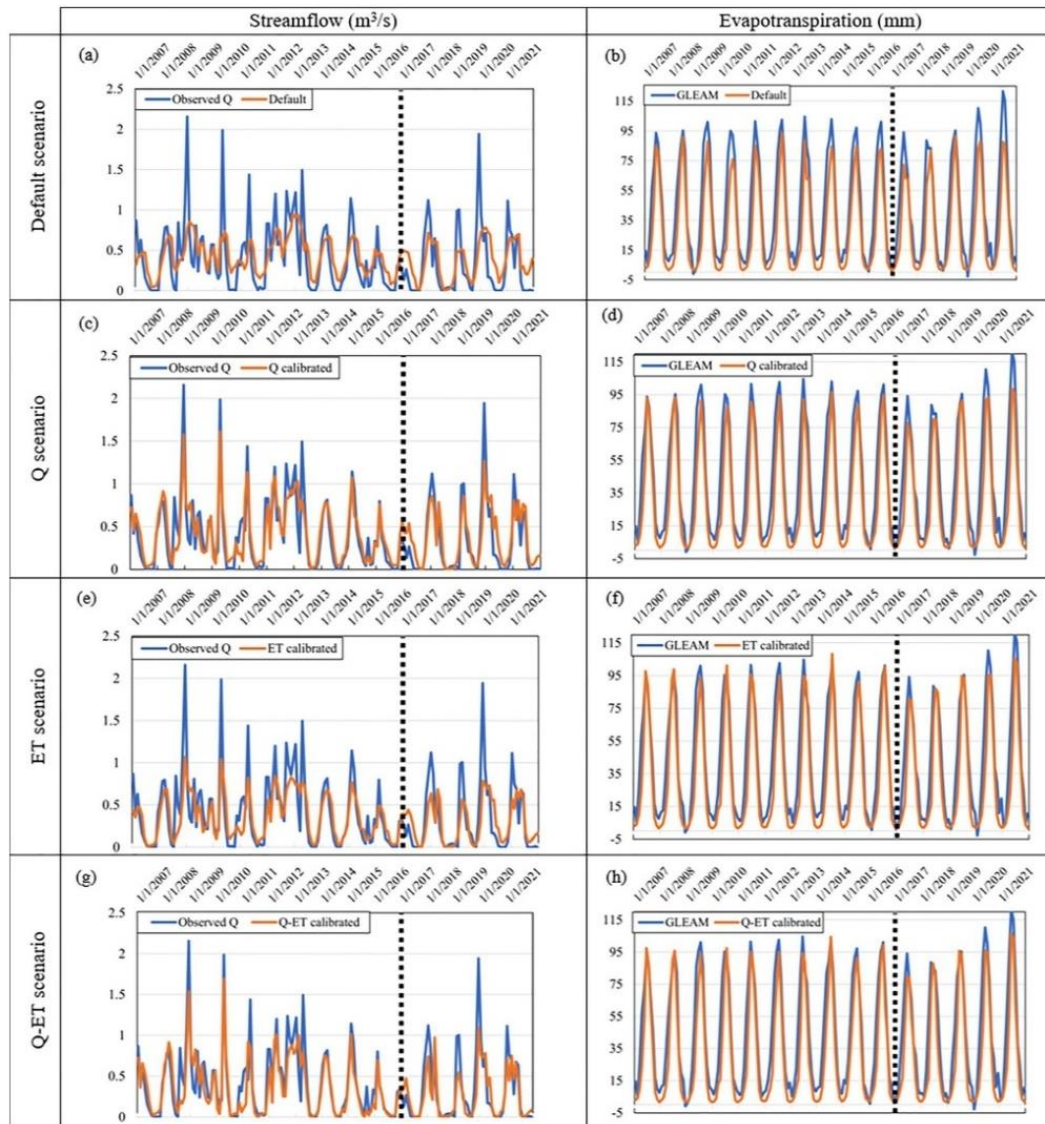
Each of the calibrations applied in this study has resulted in different calibrated parameter values, which are documented in Table 4. The parameter ranges remained the same as in the sensitivity analysis, except for two: *perco* and *esco* were constrained. The *esco* range was reduced from 0–1 to 0.6–1 to be realistic for the Erken basin. The lower the *esco*, the higher the evapotranspiration. In semi-arid basins according to Bressiani et al. (2015) *esco* can be up to 0.6, so for a wet basin like this one the parameter is limited from 0.6 to 1. In addition, the range of *perco* has been limited to between – 20% and 20% also to keep it within realistic parameters. As its initial value was 0.5, the parameter would be between 0.4 and 0.6. The dominant soil in the Erken Lake basin is eutric cambisol (Nachtergaele et al. 2010). Cambisol is one of the most abundant soils on the planet (Montanarella et al. 2015) and does not usually have extreme percolation and permeability values.

An examination of parameter values across the three scenarios reveals that certain parameters exhibit variations, including *cn3\_swf*, *bd*, *cn2*, *canmx*, *latq\_co*, *flo\_min* and *alpha* (Table 4). Conversely, other parameters exhibit minimal discrepancies among the scenarios, such as *epco*, *esco*, *lat\_ttime*, *chn* and *revap\_co*. Notably, some parameters display larger disparities, and in some instances, these differences even suggest opposing trends. This is particularly evident in parameters like *awc*, *k*, *revap\_min* and *perco*. In light of their sensitivity and significance to the basin (as detailed in Sect. 4.1), special attention is given to the values of the seven primary parameters: *perco*, *flo\_min*, *epco*, *cn3\_swf*, *cn2*, *revap\_co*, *awc*.

The parameter *perco* represent the percolation to the shallow aquifer. In Q and Q-ET scenarios shows an increase of approximately 20%. Conversely, in the ET calibration *perco* the value is reduced almost a 20%. This reduction of the parameter value seems to be related to *latq\_co* and *k* in the ET scenario. Notably, *K*, *perco* and *latq\_co* assume lower values in the ET scenario, signifying both reduced resistance to soil water movement, decreased percolation to the shallow aquifer and a reduction in lateral flow. The divergence in values for these three parameters when calibrated solely with ET data might be attributed to their primary influence on surface flow and runoff dynamics, despite their secondary impact on ET. *Flo\_min* exhibits insensitivity to ET, with a tendency to increase in the other two scenarios. This behavior results in a reduced magnitude of water return from the shallow aquifer, as *flo\_min* represents the critical aquifer depth required for the initiation of return flow. *Epco*, known as the vegetative absorption compensation factor, hinges

upon the vegetation's transpiration water requirements and the available soil moisture content. Higher values of *epco* within the range of 0.01 to 1 result in the model simulating increased ET within the watershed, permitting greater water uptake from the soil. Similarly, *esco*, or the soil evaporation compensation factor, governs soil evaporation rates, with higher *esco* values leading to greater basin-wide evaporation. Across all three scenarios, both *epco* and *esco* consistently manifest high values, closely approximating 1. These elevated values align with expectations for watersheds characterized by substantial ET, a typical condition observed in forested watersheds (Julian and Gardner 2014). Moreover, the convergence of *esco* and *epco* values between the ET scenario and flow-based calibration scenarios suggests that the model effectively captures the catchment's ET processes when relying solely on streamflow data. *Cn3\_swf*, which governs soil moisture dynamics following dry periods before surface runoff initiation (Wagner et al. 2022), exhibits lower values in the Q scenario, contrasting with higher values observed in the Q-ET and ET scenarios. This disparity suggests that in the latter two scenarios, the soil retains a higher degree of saturation before the onset of surface runoff. *Cn2*, also known as the curve number, plays a pivotal role in runoff dynamics, as it depends on soil permeability, land use, and prior soil moisture conditions. In each of the three scenarios examined, the curve number undergoes a reduction of its initial value. This reduction signifies an enhancement in soil permeability, resulting in increased moisture retention and reduced runoff. The parameter *awc*, representing available water capacity and indicating the water level accessible to plants, exhibits notable variations across the calibration scenarios. In the Q and ET scenarios, *awc* experiences a reduction of approximately 20–15%, whereas in the Q-ET scenario, it registers an increase of 4.6%. In this scenario *cn2* also shows its biggest reduction, Q-ET scenario seems to represent a bigger retention of soil water.

Given the greater sensitivity of these parameters within the hydrological context of the watershed, it is possible to glean some insights into the basin's characteristics based on the established fixed parameter values. Overall, the calibration results depict a humid basin characterized by elevated evapotranspiration rates and a capacity for modest surface water retention within the soil. Runoff in such a basin tends to be mild and non-aggressive. These conditions are commonly associated with forested watersheds, as forests play a crucial role in moderating and acting as a buffer against extreme hydrological events (Richter and Richter 2000; Cao et al. 2013; Julian and Gardner 2014; Wang et al. 2021).



**Fig. 3** Graphical comparison of GLEAM evapotranspiration and observed flow at kristineholm with evapotranspiration and flow simulated by SWAT+ in each scenario. Each graph is divided by a black line into calibration (2007–2015) and validation (2016–2021).

Graphs (a), (c), (e) and (g) represent the temporal evolution of flow in m<sup>3</sup>/s at monthly scale, while graphs (b), (d), (f) and (h) represent the temporal evolution of evapotranspiration in mm at monthly scale

#### 4.3 Assessment of the Calibration and Validation

With the calibrated parameter values in place, the model's reliability in each scenario was assessed using the statistical measures outlined in Sect. 2.4, alongside

graphical comparisons illustrated in Fig. 3. These statistical evaluations were conducted for both the calibration period spanning from 2007 to 2016 and the subsequent validation period from 2017 to 2021 (Table 5). The details and



The Implications of the Use of ET Remote Sensing Data for Calibrating Hydrological Models: A...

**Table 5** Performance of the simulated discharge (Q) ( $\text{m}^3/\text{s}$ ) and evapotranspiration (ET) (mm) from each SWAT + scenario during the calibration period (2007–2016) and the validation period (2017–2021) on a monthly basis

| Scenario                           | Statitics      | Q                              |                               | ET                             |                               |
|------------------------------------|----------------|--------------------------------|-------------------------------|--------------------------------|-------------------------------|
|                                    |                | Calibration period (2007–2016) | Validation period (2017–2021) | Calibration period (2007–2016) | Validation period (2017–2021) |
| Default scenario<br>Not Calibrated | R <sup>2</sup> | 0.413                          | 0.397                         | 0.927                          | 0.895                         |
|                                    | NSE            | 0.400                          | 0.406                         | 0.764                          | 0.727                         |
|                                    | PBIAS          | − 3.659                        | − 5.525                       | 30.416                         | 31.663                        |
|                                    | RSR            | 0.775                          | 0.771                         | 0.486                          | 0.523                         |
| Q scenario                         | R <sup>2</sup> | 0.778                          | 0.800                         | 0.920                          | 0.896                         |
|                                    | NSE            | 0.774                          | 0.777                         | 0.794                          | 0.758                         |
|                                    | PBIAS          | − 2.201                        | − 3.921                       | 27.425                         | 29.467                        |
|                                    | RSR            | 0.476                          | 0.472                         | 0.454                          | 0.492                         |
| ET scenario                        | R <sup>2</sup> | 0.680                          | 0.574                         | 0.909                          | 0.888                         |
|                                    | NSE            | 0.629                          | 0.620                         | 0.813                          | 0.779                         |
|                                    | PBIAS          | 12.622                         | 11.916                        | 23.963                         | 26.586                        |
|                                    | RSR            | 0.609                          | 0.617                         | 0.432                          | 0.471                         |
| Q-ET scenario                      | R <sup>2</sup> | 0.759                          | 0.716                         | 0.913                          | 0.889                         |
|                                    | NSE            | 0.738                          | 0.731                         | 0.807                          | 0.773                         |
|                                    | PBIAS          | 14.161                         | 14.663                        | 25.182                         | 27.243                        |
|                                    | RSR            | 0.512                          | 0.519                         | 0.439                          | 0.476                         |

implications of the data presented in Table 5 and Fig. 3 are elaborated upon in the subsequent discussion.

Across most scenarios, the statistical analyses yield results that fall within acceptable and highly satisfactory ranges. There are, however, two notable exceptions. The first scenario, the default configuration, exhibits inadequate performance in streamflow-related statistics, with the NSE below 0.5, an RSR exceeding 0.7, and a low R<sup>2</sup>, collectively signaling unsatisfactory outcomes. In contrast, the PBIAS values in this scenario are remarkably satisfactory, suggesting that the model accurately predicts the total water quantity but struggles with proper distribution, as evident in Fig. 3a. The second issue with suboptimal statistical outcomes involves the PBIAS values observed across all ET simulations. Remarkably, none of the scenarios, including the ET scenario, achieve satisfactory PBIAS values (within  $\pm 25\%$ ) for ET. Nevertheless, a comprehensive examination of both statistical metrics and graphical comparisons (Fig. 3) reveals that, despite these isolated deficiencies, the model's overall performance remains acceptable across all scenarios.

In the Default scenario, while the flow simulation does not meet statistical acceptability criteria—given that uncalibrated SWAT + struggles to replicate flow peaks effectively (Fig. 3a)—the simulated ET, surprisingly, attains a satisfactory level of accuracy (Table 5 and Fig. 3b). Although the uncalibrated evapotranspiration gives satisfactory values, this is probably due to the specific conditions of Erken Lake and its catchment. In fact, a more holistic examination of the performance of each model shows

that a calibration is necessary for a more realistic simulation of the hydrological cycle. This will be further explored in Sect. 4.4. In the Q scenario, all statistical metrics exhibit highly satisfactory results for streamflow, and visually, the simulation aligns well with observations, considering some minor underestimation of flow peaks by SWAT+ (Fig. 3c). Furthermore, the calibration with flow data enhances the ET simulation when compared to the Default scenario. Notably, the NSE and RSR values indicate a significant improvement in model performance, and graphically, the simulation captures peak events more accurately (Fig. 3d). The ET scenario yields the most accurate simulation of ET, in line with expectations. Although the streamflow simulation in this scenario presents slightly inferior statistical results compared to the previous one, it still maintains a satisfactory level of performance, both from a statistical and graphical perspective. Our findings indicate that when a single variable, whether streamflow or ET, is employed for calibration, it demonstrates strong performance concerning the calibrated variable, yet concurrently leads to a decrease in performance regarding the other variable. Other studies have reached the same conclusions (Sirisena et al. 2020). Lastly, within the Q-ET scenario, achieve favorable statistical outcomes for both streamflow and ET, presenting values that fall between those of the Q and ET scenarios. Specifically, the streamflow simulation, while slightly less accurate than that of the Q scenario, demonstrates an improvement over the ET scenario, except for the PBIAS, which shows an overestimation of water in the Q-ET scenario. Similarly, the simulated ET, while marginally less precise than in the ET

scenario, exhibits an enhancement over the Q scenario. This transition is discernible in the statistical results (Table 5), yet at the graphical level (Fig. 3), the distinctions among the three calibrated scenarios (Q, ET, and Q-ET) are notably inconspicuous.

As depicted in Fig. 3, it becomes apparent that across all SWAT+ scenarios, the model consistently exhibits a tendency to underestimate discharge within the Lake Erken watershed, specially in the ET-scenario. But this trend does not appear to be uniform across all SWAT applications. Some investigations have reported analogous findings (Koltsida and Kallioras 2022), while contrasting results have been documented in other studies (Parajuli et al. 2018). It is plausible that this phenomenon is primarily shaped by the unique attributes and features of the specific watershed under examination.

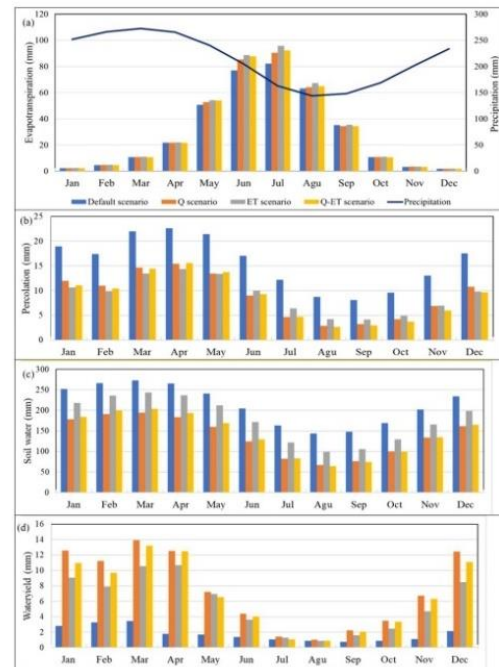
One of the key findings of this study is the robustness of the SWAT+ model when calibrated using only ET data (the ET scenario). Both graphical (Fig. 3) and statistical (Table 5) analyses demonstrate a substantial improvement in the discharge simulation by the ET scenario when compared to the uncalibrated model. Furthermore, the discrepancies between the evaporation and discharge simulations obtained from the three calibrated scenarios are minor. This suggests that, at least within the studied region of Sweden and in catchments with similar characteristics, using remote sensing-derived evapotranspiration data for calibration is a viable alternative for uncalibrated catchments. These findings are consistent with those of prior studies that have drawn similar conclusions (Parajuli et al. 2018; Sirisena et al. 2020; Odusanya et al. 2021).

#### 4.4 Comparison of the Hydrological Cycle

To facilitate a comprehensive comparison of the hydrological cycle across each scenario, we utilize data derived from various simulation components, besides streamflow and ET. In Table 6 some of the components of the hydrological cycle are shown in millimeters, extracted with the SWATdoctR package (Plunge et al. 2024). Figure 4 compare the annual distribution, measured in millimeters, of percolation, water yield, and soil water content within the basin. This holistic approach provides a nuanced understanding of the hydrological dynamics in each scenario.

**Table 6** Annual average of the precipitation, evapotranspiration, water yield and groundwater contribution in mm, in the Erken Lake basin for each simulated scenario

| Scenario         | Precipitation | Evapotranspiration | Water yield | Groundwater contribution |
|------------------|---------------|--------------------|-------------|--------------------------|
| Default scenario | 578.83        | 334.79             | 21.50       | 133.96 (86.2%)           |
| Q scenario       | 578.83        | 345.47             | 73.29       | 84.39 (53.5%)            |
| Et scenario      | 578.83        | 360.02             | 55.96       | 69.32 (55.3%)            |
| Q-ET scenario    | 578.83        | 355.88             | 65.73       | 51.93 (44.1%)            |



**Fig. 4** Mean annual distribution of (a) evapotranspiration and precipitation, (b) percolation, (c) soil water content and (d) water yield, in millimeters, simulated in each scenario in the Erken lake basin

The default scenario exhibits some differences, featuring higher percolation rates, increased soil water content and lower water yield (Fig. 4), and with a much greater groundwater contribution (Table 6). In the absence of calibration, SWAT generates watershed simulations characterized by reduced runoff, resulting in enhanced groundwater accumulation and contribution. While percolation and soil moisture are overestimated in this scenario, it exhibits consistent annual distribution patterns relative to other scenarios (Fig. 4). The remaining scenarios display subtle distinctions.

In the Q calibrated scenario, the water yield and groundwater contribution are higher, implying more water



flow in the basin. The Q-ET scenario is the only one in which groundwater contribution is less than a 50%, but the three calibrated scenarios simulate a groundwater contribution around 50%. This number makes sense considering that the estimated baseflow in this area is around to 65% (see Sect. 2). Regarding the annual distribution, runoff displays greater temporal stability throughout the year in the Default scenario. All the components analyzed graphically (percolation, soil water and water yield) except evapotranspiration, follow the same annual distribution pattern, characterized by the precipitation in the basin (Fig. 4). During months of snowmelt and rainfall (February, March, April), calibration based on GLEAM ET yields marginally reduced percolation rates, but during all year this scenario present reduced water yields and higher soil water content. Conversely, a mixed calibration approach yields slightly reduced percolation rates and diminished water yields during the same months. Calibration based on observed flow appears to produce intermediate results between these two extremes. Finally, soil moisture content remains modestly elevated throughout the year in the ET-only calibration, whereas it exhibits similar year-round patterns in the calibration based on flow and the mixed calibration.

In the process of model calibration using ET as the sole parameter, SWAT enhances the simulated soil moisture levels to attain improved conformity with GLEAM data and elevates the evapotranspiration in the basin. Preceding research (Rajib et al. 2018) have demonstrated that exclusive calibration solely reliant on ET can lead to either an overabundance or insufficiency of vertical water flow unless a concurrent calibration of horizontal water flow is undertaken. This could also elucidate the increased soil water content and reduction in the water yield noted in this scenario. Significantly, this phenomenon aligns with the findings of a recent study (Odusanya et al. 2021) which reported a similar outcome when employing exclusive GLEAM ET calibration, resulting in an excessive vertical flow.

An analysis of the calibrated parameters within this scenario (Table 4) reveals some distinctions in the simulated basin. Specifically, it exhibits a significantly lower  $latq\_co$  in comparison to both the Q scenario and the Q-ET scenario. This change implies a lower lateral water flow. Conversely,  $k$  displays a lower value, indicative of reduced resistance to soil water displacement within the basin. Furthermore,  $perco$  also exhibits a lower value, signifying decreased percolation from the basin to the shallow aquifer, thereby enhancing surface water retention. These three parameters emerge as the primary drivers behind the observed disparities elucidated in Fig. 4 and discussed upon in this Sect. 3.4. The ET scenario simulates a basin with less lateral and surface water movement, and more water retention

on the soil. Despite the differences in the fixed values of these parameters (as discussed in Sect. 3.2.), the model simulation remains acceptable, as it is detailed in Sect. 3.3, underscoring the possibility of equifinality. Equifinality concerns can be mitigated by augmenting the calibration process with additional observations, as recommended by Qiao et al. (2013, 2014). Consequently, the calibration in the Q-ET scenario may offer increased reliability for this specific parameter group, as it aligns with the Q scenario calibration, both of which rely on flow data—a variable significantly influenced by these parameters.

#### 4.5 Limitations of the Study

This study presents some limitations that should be considered. Below, these limitations are outlined.

First, the area where the studied basin is located experiences a cold and humid climate. This makes obtaining ET data for the basin through remote sensing technology susceptible to cloud interference. In this study, version 3.7b of GLEAM has been used. According to its own website (<https://www.gleam.eu/>), one of the key features of this version is the 'Extensive use of microwave observations, which provides an advantage under cloudy conditions,' adding more confidence to the ET data used in the study.

Secondly, the resolution of the ET data used also poses a limitation considering the size of the basin. However, it is considered that the entire basin exhibits very similar ET as it demonstrates a high level of homogeneity in its land uses (Fig. 1c), with almost the entire basin comprising green areas (forests, grasslands, or extensive agriculture).

This study relied on a single weather station, which, while a limitation, aligns with the World Meteorological Organization (WMO, 2008) guidance stating that for lowland regions like the Erken lake's drainage basin (141 km<sup>2</sup>), one station suffices.

Finally, this study focuses on a specific case: Lake Erken. This implies that some of the conclusions cannot be extrapolated to other areas. For example, that the SWAT model simulates the evapotranspiration of Lake Erken acceptably even before calibration is possibly due to the specific conditions of the watershed we are studying, and it should not be assumed that the SWAT model performs better without calibration.

#### 5 Conclusions

In this study, we employed the SWAT + hydrologic model, observed flow data, and ET data from GLEAM to investigate multi-criteria calibration techniques in the Erken Lake basin (Sweden). Our findings provide several key insights:

- Sensitivity analysis revealed that crucial parameters affecting the watershed (perco, epco, cn2, flo\_min, awc, cn3\_swf) affected both soil characteristics and hydrological processes, specially the surface water, but also evapotranspiration and groundwater.
- While the three calibrations conducted in this study displayed minor differences, they collectively depicted a humid watershed characterized by high evapotranspiration and limited water retention in forested areas.
- Through different calibrations, four scenarios were obtained, each one offered valuable insights into the hydrologic cycle's dynamics, with improvements observed in streamflow and evaporation simulations in various scenarios.
- In the Default scenario, the model demonstrated unsatisfactory performance for flow distribution, despite accurately simulating discharge amounts. The default simulation of ET was surprisingly good except for the calculated PBIAS. The Q scenario yielded notably improved streamflow simulations and slightly enhanced ET simulations compared to the Default scenario. Conversely, the ET scenario excelled in ET simulation and improved simulations of streamflow even though it had slightly lower streamflow simulation performance compared to the Q scenario. The Q-ET scenario displayed intermediate performance between the ET and Q scenarios.
- Although acceptable simulations were achieved for both ET and flow variables in all scenarios, a small bias persisted in monthly ET estimations.
- Our results underscore the trade-off between calibrating with a single variable, either streamflow or ET, where improved performance is observed in the calibrated variable at the expense of the other variable. However, all calibrations maintained statistical acceptability.
- When we compare different components of the hydrologic cycle in the four scenarios, it is noticeable that calibrating the SWAT + model with ET alone enhances water retention in the soil, with a decrease in vertical flow to the shallow aquifer and also a reduction in water yield.
- The Erken Lake basin or one with similar characteristics can be calibrated using only ET data obtained from GLEAM, as the SWAT + model has been shown to be able to simulate its conditions acceptably.
- Multi-criteria calibration emerged as the most realistic approach, with flow-sensitive parameters initially calibrated, followed by those affecting ET. This approach led to a more realistic representation of the hydrological cycle by considering multiple components in the calibration and validation process.

In summary, this study represents an initial step toward implementing multi-criteria calibration techniques for the SWAT + model using the Toolbox software. Future research can explore the inclusion of additional variables in the calibration process to further enhance our understanding of watershed dynamics.

**Author Contributions** DP and JS-A conducted the conceptualization of the study. The methodology was developed by ICJN and JS-A. The formal analysis and investigation were carried out by ICJ-N. The first draft of the manuscript was written by ICJ-N and all authors commented on previous versions of the manuscript. All authors read, review and approved the final manuscript.

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**Data availability** The datasets used and/or analyzed during the current study are available from the first author on reasonable request.

## Declarations

**Conflict of 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.

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#### 5.4. RESEARCH PAPER 4: ECOLOGICAL CRISIS FROM CHILDREN'S PERSPECTIVE: LESSONS LEARNED AND THEIR IMPORTANCE IN SHAKING UP SOCIAL AWARENESS

Jiménez-Navarro, I. C., Prandi, C., Pérez-Lucia, J. G., Cecilia, J. M. & Senent-Aparicio, J. (2024). Ecological crisis from children's perspective: Lessons learned and their importance in shaking up social awareness. *Sustainability*, 16 (24), 10824. <https://doi.org/10.3390/su162410824>.



## Article

# Ecological Crisis from Children's Perspective: Lessons Learned and Their Importance in Shaking Up Social Awareness

Inmaculada C. Jiménez-Navarro <sup>1,\*</sup>, Catia Prandi <sup>2</sup>, José Giner Pérez de Lucía <sup>3</sup>, José M. Cecilia <sup>3</sup> and Javier Senent-Aparicio <sup>1</sup>

<sup>1</sup> Department of Civil Engineering, Catholic University of San Antonio, Campus de los Jerónimos s/n, 30107 Guadalupe, Spain; jsenent@ucam.edu

<sup>2</sup> Department of Computer Science and Engineering, Università di Bologna, Via Zamboni 33, 40126 Bologna, Italy

<sup>3</sup> Department of Computer and Systems Informatics, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

\* Correspondence: icjimenez@ucam.edu

**Abstract:** The Mar Menor (Murcia, Spain) has faced a eutrophication crisis in recent decades, significantly affecting local residents, including children. Considering the importance of involving children in scientific activities and the potential societal benefits of working with them, we conducted two environmental citizen science activities with students from the Los Nietos school. The study aimed to evaluate their knowledge about the Mar Menor crisis, understand their opinions and experiences, and assess the broader social impact of these activities. The children first created drawings related to the Mar Menor during a visit to Los Nietos beach, followed by a survey completed weeks later. Analysis of the drawings and survey responses revealed that while children may not fully grasp the causes of the ecological catastrophe, they are aware of its existence and maintain a hopeful perspective on the lagoon's future. Additionally, a social network analysis of texts referencing children highlighted the societal reach of their actions and voices regarding the Mar Menor crisis. Our findings demonstrate that citizen science activities not only engage and educate children but also position them as influential communicators within their communities. This underscores the potential of such initiatives to amplify environmental awareness and drive social change by empowering younger generations as advocates for ecological sustainability.

**Keywords:** children's drawings; citizen science; endangered ecosystem; social sensing; young children



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## 1. Introduction

A series of transformations and degradations are currently taking place in the global environment as a result of human activity. This threat has been considered in legislation for many years, but it is complex to contain and the scientific community foresees consequences that future generations will have to face. In this context, environmental education is becoming increasingly important worldwide, including in Europe, as it helps to raise children's awareness of environmental values and sustainable development while also providing them with the tools to address these challenges [1]. To achieve this, there are different strategies, but one of the most effective is the direct interaction of children with ecosystems. In recent years, there have been several examples in the literature studying the benefits of children learning from nature in natural settings, rather than in the classroom, and the skills they develop from it. For example, Ardoin and Bowers [2] conducted a review of 66 studies focused on children's environmental education over a 25-year period. The main conclusions of this study are that environmental education favors the cognitive, social, and emotional development of children in addition to showing results of a better understanding of the ecosystem by children.



Children have a natural curiosity that pushes them to approach both science and the natural environment. In addition, children see the world in a very different way than adults, and they perceive the environment and the place where they live differently as well. Working with children can bring new questions, ideas, and novel perspectives to the table in the creation, processing, and presentation of scientific information. This can lead to a different understanding of current problems and alternative solutions [3]. In addition, younger demographics may have different priorities in ecosystem evaluation [4]. Giving a voice to this less heard sector of society can help move towards intergenerational equity in ecosystem evaluation [5]. In this context, citizen science, defined as research conducted with participation from the general public to increase scientific knowledge, can be exploited to engage children. In fact, it has been proved that children participating in citizen science activities not only contribute to scientific advancement but also experience physical, emotional, social, interpersonal, and educational benefits [6].

To make children's participation in science activities successful and positive, activities must be child-centered and their opinions and attitudes must be taken seriously [7]. There are many examples of previous studies in which drawings have been used as tools to elicit children's opinions and knowledge [8–13]. Drawing allows children to invent and experience their own ideas, actions, ideas, feelings, and emotions in different ways. Children's drawings provide insight into their understanding and perception of their surroundings [14]. When children depict their environment, they illustrate the elements within their living space, offering a glimpse into their familiarity and relationship with these elements [15].

Another additional benefit of introducing children to specific areas of science is that making it closer to them can greatly help to raise the awareness of specific problems or studies that are being conducted among their inner circle of people (friends and family) [16,17]. This is because children are capable of understanding and discussing the necessity of preserving the ecosystems and their biodiversity, particularly when they are familiar with it [18]. This can be especially relevant at the local level, with the case of the Mar Menor as an example, as the salt lagoon is present in the daily lives of children living in its proximity.

The Mar Menor is one of the largest coastal lagoons in the Mediterranean basin. This ecosystem of high ecological value, included in the list of RAMSAR wetlands, has suffered in recent decades a severe environmental degradation due to multiple human-induced factors [19]. These factors include an uncontrolled expansion of irrigated land and a significant increase in tourism, as well as mining and fishing activities [20]. Since 2016, water transparency has been considerably reduced as a result of the eutrophication process, which is affecting the tourism sector and the local economy [21]. Recent studies quantify that each 1 mg per cubic meter increase in chlorophyll value increases the probability of failure of the companies located in the study area by 5.5% [22]. Other authors quantify the non-use economic value as more than EUR 40 million per year, which gives an idea of the environmental, economic, and social importance of this ecosystem [23]. The regional and national governments have proposed several measures to improve agricultural practices and, as shown in López-Ballesteros et al.'s work [24], their implementation cost is much lower than the value of the products and services that this ecosystem generates. However, the conflicts of interest between the different stakeholders have led to a radicalization of their positions, making it difficult to reach an agreement on solutions [25]. This study aims to demonstrate how activities carried out through children are a good alternative in the search for consensus in the face of environmental crises of this magnitude.

As stated before, environmental education offers numerous benefits for children, empowering them to engage in scientific activities and fostering societal awareness, particularly at the local level. This study focuses on a children-centric citizen science campaign in the Mar Menor region, and it is divided in two parts.

The first part aims to answer two research questions: What are the opinions and knowledge of children regarding the environmental crisis in their area? Did the activity have an impact on the children? The hypothesis for the first one is that understanding children's



perspectives will provide insights into the opinions of their families and local communities, offering a window into broader societal attitudes. For the second question, the hypothesis is that by using techniques such as immersive experiences in nature and active participation, the activity will have a lasting impact on the children, enhancing their ability to recall it over time. To investigate these questions, the campaign involved two distinct activities. First, an immersive field trip to the beaches of the Mar Menor allowed children to experience the natural environment firsthand. Second, a classroom-based activity followed a more traditional approach, reinforcing their understanding of environmental issues.

The second part of this study aims to determine whether such activities can have a tangible impact on society, particularly by examining the local media coverage they received. The research question guiding this part of the study is as follows: can children-centric environmental activities influence societal awareness and engagement with environmental issues? To address this question, we hypothesize that the visibility and discussion of these activities on social media platforms reflect a measurable societal impact, indicating that such initiatives resonate beyond the immediate participants. To evaluate this, we employed a social sensing approach, which involves analyzing public opinions expressed on social media platforms such as Twitter and Facebook. Social sensing provides a broader perspective on societal impact, moving beyond anecdotal evidence to capture the real-world significance of issues and their influence on everyday lives [26].

## 2. Materials and Methods

This study is part of the H2020 FET SMARTLAGOON project (GA no. 101017861), whose main objective is to develop a digital twin to build a systemic understanding of the socio-environmental inter-relationships affecting coastal lagoons and their ecosystem [19]. This study has been carried out with the students of the CEIP Félix Rodríguez de la Fuente school, located in Los Nietos, Murcia, Spain. This town is located on the south inland coast of the Mar Menor.

The methodology of this study is divided into three main parts, which are explained in detail throughout this section. The first consisted of a nature activity with the children. A short talk was given in which both the Mar Menor and its problems were discussed, as well as the SMARTLAGOON project. At the end of this activity, the children were asked to draw a picture related to the Mar Menor with total freedom. The second activity consisted of a survey in the children's classroom sometime after the first activity. The intention was both to check if the children remembered the activity in nature and to know their personal experiences and their opinion regarding the Mar Menor. Lastly, to check the impact on society, we used a social sensing tool developed in the SMARTLAGOON project to evaluate the social repercussions of these activities at the local level. The three parts of this study are explained below.

### 2.1. Nature Activity for Children

The first activity with the children took place on 29 October 2021 at the beach of Los Nietos. A total of 26 children participated in this activity, divided into two groups. A classroom was prepared in the natural environment, and an environmental education lecture was given to each of the two groups of children who participated. In this presentation, the children were told about the problems of the Mar Menor and the main objectives of the SMARTLAGOON project. Regarding the SMARTLAGOON project, the talk focused on the importance of collecting data in real time and talked about the “smart buoy” that the project was developing to collect water and environmental-related data. The intention was to make the talk as simple and interactive as possible for the children. Therefore, it was conducted in small groups of approximately 13 children, who were encouraged to participate in the conversation, ask questions, and discuss among themselves. Conducting the activity outdoors and outside the classroom also encourages children to show more interest in the activity and to feel a more relaxed and less formal atmosphere than in the classroom.

Once the presentation was concluded (25 min), the children were given drawing materials and asked to draw a picture related to the Mar Menor (45 min). They were encouraged to draw anything they wanted or what came to their mind when talking about the Mar Menor. As developed in the introduction, drawings are an effective way both to conduct child-focused activities and to learn about children's opinions and the relationships they conceive of in their environment. So, this was one of the key parts of this study. Later, those drawings were analyzed by two authors to extract the opinion of the children, and the elements that were repeated most often in them were counted to draw conclusions about what the children relate most to the Mar Menor. All the drawings can be consulted in Appendix A. Finally, a brainstorming session (20 min) concluded the activity. The main researcher who administered the protocol is a biologist with a central role in the SMARTLAGOON project.

#### Data Analysis

The nature activity enabled us to collect data in the form of drawings, a widely recognized method in research with children for capturing their feelings, representations, and perceptions regarding specific topics [27–29]. To extract qualitative data, we conducted a visual analysis focusing on the elements depicted in the drawings, such as the number and species of jellyfish. This analysis was carried out independently by two authors of this paper, and the results were subsequently compared and discussed collaboratively to ensure validity and reliability.

#### 2.2. Classroom Evaluation of the Activity and Children's Opinions and Knowledge

On 14 March 2022, a few months after the beach activity, the children were surveyed. In this part, 23 children participated in the activity, and three of these children had not participated in the first activity. This second part was carried out in their classrooms, within the CEIP Félix Rodríguez de la Fuente school. The survey consisted of 26 questions of different types. There were eight open questions in which the children were asked to write some sentences to reflect their opinion or check their knowledge (e.g., "How would you describe the SMARTLAGOON project to a friend?", "What do you like most about the Mar Menor?", "What is climate change?") The remaining 18 questions consisted of yes/no questions, multi-response questions, scale questions (exploiting smiley face-like scales), or short answer questions (ex., "What beach do you swim at?", "How old are you?"). To make the questionnaire more enjoyable and informative, we also used images and included "fun facts" about the Mar Menor biodiversity. All the questions of the survey can be consulted in Appendix B. The duration of this activity was 30 min. The main researcher who administered the survey was the same who conducted the nature activity.

The purpose of this activity was twofold. Firstly, to understand and document the children's personal experiences of the Mar Menor, its influence on their daily lives, and their opinion regarding the current environmental crisis. Secondly, to check if the children remembered the nature activity and what elements of the talk they retained in their memory.

#### Data Analysis

The self-report questionnaire allowed us to collect both qualitative and quantitative data through a playful activity. Due to the very limited sample size, which does not permit statistical analysis, we aggregated the numerical responses to provide an overview of the different children's opinions, using data visualization as an effective tool to summarize the findings.

#### 2.3. Social Sensing of Scientific Activities with Children

Due to the environmental problems described in the Introduction, the Mar Menor has a great media impact both in the media and social networks. Citizens are highly aware of the environmental issues that are happening in its surroundings and, as a result of this awareness, the citizens' movement convinced the Spanish Senate through a popular

legislative initiative, which reached more than 600,000 signatures to approve the “Mar Menor Act” (Law 19/2022, <https://www.boe.es/buscar/doc.php?id=BOE-A-2022-16019>, accessed on 2 December 2024), which granted legal personality to the Mar Menor lagoon and its basin.

Social media analysis is a tool to measure in real time the impact that certain actions and/or measures have on the population. The SMARTLAGOON project has developed SensingTool (<https://marmenorsensing.com/aplicaciones/5f8edc99a3302d002d06241d>, accessed on 2 December 2024), a social sensing tool to measure the social impact of different political, economic, and/or environmental actions on the citizens living in the surrounding Mar Menor. In this study, we are interested in determining the impact that conducting citizen science activities on the environmental problems of the Mar Menor can have on society at the local level, especially when the activities are focused on children.

#### Data Analysis

To carry out this task, SensingTools has focused on the messages posted by users on Twitter from 2011 to 2023 about the Mar Menor, thanks to the Twitter Academic Research API version. The first task then was to determine which messages were relevant to the Mar Menor context, i.e., when a message was considered to be relevant to the Mar Menor environmental issue.

Contexts were assessed by analyzing different key location words (toponyms) that are present in the texts. Firstly, the context C1 included all tweets that may have the keyword “Mar Menor” or “#MarMenor”, i.e.,  $C1 = \{\text{“Mar Menor”} \cup \text{“#MarMenor”}\}$ . However, this approach significantly reduced the number of tweets related to the issue, i.e., the coverage of texts on the issue. Indeed, many texts do not explicitly mention the keywords “Mar Menor” or “#MarMenor”, but they are related to the environmental issue. For example, the lagoonside villages are locations that belong to the Mar Menor basin and are strongly related to the environmental issue. That is why we decided to include  $C2 = \{\text{“Mar Menor”} \cup \text{“#MarMenor”} \cup \text{LagoonsideVillages}\}$ , where LagoonsideVillages includes all well-known Mar Menor lagoonside villages, more specifically, these keywords are “San Javier”, “Los Alcázares”, “La Manga”, “Lo Pagan”, “Los Narejos”, “Santiago de la Ribera”, “Los Cuarteros”, “Las Lomas del Rame”, “El Carmolí”, “Bahía Bella”, “Los Urrutias”, “Los Nietos”, “Islas Menores”, “Mar de Cristal”, and “Playa de la Llanza”. The last context to analyze was to include the locations with the densest population core, i.e., Murcia and Cartagena,  $C3 = \{C2 \cup \text{“Murcia”} \cup \text{“Cartagena”}\}$ .

Once the contexts were defined and applied, the percentage of false positives for each of them were identified. The false positive metric is defined as the fraction of total messages which do not express any concern or relevant issue that affects the perception of other users about the Mar Menor. This task was performed manually by several experts and local citizens through the SensingTools app, which allows for tagging several text features such as the problem perception, relevant entities (i.e., locations, organizations, or persons), and feelings for each tweet. Indeed, such a hand-made labeling is quite subjective and nontrivial, strongly depending on the expert knowledge of the area. Due to the large amount of retrieved data, a random sample of 500 texts from each context was labeled.

Once the context was analyzed and we had a sample of texts that were of interest to our problem, the next step was to analyze the topics of these tweets. To achieve this, a topic discovery of those tweets was carried out using BERTopic [30], which contains a topic modeling pipeline that tries to produce coherent topics. First, document embeddings are generated with a specified pre-trained transformer-based model from the Sentence-BERT framework (SBERT). Embeddings are just representations or vectors of multiple dimensions that allow documents to be compared based on semantic similarities. Therefore, if two texts belong to the same topic, it is expected to have similar embeddings. Transformer architectures are considered the state of the art in natural language processing tasks, and they map sentences or paragraphs into dense vector representations. The next step involved reducing the dimensionality of the embeddings. There are several methods to perform



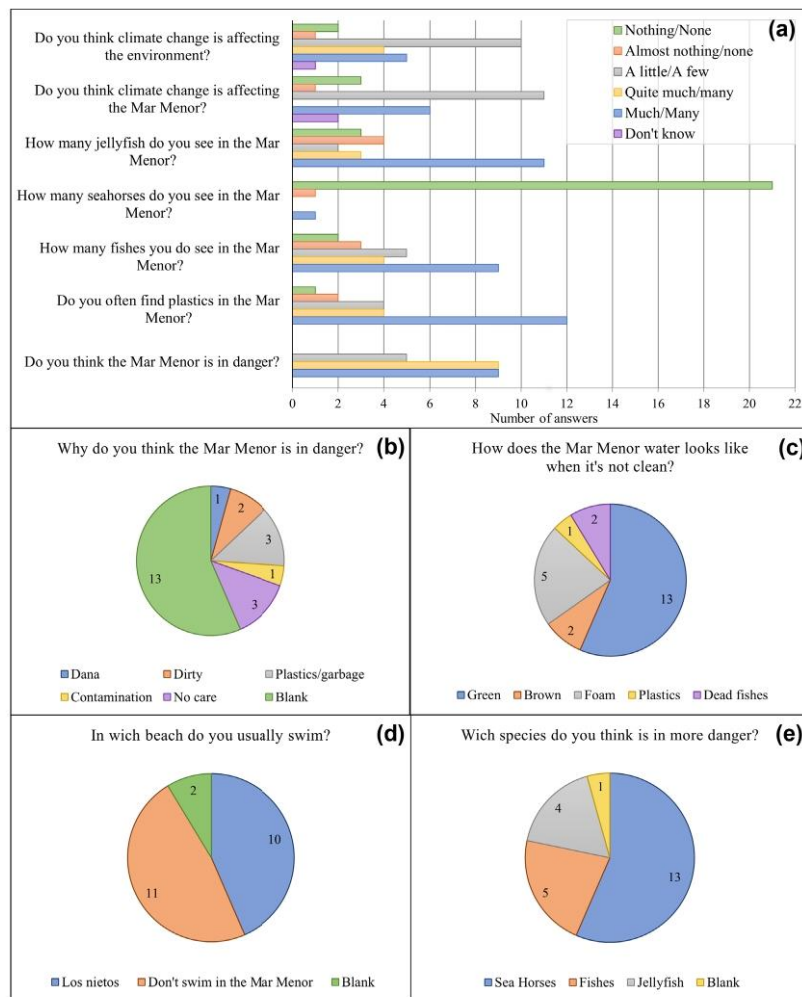
this, but UMAP (uniform manifold approximation and projection for dimension reduction) was used because it preserves more features of the high-dimensional representations. Clustering was performed with HDBSCAN (hierarchical density-based spatial clustering of applications with noise) based on a hierarchical clustering technique that searches for clusters of different densities, allowing outliers to be modeled. Finally, the representations of the topics were generated with a class-based term frequency-inverse document frequency (TF-IDF) matrix, which uses the word counts from a tokenizer to show the relevance of words in different topics. Optionally, the resulting number of topics could be reduced to a specified value by merging the TF-IDF representations of similar clusters.

### 3. Results

#### 3.1. Mar Menor Crisis from the Children's Point of View

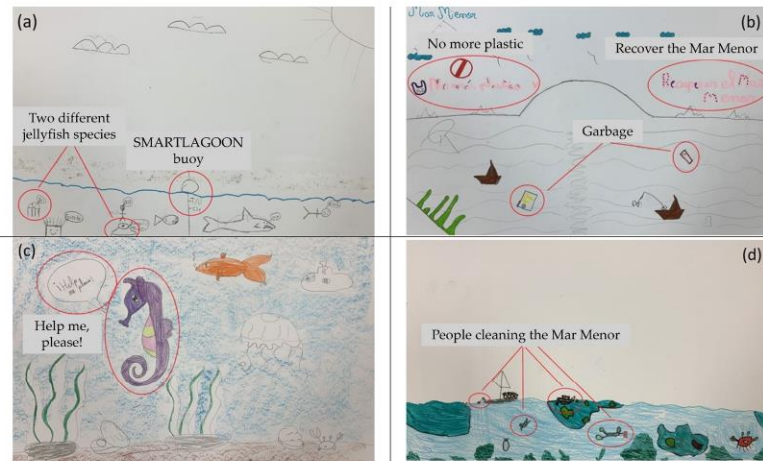
We ask the children about climate change to know their opinion and their awareness of the subject. When asked to explain what climate change is, ten kids answered that they did not know and eight gave answers that reflected they do not really know what it is. Only five kids were able to give answers that reflected that they understood, in general terms, the concept, providing answers like “It is the increase in temperature on the planet” or “It is because of the gasses and the factories”. As can be seen in Figure 1a, the answers reflect that most kids recognize that climate change is something that harms the environment, in general, and the Mar Menor in particular. Nevertheless, most of their answers say that climate change only harms the environment and the Mar Menor “a little”, so most kids do not recognize the real impact of climate change on the environment.

Another relevant aspect is the children's point of view regarding the situation of the Mar Menor. Several questions were focused on how they consider the Mar Menor state and what they usually see when they go there (Figure 1). We asked the kids why they consider it important to protect the Mar Menor. The answers were mainly of the following two: for the people to enjoy it and for animals to live in it. Some answers were “so that we can bathe and the sea creatures do not die”, “for us citizens of Los Nietos, we will never give up because it is our beach and we will recover it”, “because it has accompanied me all my life and it bathes many villages”, “because there live animals and plants that only live there”, “It is very beautiful, and it used to be full of seahorses”, “for the animals and for the mother nature”. Some children are openly optimistic about the future, (“so in the future it will be better”), but all of them agree that the Mar Menor is in danger (Figure 1a) and most of them believe the danger is too great—only five think the danger is small. Even when most of the kids recognize that the lagoon and their environment is in danger, when we asked them why it is endangered, more than half of the children did not respond (Figure 1b), which implies that they may not be able to explain the reason or do not know why. The most common responses were twofold; that it is because people “don't care” about the lagoon and that it is because of plastic and garbage pollution. Also, most of the children say that they usually find a lot of plastic in the lagoon (Figure 1a). In contrast, when we asked them how the water of the Mar Menor was most found, most of them said it was green, not with plastics (Figure 1c). The last question that helped us to understand the perception that children and their families have of the Mar Menor was that half of the children stated that they never bathe in the Mar Menor (Figure 1d).

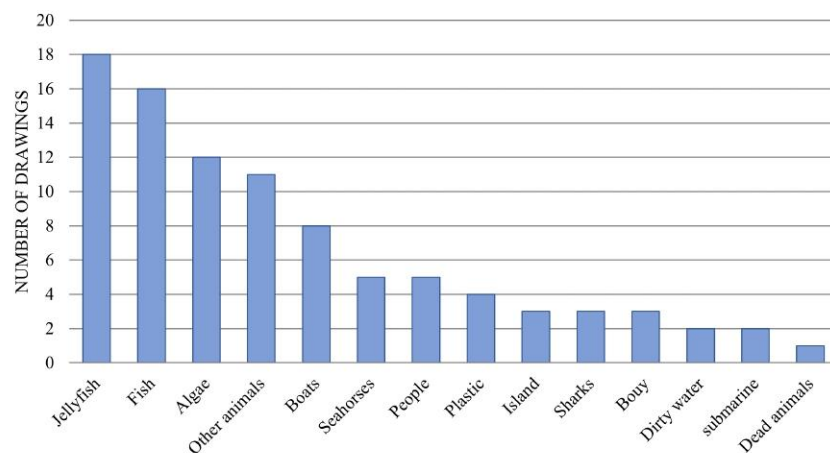


**Figure 1.** Children's responses regarding the Mar Menor: (a) scale questions on opinions about climate change, the Mar Menor crisis, and their experiences visiting the area; (b) multiple-choice question on knowledge of the causes of the Mar Menor crisis; (c) multiple-choice question on observations made during visits; (d) multiple-choice question on which part of the Mar Menor they refer to; and (e) multiple-choice question on conclusions drawn from their observations.

In terms of species, only two kids affirmed having seen seahorses in the Mar Menor (Figure 1a) and more than half of the children consider that the seahorse is the most endangered species in the Mar Menor (Figure 1e). According to their drawings, the children seem to have a deeper association between the jellyfish and the Mar Menor; when asked to draw anything they wanted related to the Mar Menor, 18 kids drew jellyfish and only five drew seahorses (Figures 2a,c and 3). When asked how many jellyfish they usually see when they go to the Mar Menor, most kids answered “many” (Figure 1a). There are four kids that consider jellyfish to be the most endangered species in the Mar Menor.



**Figure 2.** Examples of children's drawings and their elements. (a) Two different species of jellyfish and the SMARTLAGOON buoy. (b) Messages to spread awareness. (c) A seahorse, the emblematic species of the Mar Menor, asking for help. (d) People cleaning the Mar Menor, which is contaminated.



**Figure 3.** Number of drawings that presented specific elements.

### 3.2. Classroom Evaluation of the Activity

To analyze if the children were able to remember the lecture given on the beach, four of the questions of the survey were focused on this matter. The questions were "What do you remember the most about the activity?", "How will you describe the project SMARTLAGOON to a friend?", "Do you remember what you draw and why?", and "What can you tell us about the smart buoy?". From this question, we elucidated how many children remembered the activity, how many were able to explain basic things about the activity, and how many remembered basic things about the buoy and remembered the drawing activity (Figure 4). Three children did not answer these questions because they had not participated in the nature activity.



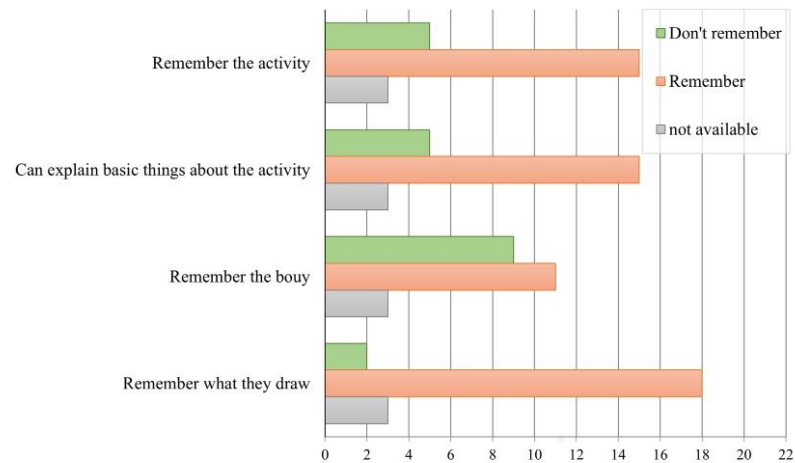


Figure 4. Number of children who remember the activity.

As reflected in Figure 4, most of the children were able to remember the activity and could explain some basic things about it; only five were not able to answer these two questions. When asked about what they remember, 10 of the answers talk about the buoy or the SMARTLAGOON project, seven about the Mar Menor characteristics, and only four about the drawing they made. When asked directly about the buoy, fewer children were able to give information about it, but still a considerable number of them (11) were able to answer. Finally, when asking directly what they drew and why, most of the children were able to recall what they drew and what they intended to reflect in their drawings. Only two children answered that they did not remember.

### 3.3. Social Sensing of Scientific Activities with Children in the Mar Menor

With the three contexts defined as explained in the methodology (Section 2.3), the number of tweets containing the specified keyword was compiled, as well as the percentage of false positives within each context. Table 1 shows that the percentage of false positives increases as the context expands, with fewer messages referring to a topic of interest related to the lagoon when considering Murcia and Cartagena terms. There is a large increase in false positives from our baseline context, i.e., C1, which only considers the keyword “Mar Menor”, reaching only 32.2% of false positives, to the C3 context, which includes all the lagoonside towns and the largest cities in the area, i.e., Murcia and Cartagena, reaching 82.6% of false positives. It is also important to note that the number of tweets also increases along with the number of concepts included in the context. Context C2 doubles the number of tweets in context C1 and the number of tweets in context C3 is more than 27 times higher than those in the context C1. In fact, 17.4% of the tweets related to the Mar Menor issue in context C3 (true positives) means 145,396 tweets, which is more than 4.8 times the number of tweets in the C1 context. In the case of C2 vs. C1, the number of true positive tweets reaches 37,620; 7000 more tweets than the number of tweets in the C1 context.

Table 1. Evaluation metrics for the different contexts.

| Context | Total Tweets | % False Positives |
|---------|--------------|-------------------|
| C1      | 30,235       | 32.2              |
| C2      | 65,999       | 43.0              |
| C3      | 835,614      | 82.6              |

With this in mind, we consider it relevant to focus on the C2 context for several reasons. Firstly, it increases the sample of tweets relevant in the context of the Mar Menor that are actually related to the Mar Menor environmental issue. Secondly, the impact of those activities carried out with children in the areas bordering the Mar Menor can have on society is measured and, therefore, the C2 context includes these populations adjacent to the Mar Menor without introducing the noise of the big cities.

The topic model applied to the C2 context returned more than 500 topics, in which quite a few of them were somehow related. Figure 5 illustrates the most representative words for some topics according to the class-based TF-IDF scores. Most of the categories found were related to tourism, politics, meteorology, or transport, but there was one formed by tweets containing words linked to children such as “niños” (children), “escuela” (school), “educarm”, and “alumnus” (students). This was Topic 9 (Figure 5). The evolution over time (Figure 6) was monitored in terms of the number of messages assigned to that topic. Two peaks can be observed close to October in 2019 and 2021, closely matching with the times that tons of dead fish were found on the shore of the Mar Menor. Further investigating the messages in the peak of 2019, most of them stated the importance of transmitting to future generations good practices to protect the environment and raise social awareness. The majority of tweets in 2021 and 2022 highlighted initiatives to give children a voice for the situation occurring at the lagoon.

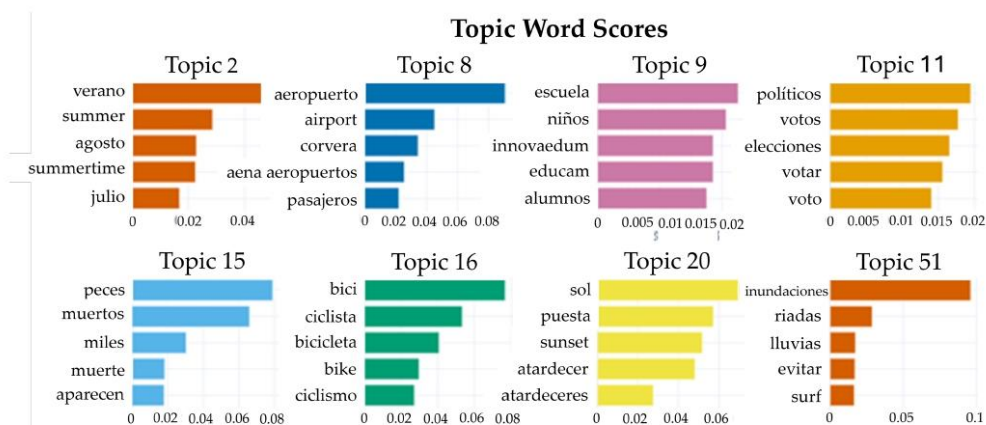


Figure 5. Words with the highest-class TF-IDF score for several topics.

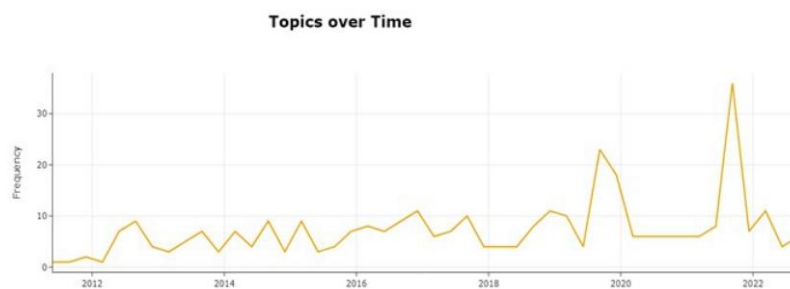


Figure 6. Dynamic topic modeling for the children category found by BERTopic.

#### 4. Discussion

After analyzing the children's answers and drawings, there are several points to explore further.

First of all, as can be seen from the analysis carried out with SensingTool, the environmental education of children regarding the Mar Menor crisis is considered an important topic in social networks. This is reflected in the results of this study, since one of the main topics of the tweets found was this one (Topic 9, Figure 5). Moreover, these types of tweets show a peak between the end of October and the beginning of November 2021 (Figure 6). The activity carried out on the beach with the children on those dates had some media repercussions, as it appeared in the news of local media (<https://www.la7tv.es/https://www.populartvmurcia.com/>, accessed on 2 December 2024); therefore, this activity could have been one of the triggers of this peak. In addition, many of the tweets between 2021 and 2022 remarked the importance of giving voice to children on the subject of the Mar Menor, which shows the interest that this study and the conclusions obtained from the children's answers and drawings may have for the Murcian population.

Regarding the children, the activity seems to have had an impact on the children, as most of them were able to remember specific things explained in the activity. The children remembered their drawings and the reasons behind them especially well. Not surprisingly, involving the children actively in the activity helped them to keep it in their memory easily, as other studies show [31]. In contrast, the children did not remember the buoy as well. When asked about a specific topic, it is normal that fewer children were able to remember it. In addition, the buoy is a complex technology; even when it was explained as simply as possible to the children, it is natural that they showed less interest in it. Still, the buoy appears in three of the children's drawings (Figure 3), and 11 children responded that they remembered it (Figure 4), so it seems to have had an impact on some of the children.

An important thing to note is related to climate change. From the answers of the children, we can assume that most of them cannot explain nor know what climate change is, as we explain in the results. Despite this, they recognize the effect that climate change has on the environment, but they do not show the same consensus about the Mar Menor. Most of them think that the Mar Menor is only affected by climate change "a little" (Figure 1a). In general, children show less concern and knowledge about the effect of climate change on the Mar Menor and do not associate the problems of the Mar Menor with climate change. This is possibly because, in their context, the Mar Menor has more striking problems that draw the attention of children. For example, children associate the problem of plastic as one of the main problems of the Mar Menor. Most of them answer that they see plastics in the Mar Menor very often (Figure 1a), and some of them affirm that the Mar Menor is in danger because of the plastics (Figure 1b). Of the total number of drawings, only five show the Mar Menor in undesirable scenarios, but four of them show plastics and garbage (Figure 2b,d). Even when plastic is not such a big issue in the Mar Menor, contamination by this type of material is still relevant due to its current global extent [32]. But the plastic has little relation with the environmental crisis that the Mar Menor ecosystem has been suffering in the last decades, since it is a eutrophication problem [33].

When asking children why it is necessary to protect the Mar Menor, we find that the majority prioritize preserving nature for its own sake rather than direct human benefit. In response to this question, 13 children mention nature elements, while only five mention humans or people. Other research has similarly concluded that children can recognize the value of ecosystems beyond those directly benefiting humans, prioritizing the preservation of extensive ecosystem processes [5]. However, two responses particularly highlight the significance of cultural identity and a sense of belonging, namely "I like everything about the Mar Menor for us citizens of Los Nietos we will never give up because it is our beach and we will recover it." and "I really like the Mar Menor because it has accompanied me all my life and seeing that it is important because it bathes many villages.". These responses underscore a notable trend observed in recent decades, showing that the Mar Menor has emerged as a symbol of cultural identity for the residents of the Region of



Murcia, particularly for those living in its surroundings. The fact of being both a unique and threatened ecosystem seems to favor people developing an identity related to the ecosystem itself.

Regarding the animal species of the Mar Menor, the seahorse is an emblematic species of the Mar Menor and is used as a symbol of vindication by the residents of the Mar Menor due to its current endangered status. Children seem to be aware of the status of this species in the Mar Menor, as they admit not seeing seahorses during their visits to the Mar Menor (Figure 1a), and more than half of them consider it to be the most endangered species in the lagoon (Figure 1e). However, jellyfish also take a protagonist role in the child's point of view. They are used to seeing "many" jellyfish in the Mar Menor (Figure 1a), which is reflected in their drawings. The jellyfish is the most common element in the children's drawings; out of 26 drawings, 18 had jellyfish in them (Figure 2). Some of the children even drew more than one type of jellyfish, implying that they know there are several species in the Mar Menor and are familiar with some of them (Figure 2a). This shows how the presence of jellyfish is remarkable in the Mar Menor in recent decades, even when its entry into the lagoon was as an alien species in the 90s [34].

One of the biggest revelations of this study was when asking the children in which part of the Mar Menor they usually go swimming, to which almost half of the children answered that they do not swim in the Mar Menor (Figure 1d). Some of them specified that this is because the water of the Mar Menor is bad for their skin or that it can be harmful for the youngest children. These statements help us to understand to what extent the state of the Mar Menor conditions affect the families living in the area around the Mar Menor and the general view of the Mar Menor at the street level.

Although the children are aware of the challenge the ecosystem is facing (mainly endangered species and poor water quality), most of them show a positive attitude towards the future. On the one hand, the children consider that it is very important to protect and recover the Mar Menor, both for the animals and for the people who live in its environment, among which they are included. Some drawings show animals asking for help (Figure 2c), people cleaning the Mar Menor (Figure 2d), or messages like "SOS Mar Menor" and "recover the Mar Menor" (Figure 2b)—both phrases being slogans used in neighborhood demands for the Mar Menor. This shows how the children reflect in their drawings their experiences related to the Mar Menor. As other studies show, children tend to reflect their close environment and personal experiences in their drawings [15].

In general, the study shows that the children's closeness to the Mar Menor is reflected both in their responses and in their drawings. The drawings also help us to understand the children's vision of the Mar Menor and their expectations for the future. On one hand, the children's vision is not only influenced by their own observations and conclusions but also by that of their immediate social circle. Analyzing their points of view helps us to approach the opinion of neighbors and citizens in general. On the other hand, when the children were asked to draw anything they wanted related to the Mar Menor, 21 of them drew positive scenarios in which the Mar Menor was fine, and only five reflected the current situation of the Mar Menor, with polluted waters and sad animals or worried people. In general terms, all the children reflect in their answers and drawings an optimistic attitude towards the Mar Menor and its future. Other studies have also noted this positive stance to which children seem to lean with respect to the future and environmental restoration [35].

#### *Limitations of the Study*

Some limitations of the study should be considered when interpreting the results. First, the research was conducted in a local context, specifically in the community of Los Nietos, meaning the findings cannot be generalized to a broader population. Nevertheless, this local focus provides valuable insight into the perspectives of a specific segment of the community regarding the ecological crisis. Additionally, the sample was small and non-random, as participants were selected based on availability. This limits the representativeness of the findings and their applicability to other contexts.

Furthermore, the connection between the activities with children and the social impact measured through tools like “social sensing” is limited. While these tools offer an interesting perspective on societal discussions around the Mar Menor, they do not provide a clear causal link to the specific activities conducted in this study.

Finally, although the activity with children yielded valuable data for the project as a citizen science initiative, it can also be framed as an environmental education activity. By involving children in data collection and awareness efforts, the activity contributes to fostering public engagement in scientific processes and addressing local environmental issues, even if it does not meet all the traditional criteria of citizen science.

## 5. Conclusions

In this study, a children-centric citizen science campaign was related to the environmental crisis of the Mar Menor ecosystem conducted with school-aged children. Additionally, a social sensing tool was utilized to assess the impact of this activity on social networks. The following conclusions can be drawn:

- Directly involving children and granting them freedom, such as through drawings, enhances the impact of the activity on them and improves their recollection.
- The interviewed children are aware of the danger faced by the Mar Menor ecosystem and understand that it is due to human activity, but they are unable to identify the specific reasons.
- Most interviewed children believe that protecting the Mar Menor is necessary for the sake of nature and animals, beyond any direct benefits it may have for people. Children tend to value natural ecosystems for their own sake more than adults do.
- By gathering children’s opinions and perspectives, insights into the general population can be inferred, such as when nearly half of the children clarify that they do not swim in the Mar Menor because it is harmful to them. This response reflects the extent to which the local population is concerned about the current state of the ecosystem.
- Children tend to maintain a positive attitude towards the future of the ecosystem and its recovery.
- Environmental education for children related to the Mar Menor ecosystem appears to be a significant topic on social networks, according to the sensing tool.

This research presents several important benefits for the future. By engaging children in a citizen science initiative, this study contributes to fostering environmental awareness at an early age and strengthens the connection between local communities and their ecosystems. The practical implications of the results highlight the importance of incorporating environmental education into local initiatives, as well as the potential of social sensing tools to measure public interest and impact. The study emphasizes the value of involving younger generations in data collection and discussions on environmental issues, even if the activities also serve as educational outreach. As a recommendation, future efforts should continue to promote such initiatives to empower local communities, particularly children, to actively participate in environmental protection and restoration. Moreover, reinforcing the link between the Mar Menor’s ecosystem and its cultural identity, especially through targeted educational programs, could lead to greater public engagement and drive local action for its recovery.

**Author Contributions:** Conceptualization, C.P. and J.S.-A.; formal analysis, I.C.J.-N. and J.G.P.d.L.; investigation, I.C.J.-N.; methodology, I.C.J.-N., C.P. and J.M.C.; resources, J.S.-A.; software, J.G.P.d.L.; supervision, J.M.C. and J.S.-A.; writing—original draft, I.C.J.-N.; writing—review and editing, C.P. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** Ethical review and approval were waived for this study due to the anonymized nature of the collected data, which did not involve personal or sensitive information. The study was conducted in accordance with the Declaration of Helsinki and relevant national legislation, including “Ley Orgánica 3/2018, de 5 de diciembre, de Protección de Datos Personales y garantía de los derechos digitales (BOE Número 294, de 6 de diciembre de 2018)”.

**Informed Consent Statement:** Informed consent was obtained from all parents or legal guardians of the children involved in the study.

**Data Availability Statement:** Data is contained within the article.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

#### Appendix A



Figure A1. Cont.



Figure A1. Cont.

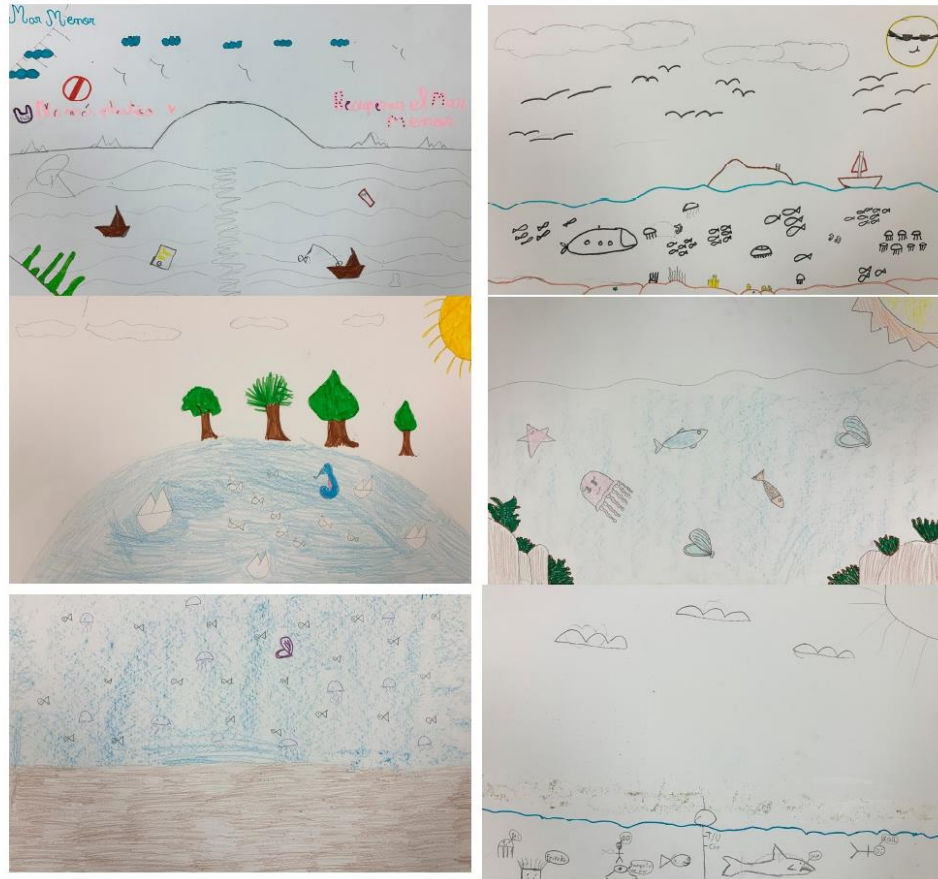


Figure A1. Children's drawings.

## Appendix B

Table A1. Questions of the survey.

| Part of the Survey | Number | Question                                                                                                                                        | Type of Answer |
|--------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| About the activity | 1      | What do you remember about the beach activity?                                                                                                  | Long answer    |
|                    | 2      | If a friend asks you what the SMARTLAGOON project is going to do with the Mar Menor, how would you explain it to him/her?                       | Long answer    |
|                    | 3      | How much did you like the activity?                                                                                                             | Scale          |
|                    | 4      | During the activity on the beach, we asked you to draw some pictures. Do you remember what you drew? What did you draw and why did you draw it? | Long answer    |

Table A1. Cont.

| Part of the Survey                    | Number | Question                                                                                                                                                                                                                                                                                 | Type of Answer         |
|---------------------------------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|
| About the activity                    | 5      | Tell us what you like about the Mar Menor and what you think makes it special. Why do we have to take care of the Mar Menor?                                                                                                                                                             | Long answer            |
|                                       | 6      | Do you think the Mar Menor is in danger? Why?                                                                                                                                                                                                                                            | Scale and short answer |
|                                       | 7      | Do you know what climate change is?                                                                                                                                                                                                                                                      | Long answer            |
|                                       | 8      | Do you think climate change harms the environment?                                                                                                                                                                                                                                       | Scale                  |
|                                       | 9      | Do you think climate change is harming the Mar Menor?                                                                                                                                                                                                                                    | Scale                  |
|                                       | 10     | Do you think technology can help us reduce the damage of climate change? If yes, how?                                                                                                                                                                                                    | Long answer            |
|                                       | 11     | During the activity on the beach, we explained that we want to use a smart buoy to collect data from the Mar Menor. Can you tell us more about it (if you remember, if you think it's a good idea, if you think it can help to save the Mar Menor or anything else related to the buoy)? | Long answer            |
| What do children see in the Mar Menor | 12     | When you go to the Mar Menor, which beach do you usually swim at?                                                                                                                                                                                                                        | Short answer           |
|                                       | 13     | When you go to the Mar Menor to swim, how clean is the water?                                                                                                                                                                                                                            | Scale                  |
|                                       | 14     | When water is dirty, which of these does it look like?                                                                                                                                                                                                                                   | Multiple choice        |
|                                       | 15     | Which species do you think is most endangered in the Mar Menor?                                                                                                                                                                                                                          | Multiple choice        |
|                                       | 16     | How many jellyfish do you usually see when you go to the Mar Menor?                                                                                                                                                                                                                      | Scale                  |
|                                       | 17     | How many seahorses do you usually see when you go to the Mar Menor?                                                                                                                                                                                                                      | Scale                  |
|                                       | 18     | How many mullets or other fish do you usually see when you go to the Mar Menor?                                                                                                                                                                                                          | Scale                  |
|                                       | 19     | How many crabs do you usually see when you go to the Mar Menor?                                                                                                                                                                                                                          | Scale                  |
|                                       | 20     | Do you usually find plastic in the Mar Menor?                                                                                                                                                                                                                                            | Scale                  |
|                                       | 21     | Do you think plastic is a problem in the Mar Menor?                                                                                                                                                                                                                                      | Scale                  |
|                                       | 22     | Which sector do you think does more damage to the Mar Menor?                                                                                                                                                                                                                             | Multiple choice        |
|                                       | 23     | Can you think of any ideas to help us improve the situation of the Mar Menor?                                                                                                                                                                                                            | Long answer            |
| Personal information                  | 24     | Are you a boy or a girl?                                                                                                                                                                                                                                                                 | Short answer           |
|                                       | 25     | How old are you?                                                                                                                                                                                                                                                                         | Short answer           |
|                                       | 26     | Do you live near the Mar Menor?                                                                                                                                                                                                                                                          | Multiple choice        |

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5.5. RESEARCH PAPER 5: MODELING CLIMATE IMPACTS ON ECOSYSTEM SERVICES IN AN ANTHROPIZED COASTAL LAGOON FOR EFFECTIVE PLANNING AND ADAPTATION

Jiménez-Navarro, I. C., López-Ballesteros, A., Mesman, J. P., Trolle, D., Pierson, D. & Senent-Aparicio, J. Modeling Climate Impacts on Ecosystem Services in an Anthropized Coastal Lagoon for Effective Planning and Adaptation. *Climatic Change*, 178, 92 (2025).  
<https://doi.org/10.1007/s10584-025-03926-3>.

Climatic Change (2025) 178:92  
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## Modeling climate impacts on ecosystem services in an anthropized coastal lagoon for effective planning and adaptation

Inmaculada C. Jiménez-Navarro<sup>1</sup> · Adrián López-Ballesteros<sup>1</sup> · Jorrit P. Mesman<sup>3</sup> · Dennis Trolle<sup>4</sup> · Don Pierson<sup>3</sup> · Javier Senent-Aparicio<sup>2</sup>

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### Abstract

Ecosystem services (ES) are nature's positive contributions to people, and recognizing them aids in landscape planning and management, highlighting the importance of preserving ecosystems. Understanding the relationship between ES and climate change is crucial for effective land management, making scenario simulation a valuable method for analyzing ES. This study focuses on analyzing regulation ES (RES) in the Mar Menor and its basin (El Campo de Cartagena) developing a satisfactory SWAT+ and GOTM-WET model. Meteorological data from five global climate models were used to simulate two scenarios for long-term RES predictions. Our results show that climate change will raise temperatures by approximately 2°C and reduce precipitation by 4–19% in Campo de Cartagena, despite an increase in torrential days. This will adversely affect all analyzed regulation ecosystem services (RES), altering nutrient dynamics (phosphorus input up by over 100%, nitrogen input down by 38%), decreasing water availability (water inflow reduced by 6–23%, green water by up to 6%, and blue water by up to 43%), and increasing flood risk, thereby compromising ecosystem resilience. Additionally, we anticipate worsened RES water conditions due to changes in the lagoon's physical, chemical, and biological characteristics, including a temperature rise of 2.2–3.7°C, decreased oxygen levels, and an increase in chlorophyll by around 1 mg/m<sup>3</sup>. As a result, hypoxia and algae blooms are anticipated to become more frequent, further stressing the ecosystem.

**Keywords** GOTM-WET · Hydrological modelling · Nutrients dynamics · SWAT+ · Water availability · Water conditions

✉ Inmaculada C. Jiménez-Navarro  
[icjimenez@ucam.edu](mailto:icjimenez@ucam.edu)

<sup>1</sup> Department of Civil Engineering, Catholic University of San Antonio, Campus de Los Jerónimos s/n, Murcia, Guadalupe 30107, Spain

<sup>2</sup> Centro de Investigaciones sobre Desertificación (CIDE), CSIC-UV-GVA, Carretera CV 315, km 10,3, Valencia, Moncada 46113, Spain

<sup>3</sup> Department of Ecology and Genetics, Limnology, Uppsala Universitet, Norbyvägen 18 D, 752 36 Uppsala, Sweden

<sup>4</sup> WaterITech, Dojsøvej 1, 8660 Skanderborg, Denmark

## 1 Introduction

In recent decades, increasing concern for ecosystem preservation has emerged due to human-induced environmental degradation (Barbero et al. 1990; Shahidul Islam and Tanaka 2004; Srinivasan et al. 2008; Liu et al. 2019; Adla et al. 2022). One of the causes of this awareness is the recognition of the essential services ecosystems provide and their ongoing decline (IPBES 2019). Ecosystems near human populations are particularly vulnerable to irreversible alterations (Harte 2007). The term "ecosystem services" (ES) refers to the positive contributions that nature provides to people (Carpenter et al. 2009) and highlights the need for their integration into political, scientific, and management practises. Recognising and quantifying ES supports better landscape planning and emphasises ecosystem preservation (Kull et al. 2015). ES are commonly classified into three categories following the Common International Classification of Ecosystem Goods and Services (<https://cices.eu/>): provisioning ecosystem services (PES), such as food, water, and materials; regulatory ecosystem services (RES), such as water purification, climate regulation, and flood control; and cultural ecosystem services (CES), such as recreational opportunities, spiritual enrichment, and aesthetic experiences.

Over the last decade, different approaches to analysing ES in aquatic ecosystem models have evolved (e.g., Frank et al. 2014; Duarte et al. 2016; Zhan et al. 2023). The SWAT model has seen rapid growth in its application to ES over the past two decades. Its effectiveness is evident from reviews by Francesconi et al. (2016) and Zhao et al. (2024), highlighting SWAT's ability to integrate ecosystem processes. Francesconi et al. (2016) noted that most studies using SWAT focus on provisioning and regulating services, with the model performing well in these areas. Zhao et al. (2024) emphasised that SWAT is particularly advantageous for quantifying water-related processes, such as water yield, soil retention, and carbon storage.

Climate change must be considered at the local scale when simulating future scenarios since it affects the hydrological cycle (Fan et al. 2016) and ultimately impacts on ES. Various studies have documented the damage climate change inflicts on ES (Bakure et al. 2022) and its hindrance to effective ecosystem remediation (Zhan et al. 2023). Proper land management and planning therefore require understanding the relationship between ES and climate change (Shaw et al. 2011), and the SWAT model can be useful to simulate climate change and address how it will affect ES.

The impact of climate change on ES may be pronounced in the case of Mar Menor (Spain), one of the largest saltwater lagoons in Europe. This coastal lagoon is unique for its saltwater ecosystem and the challenges it presents for modelling. It experiences hypersalinity conditions that support specially adapted flora and fauna and sustain diverse adjacent ecosystems (Martínez et al. 2007). The area and its surroundings also host various socioeconomic activities alongside the local population. Therefore, the degradation of its ES could pose a significant risk. Despite its societal value, Mar Menor suffers from severe environmental degradation due to tourism, intensive agriculture, and other factors (Senent-Aparicio et al. 2021). Thus, the ecosystem is already under considerable stress, which the effects of climate change will likely exacerbate.

Using an integrated modelling approach, we analysed different RES for Mar Menor by coupling SWAT+, a hydrological model, with GOTM-WET, an ecosystem model for aquatic environments. SWAT+ was selected for simulating nitrogen and phosphorus exports



to the lagoon, which is crucial given the evidence that these nutrients co-limit the lagoon's productivity. This feature, along with its proven effectiveness in prior integrations with GOTM-WET (Jiménez-Navarro et al. 2023), its flexibility in watershed delineation, and its improved representation of management practises, makes SWAT+ an ideal choice for our analysis. Using this integrated approach, we address the limitations of models that treat land and water systems separately, capturing the interactions between terrestrial and aquatic dynamics under various climate change scenarios. Their capture provides a comprehensive analysis of RES. The study offers insights into adaptive management to sustain ecosystem resilience in this ecologically and socioeconomically critical region. Our objective was to evaluate current RES in the Mar Menor lagoon and the Campo de Cartagena basin and project their trends over the medium and long term under different climate change scenarios.

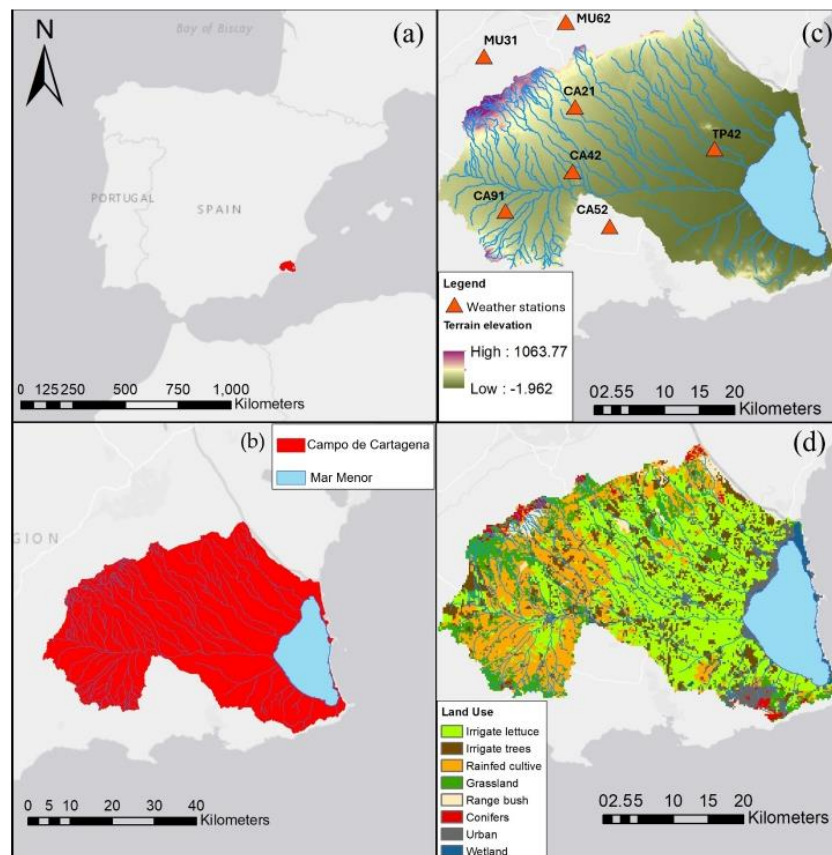
## 2 Study area: Mar Menor

Mar Menor, a hypersaline coastal lagoon in the region of Murcia, Spain, has an average depth of 4.4 m and a maximum depth of 7 m (Umgiesser et al. 2014). It covers approximately 135 km<sup>2</sup>, making it one of Europe's largest coastal lagoons, and it is separated from the Mediterranean Sea by La Manga, a 20 km long, 100–700 m wide urbanised sand bar through which water exchange between the Mediterranean and the lagoon occurs via three channels. The Campo de Cartagena, the lagoon's drainage basin, spans around 1,600 km<sup>2</sup> with gentle slopes. This area lacks permanent watercourses, with streams running only during intense rainfall (León et al. 2017), except for the Albuñón watercourse, which flows continuously in its final stretch due to a rise in the piezometric level (García-Pintado et al. 2007).

The Campo de Cartagena, a highly anthropogenic basin dominated by intensive agriculture, is considered one of Europe's main horticultural areas (Velasco et al. 2018). Land use includes 45% intensive irrigated agriculture, 30% rain-fed agriculture, and 15% conifer and shrub forest (Fig. 1(d)). Irrigated agriculture relies on groundwater, reused wastewater, seawater desalination, and the Tagus–Segura water transfer (Álvarez-Rogel et al. 2020). Its major crops include citrus trees, greenhouse produce, and horticultural crops, with common practices such as fertigation and annual crop rotation (lettuce, broccoli, and cantaloupe) (López-Ballesteros et al. 2023a).

The main human activities within Mar Menor include traditional fishing, salt extraction and tourism. Historically, its waters were transparent and oligotrophic. However, increased nutrient input in recent decades has caused severe eutrophication linked to expanded human activities in Campo de Cartagena and irrigated agriculture with fertilizer, thus altering its ecology (Velasco et al. 2006). Agriculture harms the ecosystem through direct nutrient inputs and by extracting water from the surface-near aquifer beneath the Campo de Cartagena, since this aquifer is contaminated with nitrates from irrigation return (Baudron et al. 2014). Eutrophication has severely degraded the lagoon, causing recurrent turbid waters and jellyfish and algal blooms and anoxia in deeper areas. These changes have disrupted biological composition, leading to seagrass meadow loss and reduced biodiversity (Anderson et al. 2002; Giménez-Casaldueiro et al. 2016; Ruiz-Fernández et al. 2017; Sandonnini et al. 2024). In 2016, Mar Menor experienced its largest recorded eutrophic crisis due to a harmful algal bloom, resulting in anoxia and severe consequences for its flora and fauna (Aguilar



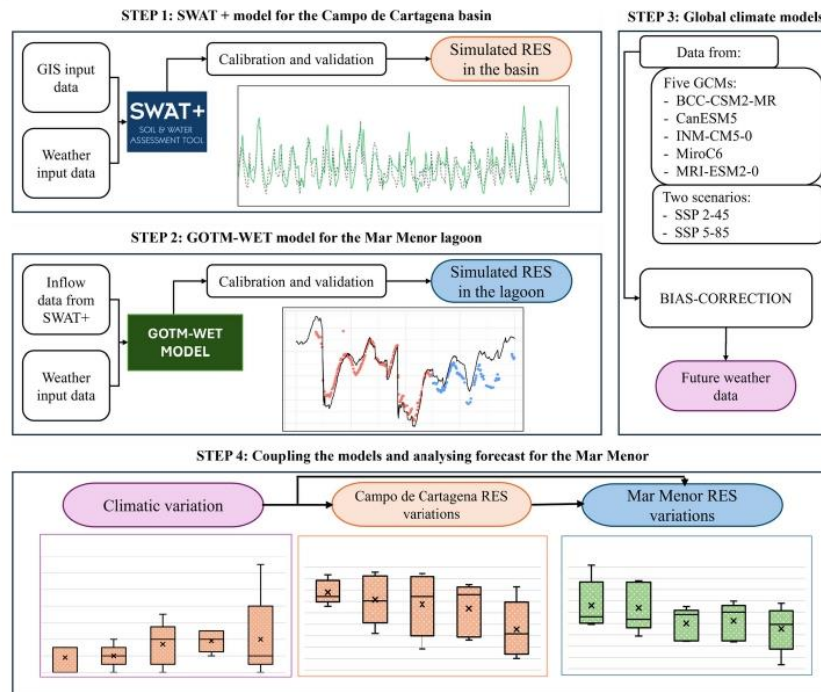


**Fig. 1** (a) Location of Mar Menor and its catchment in the Iberian Peninsula; (b) digital elevation map of the Campo de Cartagena and location of the meteorological stations; (c) water courses in the catchment; (d) land uses in the Campo de Cartagena

Escibano et al. 2016; Giménez-Casaldueiro et al. 2020). This crisis provoked strong reactions from the scientific, ecological, and tourism sectors (García-Ayllon 2018; Pérez-Ruzafa et al. 2019). Another catastrophic event occurred in September 2019 when an extreme storm caused flash floods in Campo de Cartagena, leading to a sudden drop in salinity and another anoxia event, killing thousands of fish.

### 3 Methodology

The methodology for this study followed a sequential approach (Fig. 2). In Step 1, we developed, calibrated, and validated a SWAT+ model for the Campo de Cartagena basin using the available data for a defined period. Step 2 involved creating, calibrating, and validating a



**Fig. 2** Flowchart of the study methodology showing the integrated modelling workflow to assess regulation ecosystem services (RES) in the Mar Menor and Campo de Cartagena basin. Step 1: SWAT+ simulations of basin RES with a time-series graph representing the calibration and validation results. Step 2: GOTM-WET, simulations of lagoon RES with a time-series graph representing the calibration and validation results. Step 3: five global climate models under two scenarios (SSP2-4.5, SSP5-8.5) with bias correction for obtaining future weather data. Step 4: box plots comparing climatic variation, basin RES, and lagoon RES, highlighting projected changes and variability under future scenarios

GOTM-WET model for the Mar Menor lagoon, which was also based on data from a specific timeframe. The primary goal of these steps was to couple the two models, resulting in an integrated model providing a holistic representation of the lagoon and its basin. From the outputs of these models, we derived RES for the basin and the lagoon. Step 3 focused on extracting and bias-correcting global climate models (GCMs) data to develop future climate scenarios for Mar Menor. Finally, in Step 4, these climate scenarios were used as inputs to the previously developed SWAT+ and GOTM-WET models to assess future ES in Mar Menor during predefined analysis periods.

A detailed description of all the steps followed, as well as the models and data used in the study, is provided in this section.

### 3.1 Modelling of Campo de Cartagena

#### 3.1.1 Description of the SWAT + model

The Soil and Water Assessment Tool (SWAT) is widely known hydrological modelling software introduced by Arnold et al. (1998, 2012) used worldwide to replicate basin dynamics. SWAT+ (Bieger et al. 2017) is an upgraded version characterised by treating basin elements as spatial objects and by enhanced configuration and discretisation capabilities. This version was used for this study. SWAT and SWAT+ operate by dividing the drainage basin into discrete sub-basins, further segmenting them into hydrologic response units (HRUs). Each HRU embodies a distinct combination of land use, slope, soil characteristics, and management practices, interconnected through a geographic information system (GIS) interface. This nuanced approach enables SWAT to effectively capture spatial variations in water sediment and nutrient dynamics (Mohammed et al. 2018).

This study used QSWAT+v2.4.7. to develop the model (<https://github.com/swat-model/QSWATPlus/releases>).

#### 3.1.2 SWAT + model set up

To develop a SWAT+ model, three types of data are essential: geographic data of the study area, meteorological data for the various periods and scenarios to be simulated and data on specific hydrological cycle variables for calibration and validation. The geographic information required by SWAT+ includes a digital elevation model (DEM), a land use map, and a soil map. The soil map was collected and prepared for the study area through the MapSWAT plugin (López-Ballesteros et al. 2024). The geographic and meteorological input data used is described in Table 1.

The long-term release version 3.34 of QGIS and the QSWAT+ version 2.4 plugin were used to delineate the basin and sub-basins, generate and burn the stream network, and incorporate the Mar Menor coastal lagoon as a lake object. The results comprised 144 sub-basins, 340 channels, and one lake (lagoon). In the second step, 13,889 HRUs were created by overlaying all land uses, soil types, and slope classes (<2%, 2%–8%, and >8%). We used a minimum HRU area threshold of 100 hectares reducing it to 750 HRUs. All generated files were then imported into SWAT+ Editor version 2.3.3, to which meteorological data were added, and the Penman–Monteith method was selected for calculating potential evapotrans-

**Table 1** SWAT+ input data and their sources and resolutions

| Input data            | Resolution                                                                                              | Source                                                                                                                                                                                                                            |
|-----------------------|---------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Digital elevation map | 25 m × 25 m                                                                                             | National Geographic Institute of Spain ( <a href="https://www.idee.es/csw-inspire-idee/srv/spa/catalog.search?#/metadata/spainMDT25">https://www.idee.es/csw-inspire-idee/srv/spa/catalog.search?#/metadata/spainMDT25</a> )      |
| Land use map          | 200 m × 200 m                                                                                           | Spanish Ministry of Agriculture, Fisheries and Food (2000–2010) ( <a href="https://www.mapa.gob.es/es/cartografia-y-sig/publicaciones/agricultura/">https://www.mapa.gob.es/es/cartografia-y-sig/publicaciones/agricultura/</a> ) |
| Soil map              | 250 m × 250 m                                                                                           | Digital Soil Open Land Map (López-Ballesteros et al. 2023b)                                                                                                                                                                       |
| Meteorological data   | Daily precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed | Murcian Institute for Agricultural and Environmental Research and Development weather stations (CA21, CA42, CA52, CA91, MU31, MU62, TP42, see Fig. 1(c))                                                                          |



piration. Given the high percentage of agricultural land use in the Campo de Cartagena basin, agricultural practices for main crops (citrus and horticulture) were also accounted for to reduce model uncertainties (See Appendix 1, Table 9).

### 3.1.3 Calibration and validation of the SWAT + model

Due to unavailable or unreliable conventional measurement data, satellite data on evapotranspiration (ET) and soil water content (SWC) from GLEAM v3.7b (Miralles et al. 2011) globally available datasets were used for calibrating and validating the SWAT + model. Several studies have successfully employed this approach (López-Ballesteros et al. 2019; Oduanya et al. 2021; Ningthoujam and Romeji 2024; Jiménez-Navarro et al. 2024).

To avoid over-parameterisation and to determine which are the most relevant parameters in the hydrological process of our study areas, a sensitivity analysis (Arnold et al. 2012) was performed before the calibration and validation. Sensitivity analysis, calibration and validation were performed using a sequential fitting algorithm (SUFI2) (Abbaspour et al. 2004) in SWATplus-CUP v3.0 software (<https://www.2w2e.com/home/SwatPlusCup>). Automatic calibration was performed using multiple variables (ET and SWC) and a multi-objective function that included the coefficient of determination ( $R^2$ ), the percentage bias (PBIAS), the Nash–Sutcliffe efficiency coefficient (NSE; Nash and Sutcliffe 1970) and the Kling–Gupta efficiency (KGE; Gupta et al. 2009). Calibration and validation were conducted at a monthly temporal resolution and a catchment-scale spatial resolution. The simulation period from 2000 to 2022 was divided into three phases: initial warm-up (2000–2002), calibration (2003–2012) and validation (2013–2022). For sediment and nutrient runoff, a soft validation was applied.

Model performance was evaluated graphically and statistically by comparing the SWAT + outputs of ET and SWC from GLEAM data. Statistical indices ( $R^2$ , PBIAS, NSE, and KGE) used in calibration were applied to assess the overall goodness of model fit, following the ratings proposed by Moriasi et al. (2015) and Kouchi et al. (2017).

## 3.2 Modelling of Mar Menor

### 3.2.1 Description of the GOTM-WET model

The General Ocean Turbulence Model (GOTM) is a vertical grid water column model used for lakes and oceans, simulating vertical mixing dynamics through turbulence closure equations (Umlauf et al. 2005). Applications of GOTM range from the study of detailed physical processes (Zou et al. 2018) to large-scale climate simulations (Golub et al. 2022). This model can be integrated with various biogeochemical models using the Framework for Aquatic Biogeochemical Models (FABM, Bruggeman and Bolding 2014), to resolve biogeochemical equations in each layer, with the vertical transport of biogeochemical substances based on GOTM's mixing.

This study coupled GOTM v5.3 (<https://github.com/gotm-model/code/releases/tag/v5.3>) with the Water Ecosystem Tool (WET v2.0), a modular aquatic ecosystem model capable of simulating detailed biogeochemical dynamics (e.g., oxygen, phosphorus and nitrogen) and organisms (e.g., phytoplankton, macrophytes, zooplankton, and zoobenthos) in the water column and sediment (Schnedler-Meyer et al. 2022).

### 3.2.2 GOTM-WET set up

The GOTM-WET model was forced with weather data from ERA5 (European Centre for Medium-Range Weather Forecasts Reanalysis 5, Muñoz-Sabater et al. 2021) at hourly resolution, using air temperature, wind speed, shortwave radiation, air pressure, dewpoint temperature, cloud cover, and precipitation. Used as inflow from the catchment, the output of the SWAT+ model comprised discharge, organic nitrogen, organic phosphorus, nitrate, ammonium, dissolved mineral phosphorus, and inorganic sediment. The organic nitrogen and phosphorus inputs were assumed to be 90% particulate and 10% dissolved to provide the required inputs for the GOTM-WET model. The dry weight of the organic material was derived from the organic nitrogen loading using a fixed dry weight to carbon ratio of 1.724 (Minasny et al. 2020) and a fixed C:N molar ratio of 6.625 (Redfield 1958). Conductivity measurements in the Albuñón water course (Dirección General del Mar Menor 2023) were also used to set salinity concentrations for the inflows, dependent on discharge (ranging from up to 7 PSU at low flows, to almost 0 PSU at high flows).

The exchange between the Mediterranean Sea and the lagoon through the three channels is important for nutrient and phytoplankton export and salinity regulation. While the net flow direction is into the lagoon (Senent-Aparicio et al. 2021), tidal or meteorological effects often cause bidirectional flows throughout the day, especially affecting areas near the channels and affecting the total residence time of the lagoon (García-Oliva et al. 2018). Without 3D simulations, the results of Senent-Aparicio et al. (2021) were used to parameterise this exchange. Senent-Aparicio et al. estimated the monthly average net exchange through the channels, which were fitted using a sinusoidal function. This net exchange was used as an inflow into the lagoon and a calibrated offset was added based on salinity measurements (see Section 3.1.6). We then kept the water level in the lagoon constant to calculate the residual flow out of the lagoon, considering catchment inflow and evaporation. This approach reproduced the seasonal exchange cycle, mostly driven by evaporation, while the added amount and the fixed water level estimated the subdaily water exchange between the sea and the lagoon. We assessed this method's effectiveness by comparing residence times with previous studies and camera data (Appendix 3, Fig. 10).

The food web in the WET model was configured to include macrophytes, phytoplankton, zoobenthos, and zooplankton modules. Multiple functional groups within the modules were not simulated to maintain simplicity and not exceed the data's capacity to validate the model. The parameterisations of the different modules were representative of the groups rather than the specific subgroups (e.g. cyanobacteria or diatoms for the phytoplankton module). All the configuration files of the GOTM-WET model set-up could be found in Mesman (2024).

### 3.2.3 Calibration and validation of the GOTM-WET model

The GOTM-WET model was calibrated using observations of temperature, phosphate, nitrate, ammonium, Secchi depth, oxygen, salinity, and chlorophyll (IMIDA 2023; Pérez-Ruzafa 2022). Summer macrophyte biomass estimates and their depth distribution for 2016, 2017, and 2018 were compiled from the literature and also used to calibrate the model (Ruiz-Fernández et al. 2020; Belando et al. 2021; Bernardeau et al. 2023). Relevant parameter values for the Mar Menor system were set based on a literature search. A sensitivity analysis was performed to select over 200 parameters from the model using the same meth-



odology as Jiménez-Navarro et al. (2023). In addition, sensitive biogeochemical parameters, meteorological scaling factors, the light extinction coefficient, and the minimum level of turbulence were calibrated. Due to the uncertainty in the catchment model and ground-water contribution, we allowed a 25% calibration margin on inlet nutrient concentrations from the SWAT+ model. Finally, we varied an “offset” to the Mediterranean Sea inflow (see Section 3.1.5) to estimate the lagoon–sea exchange. We used a differential evolution algorithm implemented in the Parsac Python library (Bruggeman and Bolding 2020) to perform an automatic parameter optimization, using a maximum likelihood function as an objective function. Calibration was iterative: model fits were plotted after numerous model runs in the differential evolution routine, parameter ranges were then adjusted (typically narrowed), and the calibration step was repeated until improvements became marginal.

The period 2008–2015 was used for spin-up, data from 2016–2020 were used to calibrate and data from 2021–2023 were used for validation. Beginning in September 2022, high-frequency data from a monitoring buoy for temperature, oxygen, and chlorophyll was also used to validate the model, and observed flow data from the main channels to assess the lagoon–sea exchange. Time series were plotted to further assess the model’s performance and the root mean square error (RMSE) and  $R^2$  were calculated.

### 3.3 Global climate models (GCMs)

To simulate future scenarios, meteorological data were extracted from Phase 6 of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al. 2016). Five GCMs with the necessary climate variables for each model (see Sections 3.1.2 and 3.2.2) were selected: BCC-CSM2-MR, CanESM5, INM-CM5-0, MiroC6, and MRI-ESM2-0. An ensemble of these five GCMs was used to address variability and uncertainty, and their mean was analysed.

This climate change study used two shared socioeconomic scenarios (SSPs) (O’Neill et al. 2016): SSP 2–45 and SSP 5–85. These scenarios offer a view of how the climate could evolve under different socioeconomic trajectories. SSP 2–45 follows current global emissions patterns with moderate barriers to climate change reduction, while SSP 5–85 prioritises economic development over environmental impact, leading to severe climate challenges. By comparing a more aggressive climate change scenario (SSP 5–85) with a milder one (SSP 2–45), we assessed the implications of different policy and economic approaches to climate change (O’Neill et al. 2014).

The analysis of future predictions was performed by comparing periods of the same duration (25 years): historical (1990–2014), mid-future (2050–2074) and far future (2075–2099). In this way, our simulations were grouped into five groups: a historical period that served as a base scenario, the SSP 2–45 scenario divided into mid-future (SSP 2–45 M) and far future (SSP 2–45 F), and the SSP 5–85 scenario, also subdivided into mid-future (SSP 5–85 M) and far future (SSP 5–85 F).

The historical period for each GCM was used to apply bias correction to all data from CMIP6 using two methods. The first method, empirical quantile mapping, a technique commonly used to correct atmospheric variables in climate change studies (Enayati et al. 2020), was applied for the bias correction of wind speed, atmospheric pressure, temperature, relative humidity, cloud cover, and solar radiation. The results of this correction are presented in Table 11 in Appendix 4. Due to the region’s low rainfall except on storm days, a linear

monthly correction was used to avoid amplifying extreme values for precipitation (Thiemeßl et al. 2012; Maraun 2013; Maurer and Pierce 2014; Cannon et al. 2015). Table 12 (Appendix 4) provides the results of this bias correction. Bias correction was performed using data from the ERA5 dataset, following approaches in other recent climate-related studies (e.g., Zhai et al. 2020; Xu et al. 2021; Carvalho et al. 2021; Jamal et al. 2023).

### 3.4 Analysis of regulation ecosystem services (RES)

Different RES in the Mar Menor lagoon and the Campo de Cartagena basin were assessed across three time periods: from 1990 to 2014 (historical), from 2050 to 2074 (mid-future) and from 2075 to 2099 (far future). Five specific RES for the catchment were chosen for analysis (Table 2), using SWAT+ outputs. These five RES have been estimated in previous studies using SWAT models (Kauffman et al. 2014; Cong et al. 2020; Aznarez et al. 2021). RES related to water quality in the lagoon itself were also examined. For this, five variables of the Mar Menor model were analysed, using outputs from the GOTM-WET model (Table 2). Days with hypoxia (oxygen level below  $2 \text{ g/m}^3$  according to the National Oceanic and Atmospheric Administration <https://oceanservice.noaa.gov/hazards/hypoxia/>) and days with algal blooms, defined by Spanish regulation as chlorophyll-a concentrations above  $10 \text{ mg/m}^3$  in shallow coastal lagoons (Soria and Sahuquillo 2009), were also analysed.

## 4 Results and discussion

### 4.1 Hydrological and ecological models of Campo de Cartagena and Mar Menor

#### 4.1.1 Calibration and validation of the SWAT+ model

Before calibrating the model, a sensitivity analysis was performed with 14 parameters of the SWAT+ model using SWATplus-CUP software (Appendix 2, Table 10). These parameters are commonly used in SWAT+ calibration (Jiménez-Navarro et al. 2024) in addition to others specifically related to aquifers due to their significance to the geography of the study area. Two parameters related to the soil's porosity conditions exhibited significant sensitivity, as indicated by a p-value of less than 0.1: the percolation coefficient (perco) and the moist bulk density (bd). Four additional SWAT+ parameters (cn2, esco, epco, and awc) were selected for the calibration of the Campo de Cartagena model based on prior modelling experience in the study area (López-Ballesteros et al. 2023a). Calibration of these six parameters was then performed as described in Section 3.1.3. The calibrated value of all calibrated parameters can be seen in Table 3.

The SWAT+ model of the Campo de Cartagena successfully simulated the trends and magnitudes of ET and SWC (Fig. 3). In semiarid areas, such as the Mar Menor basin, ET and SWC are crucial components of the hydrological cycle. Therefore, achieving good results during the calibration and validation of these variables would lend credibility to the model.

Statistically, the SWAT+ model performed acceptably well for ET and SWC, according to the criteria that Moriasi et al. (2015) and Kouchi et al. (2017) proposed. The  $R^2$  values for ET (Fig. 3) indicated some challenges in simulating ET trends in this intensively irri-

**Table 2** Definitions and sources of the RES analysed in the Campo de Cartagena basin and Mar Menor lagoon

| Location                   | Ecosystem service                              | Definition                                                                                                                             | Resolution                                    | SWAT+ or GOTM-WET output                                                                                                                                                                                                     |
|----------------------------|------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Campo de Cartagena (SWAT+) | Soil erosion control                           | Sediment retention service provision                                                                                                   | Basin scale (total discharge into the lagoon) | Sediment yield t/ha (SYLD)                                                                                                                                                                                                   |
|                            | Natural hazard protection                      | Floods, storms and climate extreme events mitigation                                                                                   | Basin scale (total discharge into the lagoon) | Average daily outflow rate from the basin to the lagoon mm (FLO_OUT)                                                                                                                                                         |
|                            | Water flow regulation                          | Green water (GW): water stored in the unsaturated soil above the groundwater table available for evapotranspiration (Falkenmark 1995)  | Basin scale (average of the basin)            | Evapotranspiration mm (ET) and Soil water content mm (SW_AVE)                                                                                                                                                                |
|                            |                                                | Blue water (BW): water found in surface and underground bodies (rivers, lakes, and aquifers) available for human use (Falkenmark 1995) |                                               | Water yield mm (WYLD) and Deep aquifer recharge mm (RCHRG)                                                                                                                                                                   |
|                            | Mediation of nuisances of anthropogenic origin | Transformation of nitrogen inputs to the ecosystem<br><br>Transformation of phosphorus inputs to the ecosystem                         | Basin scale (total discharge into the lagoon) | Organic nitrogen transported KgN (ORGN_OUT), nitrate transported KgN (NO3_OUT) and ammonium transported KgN (NH3_OUT)<br><br>Organic phosphorus transported KgP (SEDP_OUT) and mineral phosphorus transported KgP (SOLP_OUT) |
| Mar Menor (GOTM-WET)       | Water quality                                  | Regulation of physical, chemical and biological conditions                                                                             | Lagoon scale (average of the lagoon)          | Chlorophyll-a mg/m <sup>3</sup><br>Water temperature °C<br>O <sub>2</sub> conc g/m <sup>3</sup><br>Total N g/m <sup>3</sup><br>Total P g/m <sup>3</sup>                                                                      |

**Table 3** The adjusted values for the calibrated parameters of the SWAT+ model, represented either as an absolute value or as the change in percentage relative to the model's initial default value

| Parameter | Description                                | Adjusted value |
|-----------|--------------------------------------------|----------------|
| cn2       | Condition II curve number                  | + 6.31%        |
| esco      | Soil evaporation compensation factor       | 0.47           |
| epco      | Plant uptake compensation factor           | 0.25           |
| awc       | Available water capacity of the soil layer | + 13.25%       |
| bd        | Moist bulk density of the soil layer       | + 6.72%        |
| perco     | Percolation coefficient                    | 0.96           |



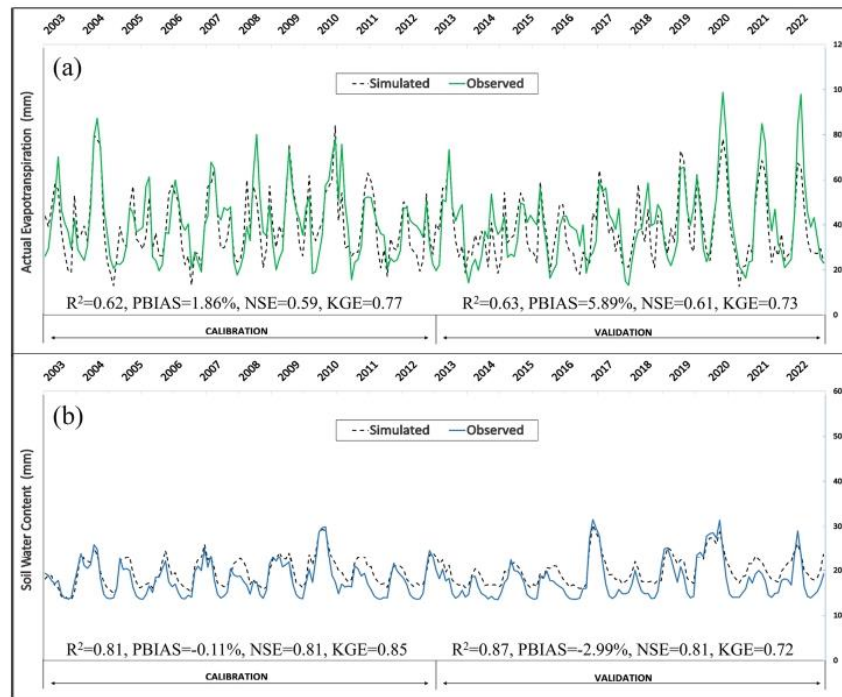


Fig. 3 Monthly calibration and validation of (a) ET and (b) SWC

gated area. However, by simulating local agricultural practices, we achieved a good total ET magnitude (PBIAS close to 0) and overall strong performance (NSE and KGE above 0.5). Regarding SWC, the SWAT+model accurately simulated the trend and the total magnitude, with PBIAS values close to 0% and  $R^2$  values greater than 0.8. The SWAT+model demonstrated good performance in simulating the water balance of Campo de Cartagena, with values of key water balance components similar to those found by Senent-Aparicio et al. (2021).

The simulated sediment yield in the baseline scenario was 0.016 t/ha/year, similar to the sediment yield reported in the Campo de Cartagena area's National Soil Erosion Inventory (INES 2012). The simulated total nitrogen and phosphorus loads to the lagoon were also similar to those reported by García-Pintado et al. (2007). From 2003 to 2022, the SWAT+ simulated average annual total nitrogen loads were 407 t/year and the total phosphorus loads were 71 t/year.

#### 4.1.2 Calibration and validation of the GOTM-WET model

The GOTM-WET model successfully reproduced temperature, salinity, oxygen, nitrate, phosphate, and chlorophyll trends during calibration (Fig. 4, Table 4). Most of these vari-

ables were also well reproduced in the validation period, although salinity, chlorophyll, and phosphate simulations showed unexpected behaviour. Temperature and oxygen exhibited clear seasonal cycles, while salinity, nutrients, Secchi depth, and chlorophyll were more strongly driven by sporadic (inflow) events. The model captured some short-term stratification events (Appendix 3, Fig. 8). The most intense of these events were due to salinity stratification, while more frequent, less intense events were caused by temperature stratification.

While the overall performance was satisfactory, the model also exhibited shortcomings. Salinity varied from observations during validation, indicating inaccuracies in evaporation or sea exchange parameters. The model also captured hypoxia and high turbidity events but missed others. For instance, in 2021, the model correctly timed a decrease in oxygen and Secchi depth and an increase in chlorophyll but with too low intensity. Nitrate and phosphate concentrations were commonly low, except after intense inflows. Nitrate peaks matched observations moderately well, but phosphate peaks were difficult to assess due to the measurement timing. Ammonium observations varied throughout the simulation period, but ammonium dynamics were not accurately simulated. The model captured long-term trends and many significant event impacts, but it was likely to miss or underestimate some events and perform better for some variables (e.g., temperature and chlorophyll), than for others (e.g., ammonium).

Additional validation with high-frequency data from a monitoring buoy (from September 2022) showed that temperature and oxygen simulations aligned well with observations, although short-term hypoxia events were missed (Appendix 3, Fig. 9). The match with the high-frequency chlorophyll data was weaker. The overall pattern was similar, but an increase in chlorophyll at the end of 2022 was missed, and the model overestimated the concentrations afterwards. Comparison of the channel discharge with camera-derived discharge data could only occur over seven months but indicated that the model underestimated the flow into the lagoon (Appendix 3, Fig. 10).

However, the computed residence time of the lagoon (309 days) closely matched an estimate by Ghezzi et al. (2015), based on 3D model simulations (318 days), indicating accurate annual renewal rates and an overall well-established water balance.

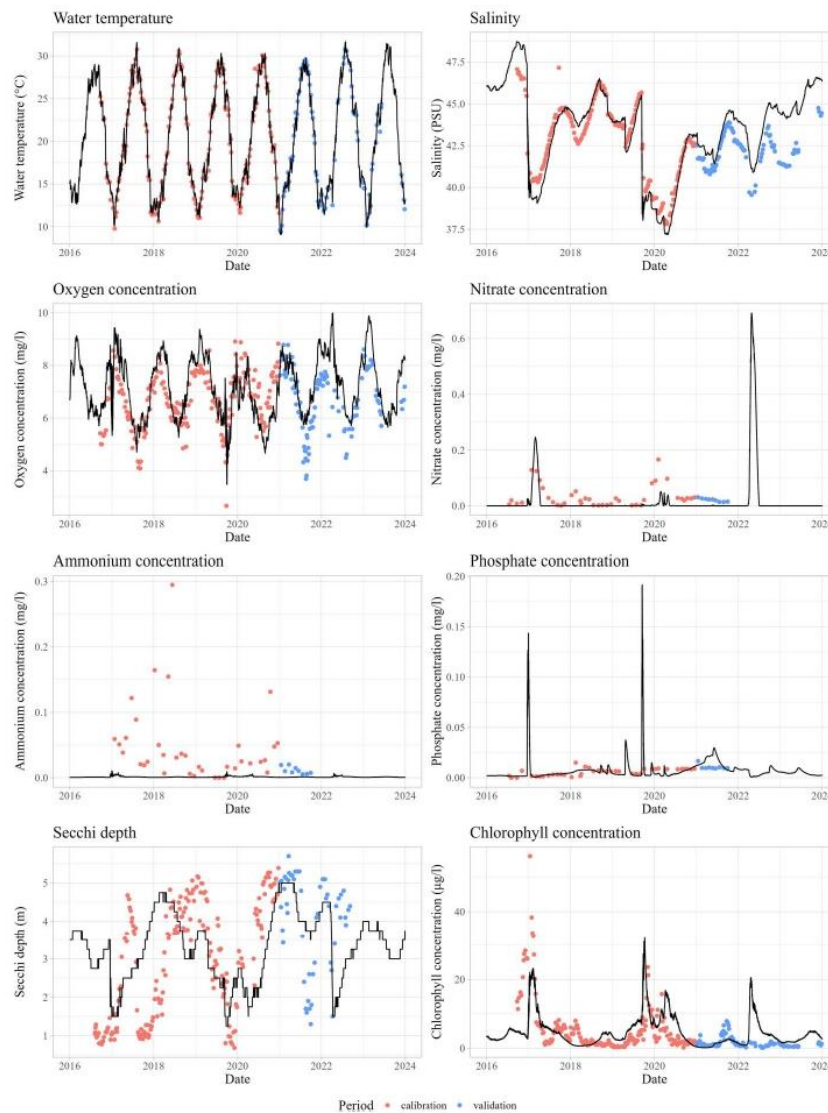
A limitation of the GOTM-WET model is its simplified representation of the exchange between Mar Menor and the Mediterranean Sea, as potential sea-level rise and dynamic changes in the communication channels of La Manga were not included. These factors depended on complex interactions between natural processes and management decisions, making them difficult to predict. Despite this limitation, the model provides valuable insights into the lagoon's processes and serves as a robust tool for understanding its current dynamics and informing future studies.

#### 4.2 Future climate variation for the study area

The five GCMs used in the study present slight variations regarding climate evolution in Campo de Cartagena (Fig. 5). The air temperature showed a uniform trend to increase over time in all five GCMs (Fig. 5(a)). This increase was more pronounced in the severe scenario (SSP 5–85). Although the temperature increase varied, the ensemble showed an increase of 3.84°C for the far future SSP 5–85 scenario (Table 5).

The GCMs collectively showed decreasing precipitation in the area (Table 5). Most of the GCMs predicted a severe decrease in precipitation (around -19%) in the far future under



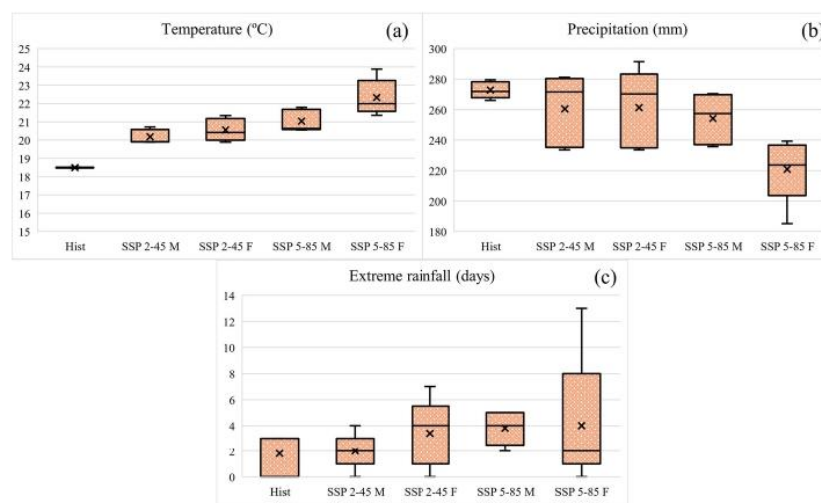


**Fig. 4** Comparison of GOTM-WET simulation (black lines) and observations (dots, red=calibration, blue=validation) for water temperature, salinity, oxygen, nitrate, ammonium, phosphate, Secchi depth, and chlorophyll. All values were taken from a 3.5 m depth

the more aggressive scenario (SSP 5–85 F). While some models showed stability or even a slight increase in other periods, the general trend was downward (Fig. 5(b)). Another relevant factor was the magnitude of the precipitation events. For this purpose, the number of days in each period in which precipitation exceeded 50 mm, the threshold the World Metro-

**Table 4** Goodness-of-fit statistics of the GOTM-WET model for Mar Menor, determined for all depths combined for the calibration (2016–2020) and validation (2021–2023) periods

| Variable                         | Calibration |                | Validation |                |
|----------------------------------|-------------|----------------|------------|----------------|
|                                  | RMSE        | R <sup>2</sup> | RMSE       | R <sup>2</sup> |
| Water temperature (°C)           | 0.520       | 0.994          | 0.403      | 0.996          |
| Salinity (PSU)                   | 0.818       | 0.948          | 1.662      | 0.538          |
| Oxygen concentration (mg/l)      | 0.924       | 0.455          | 1.082      | 0.680          |
| Nitrate concentration (mg/l)     | 0.046       | 0.257          | 0.022      | 0.006          |
| Ammonium concentration (mg/l)    | 0.075       | 0.011          | 0.012      | 0.484          |
| Phosphate concentration (mg/l)   | 0.004       | 0.219          | 0.009      | 0.072          |
| Secchi depth (m)                 | 1.518       | 0.084          | 1.274      | 0.120          |
| Chlorophyll concentration (µg/l) | 6.387       | 0.225          | 2.837      | 0.001          |

**Fig. 5** Predictions of the GCMs predictions of (a) annual average precipitation, (b) temperature, and (c) number of days with torrential rainfall for each period and scenario of Campo de Cartagena**Table 5** Annual average of precipitation, temperature, and number of days with torrential rainfall for each period and scenario of Campo de Cartagena

|            | Temp (°C) | ΔTemp (°C) | Pcp (mm) | ΔPcp (%) | Ex-treme days |
|------------|-----------|------------|----------|----------|---------------|
| Hist       | 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             |

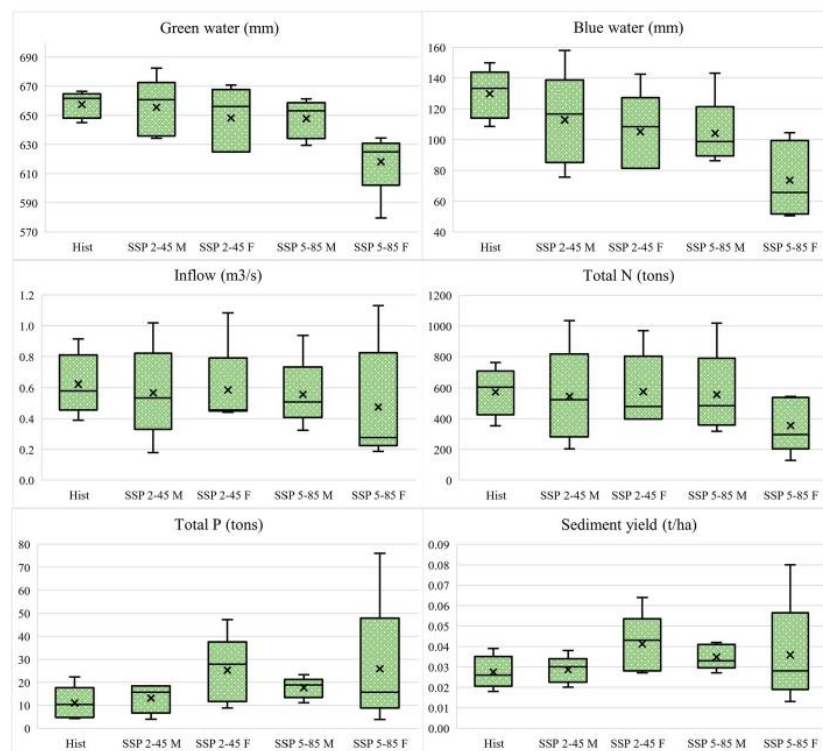
rological Organization suggested to define extreme rainfall (World Meteorological Organization 2008), was evaluated (Table 5). Our analysis revealed that despite the reduction in average precipitation compared to the historical period, the GCMs showed an increase in the torrentiality of precipitation in some scenarios and future periods. Most showed a higher increase in the far future, with some for the SSP 2-45 scenario and some for the SSP 5-85

(Fig. 5(c)). In summary, a trend was identified towards an increase in the intensity of torrential rainfall in forthcoming periods, even with notable variability regarding when and where this escalation was most pronounced.

### 4.3 Future variation of the RES of Campo de Cartagena

Predictions among the different scenarios varied significantly, especially in the far future (Fig. 6).

The analysis of GW and BW indicated a clear pattern of decreasing water availability in the lagoon's catchment for plants and people (Fig. 6). GW is related to evapotranspiration and soil water content, while BW is the sum of the water yield and aquifer recharge. The decrease in both can be linked to the reduction in precipitation expected in Campo de Cartagena and is also reflected in the pattern of decreasing inflow to the lagoon (Fig. 6). However, the reduction in inflow was not as apparent as the simulated reduction in the BW. Some scenarios showed high inflow values, as can be seen in the whiskers of Fig. 6. BW was expected to decrease around 19% in the SSP 2–45 scenario and around 43% in the SSP 5–85 scenario for the far future, while the inflow reduction was anticipated to be around 6%



**Fig. 6** Predictions of the GCMs predictions of annual average hydrological variables affecting the RES of Campo de Cartagena for each period and scenario

in the SSP 2–45 scenario and 24% in the SSP 5–85 scenario (Table 6). This difference could be caused by an increase in surficial runoff from the basin due to the expected increase in torrential events (Section 4.2).

The increase in runoff was indicated by a smaller decrease in inflow than for BW. This increase in runoff was also reflected in the observed rise in sediment yield, which was higher in the distant future for both scenarios (Table 6 and Fig. 6), and in the increase in phosphorus input (Table 6). Simulated phosphorus input into the lagoon was closely related to surface and particulate runoff in the SWAT+ model. Sediment yield and phosphorus showed a similar prediction pattern, even though phosphorus was predicted to increase more than sediment (Fig. 6).

A decrease in nitrogen input to the lagoon was simulated (Fig. 6). Since the primary source of nitrogen to Mar Menor is through the aquifer (Puertes et al. 2021), this reduction was linked to the decrease in water recharge to the aquifer, as the model indicated. Combined with a decrease in water production, this reduction led to what was observed in BW, therefore decreasing overall water availability in Campo de Cartagena. This factor is crucial, as the area's agriculture is predominantly irrigated; therefore a significant drop in water availability in surface and groundwater bodies could severely impact human activities.

Due to climate change, a decrease in all analysed RES (Table 2) was observed in the basin (Table 6). Increased runoff would reduce soil erosion control and negatively impact natural hazard protection, as the increase in runoff without a corresponding rise in total flow in Campo de Cartagena indicated an irregular, discontinuous inflow pattern, reducing ecosystem resilience to extreme weather. The ES linked to water flow regulation would diminish with the decline of GW and BW. The decline in GW implied a reduction in the available water for evaporation and transpiration (Kauffman et al. 2014), while the decrease in BW implied a reduction in the water available for human use. These trends, along with the decrease in precipitation, are concerning, as they could lead to desertification in Campo de Cartagena (Huang et al. 2020) and severely impact the agricultural sector. Since the region primarily relies on aquifer water extraction, a reduced aquifer recharge would pose further challenges to the agricultural sector. The mediation of anthropogenic nuisances would also be impacted in the future, as nutrient input patterns to the lake would be significantly altered, with less nitrogen entering through the aquifer and increased phosphorus input from runoff.

**Table 6** Annual average of hydrological variables affecting the RES 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 (tonnes)       | 573.057    | 543.905    | 575.183    | 556.267    | 355.075    |
| Δ Total N              | -          | -5.1%      | 0.4%       | -2.9%      | -38.0%     |
| Total P (tonnes)       | 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%     |



#### 4.4 Future variation of the RES of the Mar Menor

Biotic and abiotic conditions in the lagoon could change significantly in the future. Water temperature would increase progressively over time, most notably under the more severe scenario (SSP 5–85) (Table 7, Fig. 7), due to the expected atmospheric temperature rise in the basin.

Nutrient concentrations in Mar Menor would also be altered, influenced by the inflow and entrainment in Campo de Cartagena (see Section 4.3) and the internal cycling of nutrients, which would increase with rising temperatures. Phosphorus concentration was expected to rise, partially due to increased phosphorus input from runoff in Campo de Cartagena, with similar predictions for both SSP 2–45 and SSP 5–85 (Fig. 7). In the far future (2075–2099), phosphorus concentration were projected to double from 0.002 g/m<sup>3</sup> to 0.004 g/m<sup>3</sup> (Table 7). In contrast, nitrogen concentration would decrease due to reduced nitrate input from the aquifer and potentially changes in the lagoon's biogeochemical cycling. The five GCMs showed consistent results, with the largest decrease—around 50%—projected under SSP 5–85, dropping from 0.08 g/m<sup>3</sup> to 0.04 g/m<sup>3</sup> (Fig. 7 and Table 7). The models varied more for the mid-period (2050–2074), but all predicted a decrease in nitrogen concentration, though less pronounced.

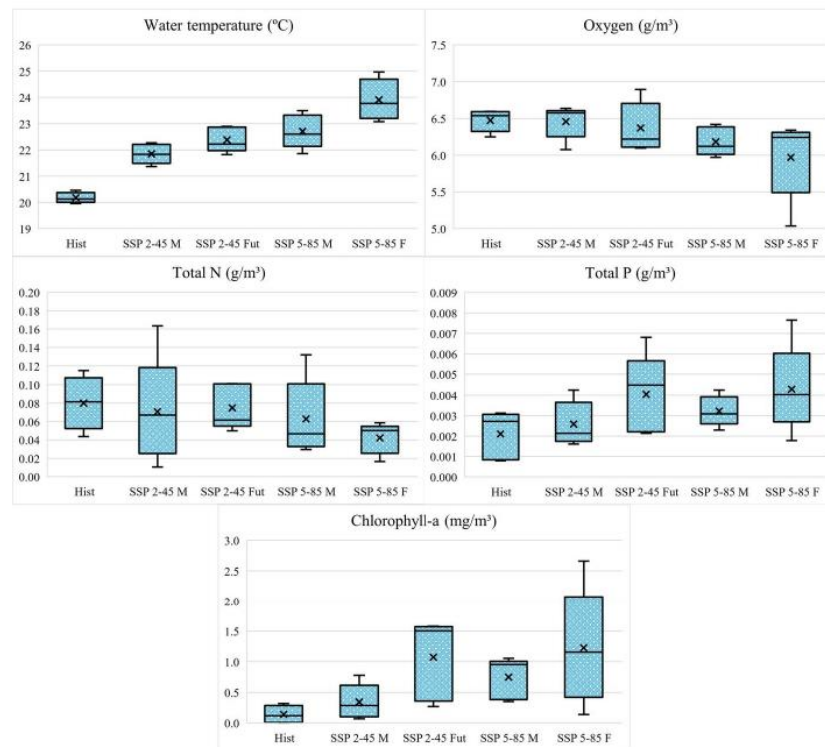
Despite the decrease in nitrogen concentration, chlorophyll-a levels were projected to rise for both climate change scenarios (Fig. 7 and Table 7). The GCMs differed in how extreme this increase would be, especially in the distant future. Chlorophyll-a is a proxy for total phytoplankton concentration and, thus, primary production (Aruga and Monsi 1963; Han and Jordan 2005). Despite the rise in chlorophyll-a, the reduced nitrogen levels in Mar Menor would typically suggest a decrease in primary production. However, according to our simulations, nitrogen and phosphorus act as limiting factors for phytoplankton growth, with short and rare periods of no limitation occurring following significant inflow events. This finding suggested that the increase in primary production is linked to the influx of limiting nutrients. When one nutrient increases, the other typically acts as the limiting factor, further influencing the system's primary production dynamics.

Finally, the oxygen concentration in the lagoon was expected to decrease, linked to lower oxygen solubility at higher water temperatures (Table 7 and Fig. 7). In the most aggressive future scenario, models varied in the predicted severity of the reduction (Fig. 7). The oxygen reduction may lead to an increase in hypoxic events. To analyse this, the days of each period in which the oxygen level was below 2 g/m<sup>3</sup> were counted (Table 8). As oxygen

**Table 7** Annual average of water conditions affecting the RES of the 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 (C°)               | 20.18      | 21.84      | 22.38      | 22.70      | 23.91      |
| Δ Water temperature (C°)             | -          | 1.7        | 2.2        | 2.5        | 3.7        |
| Oxygen (g/m <sup>3</sup> )           | 6.47       | 6.46       | 6.37       | 6.18       | 5.97       |
| Δ Oxygen (g/m <sup>3</sup> )         | -          | -0.02      | -0.10      | -0.29      | -0.50      |
| Total N (g/m <sup>3</sup> )          | 0.080      | 0.071      | 0.075      | 0.063      | 0.042      |
| Δ Total N (g/m <sup>3</sup> )        | -          | -0.01      | -0.01      | -0.02      | -0.04      |
| Total P (g/m <sup>3</sup> )          | 0.0021     | 0.0026     | 0.0040     | 0.0032     | 0.0043     |
| Δ Total P (g/m <sup>3</sup> )        | -          | 0.0005     | 0.0019     | 0.0011     | 0.0022     |
| Chlorophyll-a (mg/m <sup>3</sup> )   | 0.1374     | 0.34       | 1.07       | 0.74       | 1.23       |
| Δ Chlorophyll-a (mg/m <sup>3</sup> ) | -          | 0.2        | 0.9        | 0.6        | 1.1        |





**Fig. 7** GCMs' predictions of annual average water conditions in the Mar Menor lagoon for each period and scenario

**Table 8** Number of days for each period (25 years) when extreme conditions are expected: chlorophyll-a concentration above 10 mg/m<sup>3</sup> and oxygen concentration below 2 g/m<sup>3</sup>

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

levels decline in future scenarios, and stratification periods could increase in frequency due to warming and extreme inflow events, hypoxia events were expected to increase, particularly in the SSP 5-85 scenario. We also analysed the days when chlorophyll-a concentration exceeded 10 mg/m<sup>3</sup>, indicating algal blooms, since these blooms were projected to increase in the distant future under both SSP 2-45 and SSP 5-85 scenarios. The increase in such days was strong, although it was mostly driven by a few events that lasted for a long period. Occasionally, low oxygen levels coincided with high chlorophyll-a concentrations, although this correlation was inconsistent. This phenomenon has already been seen in the Mar Menor over several years, including the episodes in 2017 and 2019 detailed in Section 2 of this study. The lagoon's eutrophic state makes it vulnerable to disturbances such as increased

storm frequency or higher temperatures, exacerbating algal blooms and hypoxia, which threaten the ecosystem services provided by Mar Menor.

In general, in the simulated climate change scenarios, a worsening of water-related RES was expected, linked to the alteration of the lagoon's physical, chemical and biological conditions. The situation would negatively affect the regulation of Mar Menor, which was already a stressed and damaged ecosystem. It could also have negative effects on the cultural ES associated with the lagoon, mainly related to ecotourism and recreation (Bryce et al. 2016; Hirons et al. 2016; Cheng et al. 2019; Zhan et al. 2023). However, climate change's effects may be mitigated to some extent by adopting best management practices in the catchment, such as those analysed by López-Ballesteros et al. (2023a).

## 5 Conclusions

This study analysed the trend of regulatory ecosystem services (RES) in the coastal lagoon of Mar Menor and its surrounding catchment, the Campo de Cartagena basin, to evaluate the impacts of climate change on the ecosystem. Two coupled models were developed: the SWAT+ model for the basin and the GOTM-WET model for the lagoon. Both models demonstrated satisfactory calibration and validation results, providing a good basis for our analysis.

Bias-corrected data from five GCMs (BCC-CSM2-MR, CanESM5, INM-CM5-0, MiroC6, and MRI-ESM2-0) were used to develop extreme (SSP 5–85) and intermediate (SSP 2–45) climate change scenarios, allowing comparisons of their impacts. Projections showed a notable increase in temperatures, especially under SSP 5–85, with overall decreased precipitation but more frequent extreme rainfall events. The future average streamflow was projected to decline, particularly under the more severe scenario. However, there would be an increase in phosphorus input and sediment yield due to enhanced surficial runoff, while nitrogen input was expected to decrease, altering the nutrient dynamics in Mar Menor. Green and blue water would decrease, reducing water availability for vegetation and human use. This would likely impair water flow regulation and increase the risk of flooding.

When running the catchment and lagoon models based on the future climates, the simulations indicated that climate change would negatively affect all analysed RES in Campo de Cartagena, resulting in reduced mediation of anthropogenic nuisances, diminished soil erosion control, decreased protection against natural hazards, and impaired water flow regulation. Such changes would lead to more frequent algal blooms and hypoxic events in the lagoon, lower water availability, and increased flood risks in the basin, thus compromising the ecosystem's resilience. The frequency of hypoxia events and algal blooms in the lagoon would likely increase, worsening Mar Menor's already stressed water quality conditions.

As a region reliant on tourism and recreational activities, the decline in RES and further deterioration of Mar Menor's ecosystem could negatively impact its cultural ecosystem services, highlighting the need for research to address stakeholder concerns and identify strategies to mitigate climate change's impacts on this valuable ecosystem.

Advanced modelling tools, such as GOTM-WET and SWAT+, open new possibilities for understanding and managing Mar Menor and its basin. The GOTM-WET model enables the analysis of key ecological processes, such as changes in fluxes, sediment, oxygen demand, nitrogen removal, and nitrification (Hipsey et al. 2020; Regev et al. 2023), improving the understanding of RES functionality in the lagoon and Mar Menor resilience.

The SWAT+ model provides a framework to simulate agricultural practices and explore strategies tailored to the region's specific challenges, such as water scarcity (Sharma et al. 2024). Building on the results of this study, future work should evaluate the effectiveness of these strategies, focusing on approaches such as land-use planning and best management practices. By doing so, SWAT+ can provide actionable insights into mitigating the impacts of climate change on agriculture and ensuring the sustainability of the region's natural resources. Together, these tools enhance the scientific understanding of Mar Menor's dynamics and offer practical resources for stakeholders seeking to mitigate climate change impacts and preserve the region's natural and cultural heritage.

### Appendix 1: Setup of the SWAT+ model

In study areas with a high percentage of agricultural land use, such as the Campo de Cartagena basin, it is important to simulate the agricultural practices used in these areas to reduce the model uncertainties. Therefore, in this study, we implemented the agricultural management plans of the main irrigated agricultural crops in Campo de Cartagena (citrus and horticulture) using SWAT+ (Table 9).

**Table 9** Agricultural management practices for irrigation

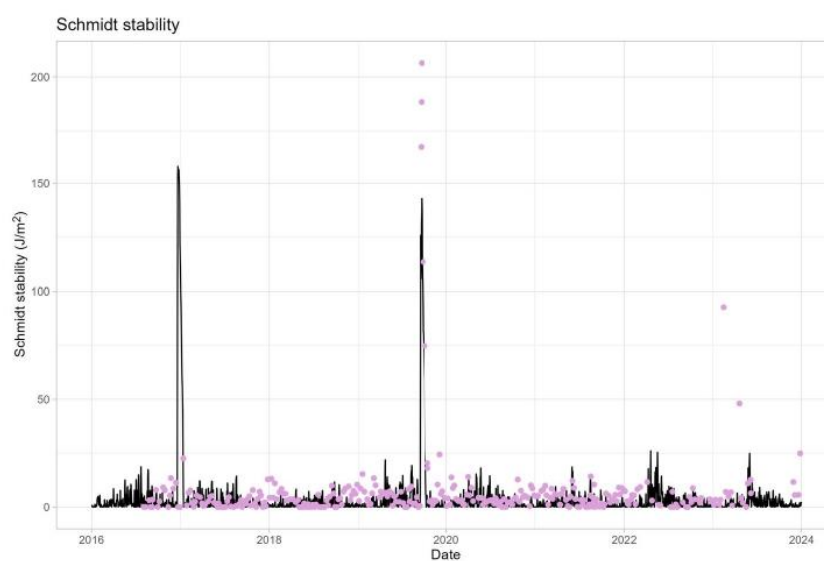
| Date      |     | Operation        | Application Rate                   | Crop       |
|-----------|-----|------------------|------------------------------------|------------|
| Month     | Day |                  |                                    |            |
| January   | 1   | Planting begin   |                                    | Broccoli   |
| January   | 1   | Irrigation       | ~45 mm/month                       | Broccoli   |
| January   | 1   | Fertilization    | 245 KgN/ha/year<br>100 KgP/ha/year | Broccoli   |
| April     | 30  | Harvest and kill |                                    | Broccoli   |
| May       | 1   | Planting begin   |                                    | Cantaloupe |
| May       | 1   | Irrigation       | ~48 mm/month                       | Cantaloupe |
| May       | 1   | Fertilization    | 225 KgN/ha/year<br>105 KgP/ha/year | Cantaloupe |
| August    | 31  | Harvest and kill |                                    | Cantaloupe |
| September | 1   | Planting begin   |                                    | Lettuce    |
| September | 1   | Irrigation       | ~31 mm/month                       | Lettuce    |
| September | 1   | Fertilization    | 100 KgN/ha/year<br>58 KgP/ha/year  | Lettuce    |
| December  | 31  | Harvest and kill |                                    | Lettuce    |

## Appendix 2: Sensitivity analysis of SWAT +

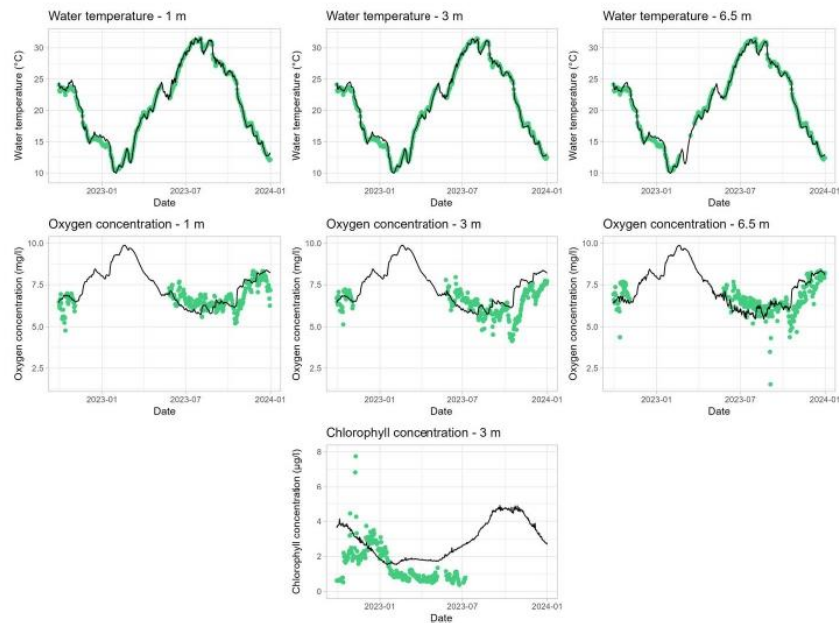
**Table 10** Results of the sensitivity analysis performed for the SWAT+model

| Parameter | t-Stat | P-Value |
|-----------|--------|---------|
| Perco     | 2.783  | 0.007   |
| BD        | 2.594  | 0.011   |
| Cn3_swf   | 1.462  | 0.147   |
| Deep-seep | -1.388 | 0.169   |
| AWC       | 1.296  | 0.198   |
| Sp-yld    | 1.099  | 0.275   |
| K         | -0.710 | 0.480   |
| Epco      | -0.667 | 0.507   |
| Cn2       | -0.516 | 0.607   |
| Esco      | 0.480  | 0.633   |
| Revap_co  | -0.133 | 0.699   |
| Flo_min   | -0.182 | 0.856   |
| Revap_min | 0.133  | 0.894   |
| Alpha     | 0.082  | 0.934   |

## Appendix 3: Calibration and validation GOTM-WET

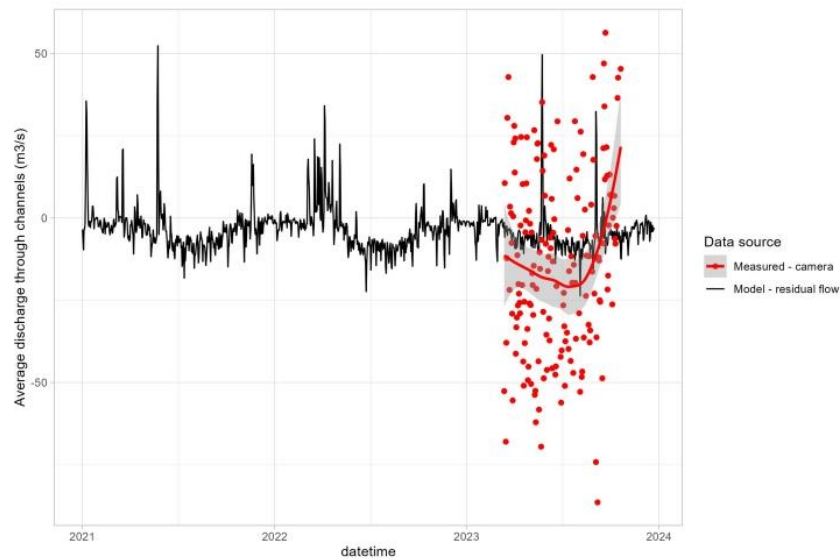


**Fig. 8** Schmidt stability in the Mar Menor; simulated (black line) and derived from temperature and salinity observations (pink dots)



**Fig. 9** Comparison of the GOTM-WET simulation (black lines) with buoy observations (green dots) for water temperature, oxygen, and chlorophyll at 1, 3, and 6.5 m depth. The oxygen sensor data were bias-corrected to the long-term monitoring data





**Fig. 10** 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 the sea, and negative the reverse

**Appendix 4: Bias-correction****Table 11** Comparison of weather data extracted from the various GCMs with actual weather data before and after bias correction

| GCM       | Variable                   | Type      | RMSE     | BIAS    | NMAE   | NSE      |
|-----------|----------------------------|-----------|----------|---------|--------|----------|
| INM-CM5-0 | Wind Speed (m/s)           | Original  | 3.953    | 3.205   | Inf    | -2.258   |
|           |                            | Corrected | 2.557    | 0.972   | Inf    | -0.363   |
|           | Atmospheric Preassure (Pa) | Original  | 824.811  | -30.782 | 0.006  | -0.762   |
|           |                            | Corrected | 808.916  | -2.773  | 0.006  | -0.695   |
|           | Average temperature (K)    | Original  | 4.131    | -1.491  | 0.011  | 0.424    |
|           |                            | Corrected | 2.780    | -0.004  | 0.008  | 0.739    |
|           | Relative humidity (%)      | Original  | 27.174   | -12.148 | 0.325  | -5.241   |
|           |                            | Corrected | 15.234   | 0.000   | 0.191  | -0.961   |
|           | Cloud cover (%)            | Original  | 41.351   | 3.786   | Inf    | -1.009   |
|           |                            | Corrected | 37.420   | -0.634  | Inf    | -0.645   |
|           | Solar radiation (W/m2)     | Original  | 223.346  | 201.234 | 11.251 | -915.024 |
|           |                            | Corrected | 4.081    | 0.001   | 0.224  | 0.694    |
|           | Max. temperature (K)       | Original  | 5.251    | 0.337   | 0.014  | 0.097    |
|           |                            | Corrected | 3.339    | 0.065   | 0.009  | 0.635    |
|           | Min. Temperature (K)       | Original  | 5.138    | -3.542  | 0.014  | 0.113    |
|           |                            | Corrected | 3.591    | 0.000   | 0.010  | 0.567    |
| CanESM5   | Wind Speed (m/s)           | Original  | 4.665    | 3.766   | Inf    | -3.538   |
|           |                            | Corrected | 2.622    | 0.966   | Inf    | -0.434   |
|           | Atmospheric Preassure (Pa) | Original  | 1008.557 | 481.765 | 0.007  | -1.635   |
|           |                            | Corrected | 856.083  | -5.862  | 0.006  | -0.898   |
|           | Average temperature (K)    | Original  | 3.669    | 0.313   | 0.010  | 0.546    |
|           |                            | Corrected | 2.765    | -0.054  | 0.008  | 0.742    |
|           | Relative humidity (%)      | Original  | 20.387   | -8.454  | 0.254  | -2.513   |
|           |                            | Corrected | 14.681   | 0.021   | 0.186  | -0.822   |
|           | Cloud cover (%)            | Original  | 41.789   | -4.686  | Inf    | -1.052   |
|           |                            | Corrected | 39.755   | -1.448  | Inf    | -0.857   |
|           | Solar radiation (W/m2)     | Original  | 222.063  | 203.221 | 11.680 | -904.535 |
|           |                            | Corrected | 4.563    | -0.016  | 0.235  | 0.618    |
|           | Max. temperature (K)       | Original  | 5.416    | 2.057   | 0.015  | 0.040    |
|           |                            | Corrected | 3.686    | -0.123  | 0.010  | 0.555    |
|           | Min. Temperature (K)       | Original  | 3.660    | -1.107  | 0.010  | 0.550    |
|           |                            | Corrected | 3.178    | -0.001  | 0.009  | 0.661    |

**Table 11** (continued)

| GCM        | Variable                            | Type      | RMSE     | BIAS     | NMAE   | NSE      |
|------------|-------------------------------------|-----------|----------|----------|--------|----------|
| MRI-ESM2-0 | Wind Speed (m/s)                    | Original  | 7.537    | 6.753    | Inf    | -10.846  |
|            |                                     | Corrected | 2.598    | 0.971    | Inf    | -0.407   |
|            | Atmospheric Pressure (Pa)           | Original  | 1003.608 | 432.106  | 0.008  | -1.609   |
|            |                                     | Corrected | 886.660  | 1.152    | 0.007  | -1.036   |
|            | Average temperature (K)             | Original  | 3.186    | -0.301   | 0.009  | 0.657    |
|            |                                     | Corrected | 3.275    | -0.006   | 0.009  | 0.638    |
|            | Relative humidity (%)               | Original  | 16.842   | -0.902   | 0.209  | -1.397   |
|            |                                     | Corrected | 15.016   | 0.014    | 0.188  | -0.906   |
|            | Cloud cover (%)                     | Original  | 43.654   | 7.090    | Inf    | -1.239   |
|            |                                     | Corrected | 39.512   | -0.835   | Inf    | -0.835   |
|            | Solar radiation (W/m <sup>2</sup> ) | Original  | 211.186  | 191.133  | 10.985 | -818.001 |
|            |                                     | Corrected | 4.944    | -0.011   | 0.265  | 0.551    |
|            | Max. temperature (K)                | Original  | 4.020    | -1.889   | 0.011  | 0.471    |
|            |                                     | Corrected | 3.674    | 0.001    | 0.010  | 0.558    |
|            | Min. Temperature (K)                | Original  | 3.621    | 1.467    | 0.010  | 0.560    |
|            |                                     | Corrected | 3.347    | -0.012   | 0.009  | 0.624    |
| MIROC6     | Wind Speed (m/s)                    | Original  | 4.415    | 3.552    | Inf    | -3.066   |
|            |                                     | Corrected | 2.631    | 0.975    | Inf    | -0.443   |
|            | Atmospheric Pressure (Pa)           | Original  | 870.870  | -281.714 | 0.007  | -0.964   |
|            |                                     | Corrected | 817.047  | -0.317   | 0.006  | -0.729   |
|            | Average temperature (K)             | Original  | 4.469    | 2.531    | 0.012  | 0.326    |
|            |                                     | Corrected | 2.774    | -0.016   | 0.008  | 0.740    |
|            | Relative humidity (%)               | Original  | 25.585   | -17.547  | 0.310  | -4.533   |
|            |                                     | Corrected | 14.964   | 0.009    | 0.189  | -0.892   |
|            | Cloud cover (%)                     | Original  | 37.103   | -2.042   | Inf    | -0.618   |
|            |                                     | Corrected | 39.146   | 0.344    | Inf    | -0.801   |
|            | Solar radiation (W/m <sup>2</sup> ) | Original  | 213.429  | 192.914  | 11.115 | -835.487 |
|            |                                     | Corrected | 5.093    | 0.003    | 0.272  | 0.524    |
|            | Max. temperature (K)                | Original  | 6.828    | 4.064    | 0.018  | -0.526   |
|            |                                     | Corrected | 3.388    | -0.005   | 0.009  | 0.624    |
|            | Min. Temperature (K)                | Original  | 3.714    | 2.013    | 0.010  | 0.537    |
|            |                                     | Corrected | 2.947    | -0.002   | 0.008  | 0.708    |

**Table 11** (continued)

| GCM         | Variable                            | Type      | RMSE    | BIAS    | NMAE   | NSE      |
|-------------|-------------------------------------|-----------|---------|---------|--------|----------|
| BCC-CSM2-MR | Wind Speed (m/s)                    | Original  | 7.442   | 6.643   | Inf    | -10.549  |
|             |                                     | Corrected | 2.591   | 0.971   | Inf    | -0.400   |
|             | Atmospheric Pressure (Pa)           | Original  | 997.551 | 366.975 | 0.008  | -1.577   |
|             |                                     | Corrected | 897.578 | -3.445  | 0.007  | -1.087   |
|             | Average temperature (K)             | Original  | 2.812   | -0.697  | 0.008  | 0.733    |
|             |                                     | Corrected | 2.549   | -0.116  | 0.007  | 0.781    |
|             | Relative humidity (%)               | Original  | 17.441  | -6.256  | 0.212  | -1.571   |
|             |                                     | Corrected | 14.921  | 0.022   | 0.187  | -0.882   |
|             | Cloud cover (%)                     | Original  | 41.502  | 18.159  | Inf    | -1.024   |
|             |                                     | Corrected | 39.631  | 0.536   | Inf    | -0.846   |
|             | Solar radiation (W/m <sup>2</sup> ) | Original  | 210.225 | 189.847 | 10.772 | -810.562 |
|             |                                     | Corrected | 4.711   | -0.057  | 0.255  | 0.593    |
|             | Max. temperature (K)                | Original  | 5.039   | -4.079  | 0.015  | 0.169    |
|             |                                     | Corrected | 2.840   | -0.062  | 0.008  | 0.736    |
|             | Min. Temperature (K)                | Original  | 3.880   | 2.629   | 0.011  | 0.494    |
|             |                                     | Corrected | 2.667   | -0.069  | 0.007  | 0.761    |

**Table 12** Monthly linear scaling factor for precipitation data extracted for each GCM

| GCM         | Month     | Scaling factor |
|-------------|-----------|----------------|
| BCC-CSM2-MR | January   | 0.79298491     |
|             | February  | 1.0484304      |
|             | March     | 1.01814199     |
|             | April     | 1.415086       |
|             | May       | 1.41511535     |
|             | June      | 0.53974756     |
|             | July      | 0.25297291     |
|             | August    | 0.32248529     |
|             | September | 0.83934436     |
|             | October   | 1.22998394     |
|             | November  | 1.13249424     |
|             | December  | 0.78942163     |
| CanESM5     | January   | 2.47464842     |
|             | February  | 2.83885993     |
|             | March     | 2.88251931     |
|             | April     | 2.14806938     |
|             | May       | 2.202916       |
|             | June      | 0.54176601     |
|             | July      | 0.38785642     |
|             | August    | 1.01085131     |
|             | September | 3.5182742      |
|             | October   | 2.04078256     |
|             | November  | 2.90132912     |
|             | December  | 1.24097913     |
| INM-CM5-0   | January   | 0.72760637     |
|             | February  | 0.70237351     |
|             | March     | 0.64107414     |
|             | April     | 0.56562532     |
|             | May       | 0.69895224     |
|             | June      | 0.51074252     |
|             | July      | 0.43041436     |
|             | August    | 1.37427389     |
|             | September | 2.23956142     |
|             | October   | 1.12501016     |
|             | November  | 0.79413591     |
|             | December  | 0.56830958     |
| MIROC6      | January   | 0.82281581     |
|             | February  | 0.73028841     |
|             | March     | 0.75184277     |
|             | April     | 0.88030713     |
|             | May       | 1.06187983     |
|             | June      | 0.77212556     |
|             | July      | 0.51738898     |
|             | August    | 0.57056826     |
|             | September | 1.39370201     |
|             | October   | 1.10635342     |
|             | November  | 1.29383526     |
|             | December  | 0.85093416     |



**Table 12** (continued)

| GCM        | Month     | Scaling factor |
|------------|-----------|----------------|
| MRI-ESM2-0 | January   | 0.7206187      |
|            | February  | 1.30814816     |
|            | March     | 1.02545342     |
|            | April     | 1.1359144      |
|            | May       | 0.99439104     |
|            | June      | 0.42723313     |
|            | July      | 0.33827114     |
|            | August    | 1.14193029     |
|            | September | 2.88333704     |
|            | October   | 1.07790776     |
|            | November  | 1.18634685     |
|            | December  | 0.85862949     |

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**Author contributions** All authors contributed to the study conception and design. Adrián López-Ballesteros developed the SWAT+model used in the study and Jorrit P. Mesman developed and applied the GOTM-WET model used in the study. Inmaculada C. Jiménez-Navarro applied the SWAT+model and work with the GCMs. Javier Senent-Aparicio and Dennis Trolle supervised the development and application of the SWAT+model. Don Pierson supervised the development and results of the GOTM-WET model. The analysis of results was carried out by Inmaculada C. Jiménez-Navarro and supervised by all authors. The first draft of the manuscript was written by Inmaculada C. Jiménez-Navarro, with collaboration in the methodology of Adrián López-Ballesteros and Jorrit P. Mesman and all authors commented on previous versions of the manuscript. Javier Senent-Aparicio was the main supervisor and was responsible of the funding acquisition for the SMARTLAGOON and AGROALNEXT projects. All authors read, review and approved the final manuscript.

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**Data availability** The data that support the findings of this study are available on request from the corresponding author.

## Declarations

**Conflict of interest** The authors have no conflict of interest to declare that are relevant to the content of this article.

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## 5.6. SINTESIS DE RESULTADOS Y DISCUSIÓN

Los resultados obtenidos en esta tesis son diversos, por ello este apartado se subdivide de la siguiente forma. Por un lado, se van a presentar los resultados del desarrollo de los distintos modelos SWAT y WET, para probar así su validez. Por otro lado, se van a mostrar los resultados obtenidos de las predicciones realizadas en el lago Erken y el Mar Menor, tanto de clima como en la cuenca y en el lago/laguna. Por último, se presentarán brevemente los resultados más importantes obtenidos en las actividades de ciencia ciudadana.

### 5.6.1. Resultados de los modelos SWAT

#### 5.6.1.1. *Cuenca del Lago Erken*

Para la cuenca del lago Erken, se realizó una comparación de las calibraciones del modelo SWAT, además de desarrollar el modelo SWAT que se acoplaría posteriormente con el modelo WET. En este apartado, presentamos los resultados de ambas metodologías.

##### 5.6.1.1.1. *Comparación de calibraciones*

En este apartado se muestran los resultados obtenidos al calibrar el mismo modelo SWAT+ con datos de caudal (Q) (Escenario-Q), datos de ET (escenario ET) y ambos datos (Escenario Q-ET). Para ello se comparan primero los valores obtenidos de la calibración de parámetros en cada escenario (Tabla 4). Al observar la tabla vemos que algunos parámetros no muestran diferencias entre escenarios mientras que otros siguen una tendencia distinta según la variable con la que se calibre, siendo perco el ejemplo más notable.

En el escenario Q, la percolación del acuífero somero (perco) es elevada, mientras que el número de curva III (cn3\_swf) tiende a ser más bajo, revelando un suelo con menos capacidad de saturación. Además, presenta el número de curva (cn2) más alto, sugiriendo una menor permeabilidad del suelo. Todo esto resulta en menor retención de agua en el suelo y mayor escorrentía. En el escenario ET, los parámetros como perco, la conductividad hidráulica saturada (k), y el coeficiente de flujo lateral (latq\_co) asumen valores más bajos, lo que indica una menor resistencia al movimiento del agua en el suelo, una menor percolación y una

reducción en el flujo lateral. También se observa que el umbral de profundidad de agua necesaria en el acuífero poco profundo para que se produzca el retorno del agua (flo\_min) es insensible a la ET, mientras que el factor de compensación de absorción vegetal (epco) y el factor de compensación de la evaporación del suelo (esco) muestran valores consistentemente altos, reflejando el modelo captura bien los procesos de evapotranspiración. En el escenario Q-ET, perco muestra un aumento similar al del escenario Q. Este escenario también muestra una mayor retención de agua en el suelo, evidenciada por la mayor reducción en el número de curva (cn2) y un leve incremento en la capacidad de agua disponible (awc). La combinación de datos de ET y Q para calibrar parece proporcionar un modelo más equilibrado, representando tanto el escurrimiento como la evapotranspiración con precisión.

*Tabla 4. Valores finales, obtenidos por calibración, de los parámetros sensibles en Jiménez Navarro et al. (2024).*

|                  |            | Valor final de los parámetros calibrados |              |                |    |
|------------------|------------|------------------------------------------|--------------|----------------|----|
| Parámetros       | Cambio     | Escenario-Q                              | Escenario ET | Escenario Q-ET |    |
| <b>Epco</b>      | Absoluto   | 0.82                                     | 0.99         | 0.99           | ET |
| <b>Esco</b>      | Absoluto   | 0.84                                     | 0.99         | 0.99           |    |
| <b>cn3_swf</b>   | Absoluto   | 0.63                                     | 0.99         | 0.99           |    |
| <b>Bd</b>        | Porcentaje | 10.18                                    | 19.77        | 18.50          |    |
| <b>cn2</b>       | Porcentaje | -11.34                                   | -16.10       | -19.35         | Q  |
| <b>Canmx</b>     | Porcentaje | 19.38                                    | 19.61        | 13.48          |    |
| <b>Awc</b>       | Porcentaje | -18.82                                   | -14.54       | 4.60           |    |
| <b>K</b>         | Porcentaje | 5.62                                     | -8.79        | -0.62          |    |
| <b>latq_co</b>   | Absoluto   | 0.97                                     | 0.22         | 0.84           |    |
| <b>Perco</b>     | Porcentaje | 19.16                                    | -19.16       | 18.54          |    |
| <b>Lat_ttime</b> | Absoluto   | 10.07                                    | -            | 6.03           |    |
| <b>flo_min</b>   | Relativo   | 0.13                                     | -            | 3.94           |    |
| <b>revap_min</b> | Relativo   | -3.85                                    | -            | 34.86          |    |
| <b>Alpha</b>     | Absoluto   | 0.30                                     | -            | 0.98           |    |
| <b>Chn</b>       | Absoluto   | 0.17                                     | -            | 0.19           |    |
| <b>revap_co</b>  | Absoluto   | 0.05                                     | -            | 0.06           |    |

Nota: Los guiones indican parámetros sin calibrar debido a su falta de sensibilidad en análisis previos.

En cuanto a la fiabilidad de cada calibración, se muestra en la Tabla 5 mediante estadísticos. La mayoría de los escenarios analizados muestran resultados estadísticamente aceptables, pero hay dos excepciones importantes. El escenario predeterminado, que utiliza los valores de los parámetros sin calibrar proporcionados por el modelo, presenta un mal rendimiento en las estadísticas relacionadas con el caudal, con un NSE inferior a 0.5 y un bajo  $R^2$ . Sin embargo, los valores de PBIAS en este escenario son muy satisfactorios, lo que sugiere que el modelo predice bien la cantidad total de agua, aunque tiene dificultades para distribuirla correctamente en el tiempo. El segundo problema se encuentra en los valores de PBIAS observados en todas las simulaciones de ET. Ninguno de los escenarios, ni siquiera el de ET, logra valores satisfactorios. A pesar de estas deficiencias, el rendimiento general del modelo es aceptable en todos los escenarios.

En el escenario predeterminado, la simulación del caudal no es estadísticamente aceptable. Sin embargo, la simulación de ET es sorprendentemente precisa, probablemente debido a las condiciones específicas del Lago Erken y su cuenca. En el escenario Q, las métricas estadísticas muestran resultados muy satisfactorios para el caudal, y la simulación mejora la ET en comparación con el escenario predeterminado. En líneas generales, la calibración con datos de caudal mejora significativamente el rendimiento del modelo. El escenario ET ofrece la simulación más precisa de la evapotranspiración, como era de esperar. Aunque la simulación del caudal en este escenario es un poco menos precisa, sigue siendo satisfactoria. Los resultados indican que, al calibrar con una sola variable, ya sea caudal o ET, el modelo funciona bien para esa variable, pero su rendimiento disminuye para la otra. En el escenario Q-ET, se logran buenos resultados tanto para el caudal como para la ET, con valores que se sitúan entre los de los escenarios Q y ET. La simulación del caudal es menos precisa que en el escenario Q, pero mejora respecto al escenario ET, a excepción del PBIAS, que muestra una sobreestimación del agua. Del mismo modo, la ET simulada es menos precisa que en el escenario ET, pero mejora respecto al escenario Q.

Un hallazgo clave del estudio es la robustez del modelo SWAT+ cuando se calibra solo con datos de evapotranspiración en el escenario ET. Las diferencias entre las simulaciones de evapotranspiración y caudal en los tres escenarios calibrados son mínimas, lo que sugiere que la calibración con datos de



evapotranspiración por teledetección es una opción viable, como también indican otros estudios (Parajuli et al., 2018; Sirisena et al., 2020; Odusanya et al., 2021).

*Tabla 5. Evaluación de la simulación mensual del caudal (Q) ( $m^3/s$ ) y la evapotranspiración (ET) (mm) para cada escenario de SWAT+ durante el período de calibración (2007-2016) y el período de validación (2017-2021) en Jiménez-Navarro et al. (2024).*

| Escenario                                       | Estadísticos         | Q                      |                       | ET                     |                       |
|-------------------------------------------------|----------------------|------------------------|-----------------------|------------------------|-----------------------|
|                                                 |                      | Periodo de calibración | Periodo de validación | Periodo de calibración | Periodo de validación |
| <b>Escenario predeterminado</b><br>Sin calibrar | <b>R<sup>2</sup></b> | 0.41                   | 0.40                  | 0.93                   | 0.89                  |
|                                                 | <b>NSE</b>           | 0.40                   | 0.40                  | 0.76                   | 0.73                  |
|                                                 | <b>PBIAS</b>         | -3.66                  | -5.52                 | 30.42                  | 31.66                 |
| <b>Escenario Q</b>                              | <b>R<sup>2</sup></b> | 0.78                   | 0.80                  | 0.92                   | 0.90                  |
|                                                 | <b>NSE</b>           | 0.77                   | 0.78                  | 0.79                   | 0.76                  |
|                                                 | <b>PBIAS</b>         | -2.20                  | -3.92                 | 27.42                  | 29.47                 |
| <b>Escenario ET</b>                             | <b>R<sup>2</sup></b> | 0.68                   | 0.57                  | 0.91                   | 0.89                  |
|                                                 | <b>NSE</b>           | 0.63                   | 0.62                  | 0.81                   | 0.78                  |
|                                                 | <b>PBIAS</b>         | 12.62                  | 11.92                 | 23.96                  | 26.59                 |
| <b>Escenario Q-ET</b>                           | <b>R<sup>2</sup></b> | 0.76                   | 0.72                  | 0.91                   | 0.89                  |
|                                                 | <b>NSE</b>           | 0.74                   | 0.73                  | 0.81                   | 0.77                  |
|                                                 | <b>PBIAS</b>         | 14.16                  | 14.66                 | 25.18                  | 27.24                 |

#### 5.6.1.1.2. Modelo final

A la hora de desarrollar el modelo SWAT+ para ser calibrado con WET en la cuenca del lago Erken, primero se realizó un análisis de sensibilidad. De esta forma obtuvimos 10 parámetros sensibles que fueron calibrados para obtener su valor óptimo (Tabla 6).

*Tabla 6. Valores ajustados de los parámetros calibrados para SWAT+ en Jiménez-Navarro et al. (2023).*

| Parámetro                    | Cambio     | Valor ajustado |
|------------------------------|------------|----------------|
| <b>Número de curva (cn2)</b> | Porcentaje | -19.44         |
| <b>Alpha</b>                 | Absoluto   | 0.18           |
| <b>Latq_co</b>               | Absoluto   | 0.72           |
| <b>Perco</b>                 | Relativo   | -0.06          |
| <b>Cn3_swf</b>               | Absoluto   | 0.57           |

|                  |            |        |
|------------------|------------|--------|
| <b>Awc</b>       | Porcentaje | -17.31 |
| <b>Flo_min</b>   | Relativo   | 420.18 |
| <b>Revap_min</b> | Relativo   | 31.02  |
| <b>Latt_time</b> | Absoluto   | 9.26   |
| <b>Revap_co</b>  | Absoluto   | 0.20   |

Después de ajustar los valores de los parámetros el modelo mostró un buen rendimiento en la calibración y validación, con NSE y  $R^2$  superiores a 0.6 y un PBIAS cercano a 0 (Fig. 5). Los estadísticos NSE y  $R^2$  mejoraron en el período de validación, posiblemente debido a la menor cantidad de eventos extremos en ese periodo. El modelo simula el caudal de forma realista, aunque tiende a subestimar los picos de caudal en eventos extremos, lo cual ya se había observado en estudios anteriores con SWAT+, a pesar de que el rendimiento general del modelo es satisfactorio (Bailey et al., 2020; Pulighe et al., 2021; Llanos-Paez et al., 2022).

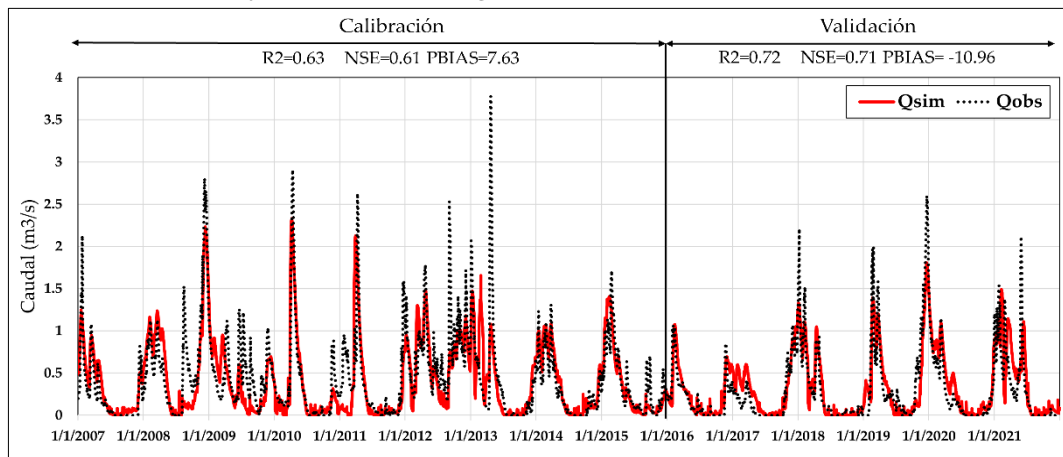


Figura 5. Caudal observado y simulado en la cuenca del Lago Erken para el periodo de calibración y validación en Jiménez-Navarro et al. (2023).

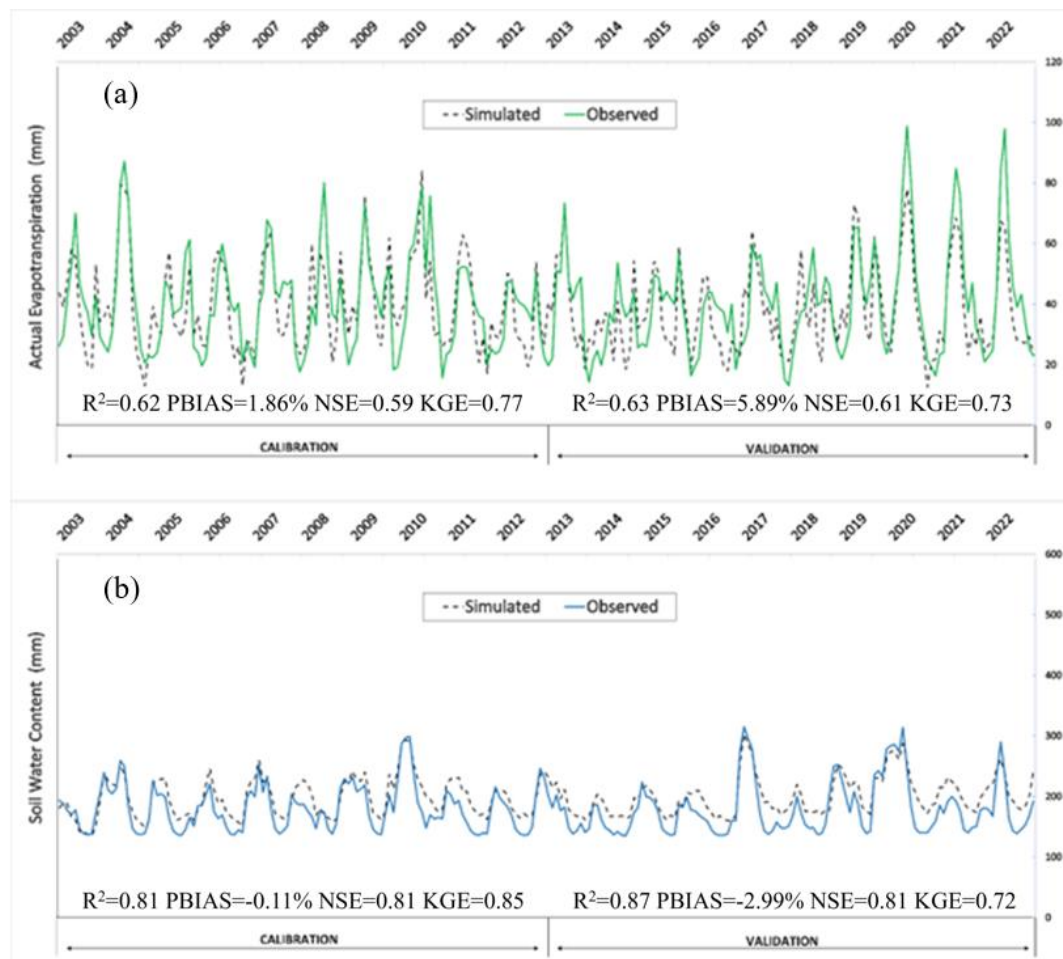
#### 5.6.1.2. Campo de Cartagena

Antes de calibrar el modelo, se realizó un análisis de sensibilidad utilizando el software SWATplus-CUP. Dos parámetros relacionados con las condiciones de porosidad del suelo mostraron una sensibilidad significativa: perco y la densidad aparente húmeda (bd). Además, se seleccionaron cuatro parámetros adicionales de SWAT+ (cn2, esco, epco y awc) para la calibración del modelo del Campo de Cartagena, basándose en experiencias previas de modelización en la zona de estudio (López-Ballesteros, Trolle et al., 2023). De esta forma seis parámetros en total fueron calibrados para el modelo SWAT+ del Campo de Cartagena (Tabla 7).

*Tabla 7. Valores ajustados de los parámetros calibrados para SWAT+ en Jiménez-Navarro, López-Ballesteros et al. (under review).*

| Parámetro             | Cambio     | Valor ajustado |
|-----------------------|------------|----------------|
| Número de curva (cn2) | Porcentaje | +6.31          |
| esco                  | Absoluto   | 0.47           |
| epco                  | Absoluto   | 0.25           |
| awc                   | Porcentaje | +13.25         |
| bd                    | Porcentaje | +6.72          |
| perco                 | Absoluto   | 0.96           |

El modelo SWAT+ del Campo de Cartagena simula con precisión las tendencias generales y magnitudes tanto de la ET como del SWC (Figura 6), siendo



*Figura 6. ET y SWC observado y simulado en el Campo de Cartagena para el periodo de calibración y validación en Jiménez-Navarro, López-Ballesteros et al. (under review).*

estadísticamente aceptable al analizar la ET y el SWC simulados. Los valores de  $R^2$  para la ET revelan dificultades para simular esta variable en esta área de riego intensivo. Sin embargo, al simular las prácticas agrícolas locales, se logró una buena estimación de la magnitud total de la ET (con un PBIAS cercano a 0) y un rendimiento general sólido (NSE superior a 0.5). En cuanto al SWC, el modelo SWAT+ logró simular con precisión tanto las tendencias como la magnitud total, con valores de PBIAS cercanos a 0% y  $R^2$  superiores a 0.8. En conjunto, el modelo SWAT+ demostró un buen rendimiento en la simulación del balance hídrico del Campo de Cartagena.

### 5.6.2. Resultados de los modelos WET

A continuación, se presenta la validez de los modelos WET acoplados con SWAT+ en el Lago Erken y en el Mar Menor.

#### 5.6.2.1. Lago Erken

El modelo GOTM-WET simuló satisfactoriamente la temperatura del agua, oxígeno, nitratos, fosfatos y clorofila (Tabla 8, Fig.7). Aunque el modelo tiende a subestimar los nutrientes en invierno, si reproduce adecuadamente la disminución de oxígeno durante el verano y el pico de clorofila en primavera. Sin embargo, la precisión disminuye en el período de validación, principalmente debido a una floración de fitoplancton en el verano de 2019 que el modelo no replicó y a desajustes de 2-3 semanas en el tiempo de la floración primaveral. A pesar de esto, las simulaciones son aceptables.

*Tabla 8. Evaluación del rendimiento del modelo GOTM-WET durante los períodos de calibración (2000-2015) y validación (2016-2021) en Jiménez-Navarro et al. (2023).*

| Variable                  | Profundidad (m) | Calibración |       | Validación |       |
|---------------------------|-----------------|-------------|-------|------------|-------|
|                           |                 | RMSE        | $R^2$ | RMSE       | $R^2$ |
| Temperatura del agua (°C) | 3               | 0.80        | 0.99  | 0.69       | 0.99  |
| Oxígeno (mg/l)            | 15              | 2.07        | 0.77  | 2.08       | 0.79  |
| Nitrato (mg/l)            | 3               | 0.04        | 0.64  | 0.05       | 0.48  |
| Fosfato (mg/l)            | 3               | 0.01        | 0.41  | 0.01       | 0.29  |

|                                  |   |      |      |      |      |
|----------------------------------|---|------|------|------|------|
| Clorofila-a (mg/m <sup>3</sup> ) | 3 | 4.89 | 0.35 | 6.81 | 0.16 |
|----------------------------------|---|------|------|------|------|

Durante la calibración, la mayoría de los parámetros se mantuvieron cerca de sus valores iniciales, con algunas excepciones, como un aumento significativo en la profundidad de extinción de la luz y una disminución en la constante de semisaturación lumínica para el crecimiento de diatomeas, lo que indica dificultades en la reproducción del pico primaveral bajo condiciones de mezcla del agua. Además, se ajustó el factor de escala de la velocidad del viento, ya que el modelo subestimaba la mezcla de las capas de agua al usar promedios diarios de velocidad del viento, un factor crucial para una representación precisa de este proceso.

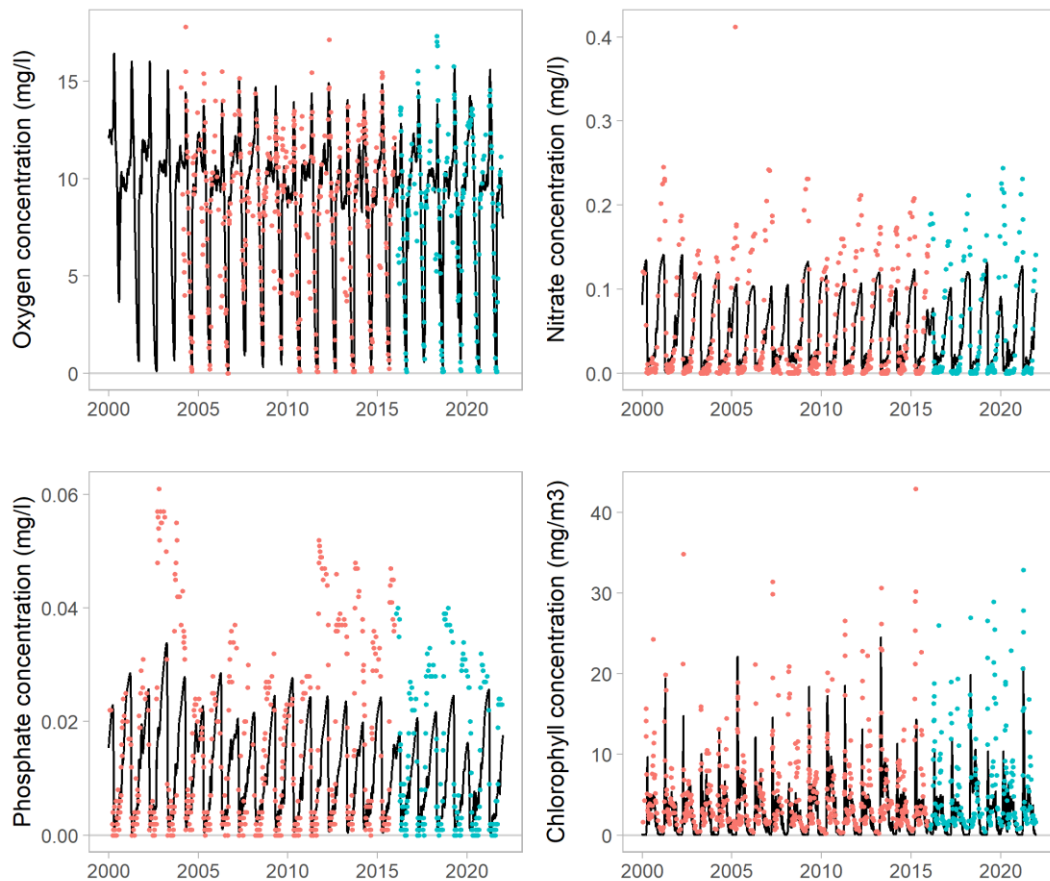


Figura 7. Concentraciones de oxígeno (mg/l, a 15 m de profundidad), nitrato (mg/l, a 3 m de profundidad), fosfato (mg/l, a 3 m de profundidad) y clorofila (mg/m<sup>3</sup>, a 3 m de profundidad) simuladas por GOTM-WET (línea negra) en comparación con las observaciones (puntos). Los puntos rojos indican el periodo de calibración y los puntos azules el periodo de validación. Extraído de Jiménez-Navarro et al. (2023)



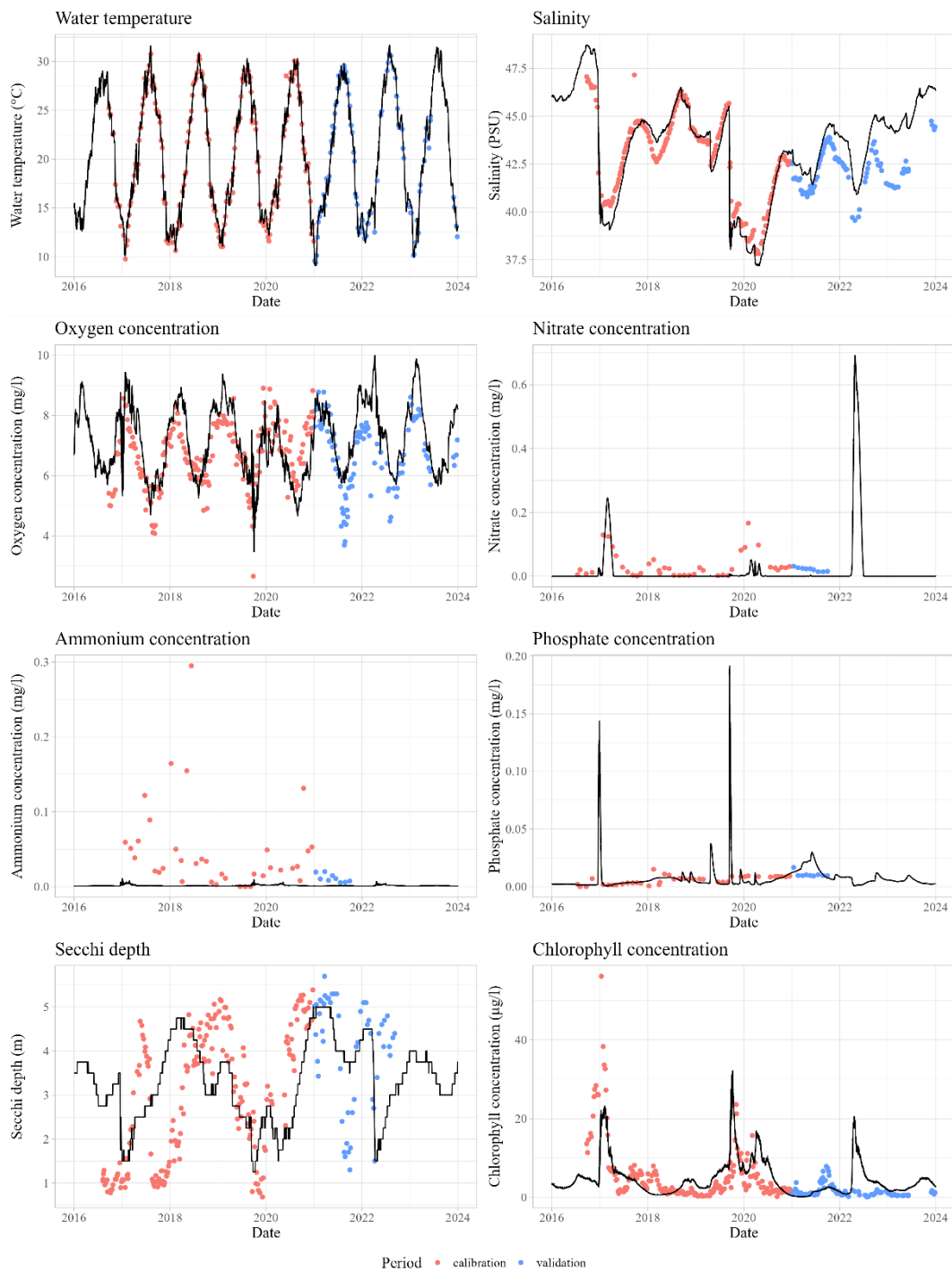
### 5.6.2.2. *Mar Menor*

El modelo GOTM-WET reproduce correctamente las tendencias en temperatura, salinidad, oxígeno, nitrato, fosfato y clorofila durante el período de calibración (Tabla 9, Fig. 8). Durante la validación, la mayoría de variables también muestran un buen ajuste, aunque la salinidad, clorofila y fosfato muestran algunos comportamientos inesperados. Mientras que temperatura y oxígeno muestran ciclos estacionales claros, salinidad, nutrientes, profundidad de Secchi y clorofila son más influenciados por eventos esporádicos, como las entradas de agua.

*Tabla 9. Evaluación del rendimiento del modelo GOTM-WET durante los períodos de calibración (2016-2020) y validación (2021-2023) en Jiménez-Navarro, López-Ballesteros et al. (under review).*

| Variable                         | Calibración |                | Validación |                |
|----------------------------------|-------------|----------------|------------|----------------|
|                                  | RMSE        | R <sup>2</sup> | RMSE       | R <sup>2</sup> |
| <b>Temperatura del agua (°C)</b> | 0.520       | 0.994          | 0.403      | 0.996          |
| <b>Salinidad (PSU)</b>           | 0.818       | 0.948          | 1.662      | 0.538          |
| <b>Oxígeno (mg/l)</b>            | 0.924       | 0.455          | 1.082      | 0.680          |
| <b>Nitrato (mg/l)</b>            | 0.046       | 0.257          | 0.022      | 0.006          |
| <b>Amonio (mg/l)</b>             | 0.075       | 0.011          | 0.012      | 0.484          |
| <b>Fosfato (mg/l)</b>            | 0.004       | 0.219          | 0.009      | 0.072          |
| <b>Profundidad de Secchi (m)</b> | 1.518       | 0.084          | 1.274      | 0.120          |
| <b>Clorofila-a (µg/l)</b>        | 6.387       | 0.225          | 2.837      | 0.001          |

Aunque estadísticamente el modelo resulta satisfactorio, posee algunas deficiencias. Durante la validación, la salinidad se desvió de las observaciones, lo que sugiere errores en los parámetros de evaporación o intercambio con el mar. Algunos eventos de hipoxia y turbidez fueron capturados, pero otros no. Por ejemplo, en 2021, el modelo acertó en el tiempo de disminución del oxígeno y la profundidad de Secchi y en el aumento de clorofila, pero la intensidad fue demasiado baja. Las concentraciones de nitrato y fosfato fueron generalmente bajas, salvo después de eventos extremos. Aunque los picos de nitrato coincidieron moderadamente con las observaciones, los picos de fosfato fueron difíciles de evaluar debido al momento de las mediciones. En resumen, el modelo captura las tendencias a largo plazo y el impacto de los eventos, aunque puede pasar por alto o subestimar algunos eventos y simula mejor algunas variables (como temperatura y clorofila) que otras.



**Figura 8.** Comparación entre la simulación del modelo GOTM-WET (líneas negras) y las observaciones (puntos; rojo = calibración, azul = validación) para la temperatura del agua, salinidad, oxígeno, nitrato, amonio, fosfato, profundidad de Secchi y clorofila en Jiménez-Navarro, López-Ballesteros et al. (under review). Todos los valores se obtienen a una profundidad de 3.5 m.

### 5.6.3. Predicciones en el lago Erken

Se han obtenido estimaciones de cómo evolucionará el clima en la cuenca del lago Erken utilizando los GCMs, y cómo esto va a afectar a las variables hidrológicas de la cuenca y a las condiciones del agua del lago en el futuro. Las predicciones abarcan dos periodos de futuro en dos escenarios climáticos distintos, tal y como se explica en la sección 4.4.

#### 5.6.3.1. Predicción del clima

El mayor cambio que se aprecia en el clima de la cuenca del lago Erken es el incremento de la precipitación y la temperatura. Se espera que el incremento de ambas sea progresivo, aunque más exponencial en el escenario SSP 5-85. La tendencia general de la temperatura es un aumento de entre 3.1 y 4.6 °C para finales de siglo; mientras que para la precipitación el incremento será de entre 13 y 24% (Tabla 10).

*Tabla 10. Media anual de la precipitación y la temperatura en la cuenca del Lago Erken para cada periodo analizado en Jiménez-Navarro et al. (2023).*

|                 |           | Prec (mm) | Temp (°C) |
|-----------------|-----------|-----------|-----------|
| <b>Hist</b>     | Histórico | 564.9     | 6.6       |
| <b>SSP 2-45</b> | 2040–2069 | 618       | 9.1       |
|                 | 2070–2099 | 637.6     | 9.7       |
| <b>SSP 5-85</b> | 2040–2069 | 657.9     | 9.5       |
|                 | 2070–2099 | 700       | 11.2      |

En cuanto a la estacionalidad de la temperatura, parece que no se alterará de manera marcada, ya que los meses más fríos y los más cálidos seguirán siendo los mismos a lo largo del siglo (Fig. 9). Sin embargo, el aumento de la temperatura media es especialmente alarmante en los meses fríos, donde la temperatura promedio actual está cerca de 0 °C. En este contexto, un aumento en diciembre, enero y febrero podría tener consecuencias en el ciclo hidrológico debido al papel de la nieve y el hielo en esta cuenca (Jiménez-Navarro et al., 2021).

Sin embargo, además del aumento esperado para la precipitación, también se notará un cambio en la estacionalidad (Fig. 10). De marzo a agosto, el incremento en la precipitación no será muy significativo, pero de septiembre a febrero, el

aumento será más marcado, especialmente en octubre, noviembre, diciembre y enero.

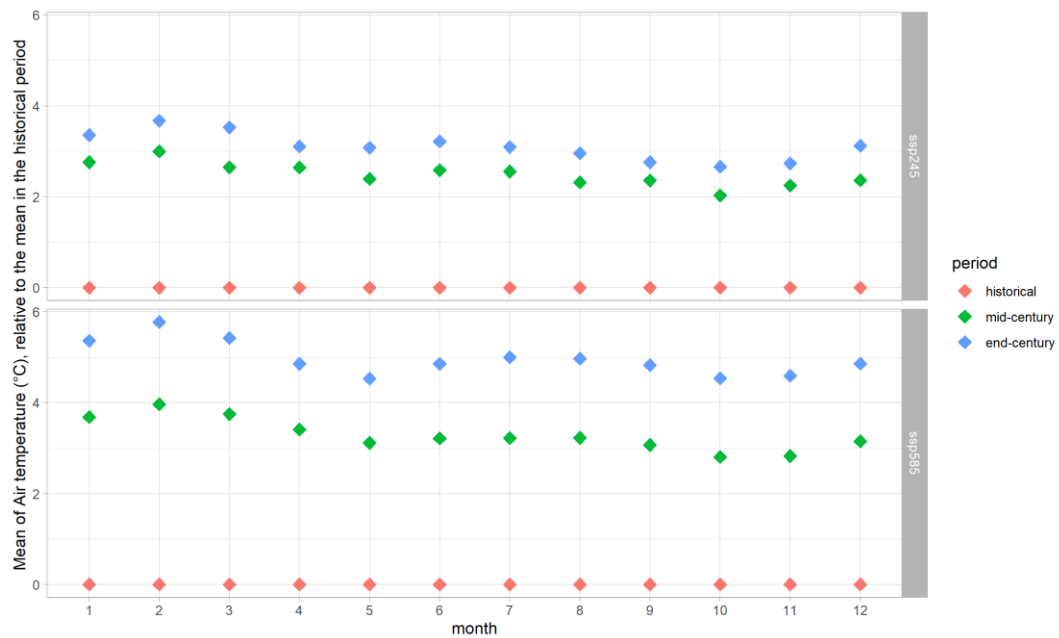


Figura 9. Distribución anual de la temperatura en el futuro con respecto al periodo histórico en la cuenca del lago Erken. Extraído de Jiménez-Navarro et al. (2023).

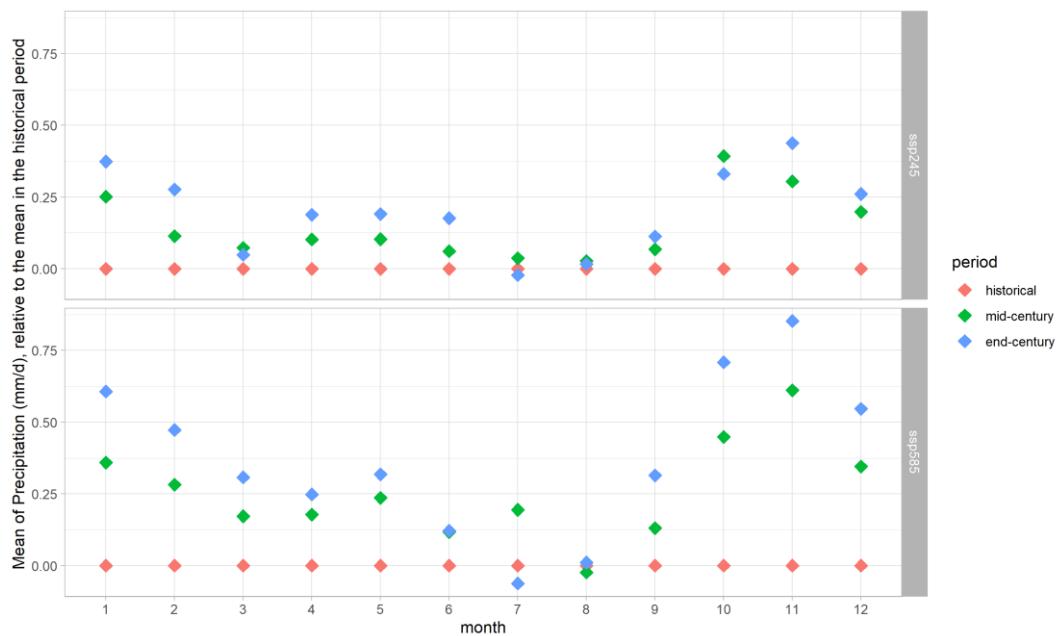
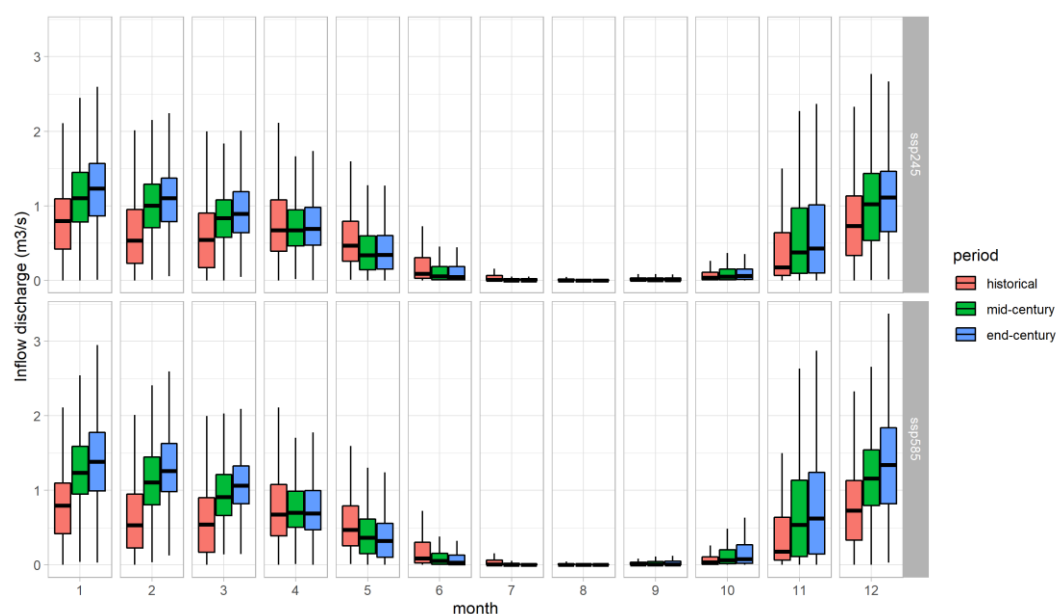


Figura 10. Distribución anual de la precipitación en el futuro con respecto al periodo histórico en la cuenca del lago Erken. Extraído de Jiménez-Navarro et al. (2023).

El aumento proyectado de temperatura concuerda con las conclusiones obtenidas en otros estudios sobre el cambio climático a nivel global (Wuebbles et al., 2017) y a nivel nacional (Lind y Kjellström, 2008). De manera similar, el aumento de la precipitación es una consecuencia esperada del cambio climático en el norte de Europa (Jacob et al., 2014; Strandberg et al., 2015).

### 5.6.3.2. Predicción de la cuenca y el lago

Considerando los cinco GCM analizados, como consecuencia del cambio climático, el caudal de entrada aumentará significativamente en el lago Erken (Fig. 11). Este aumento sería más gradual en el escenario SSP 2-45, y más pronunciado en el escenario SSP 5-85, lo que ofrecerá menos margen para mitigar sus efectos. En ambos escenarios, el incremento será lo suficientemente notable como para impactar las actividades humanas en la cuenca del lago.



**Figura 11.** Distribución mensual del caudal de entrada en el lago Erken durante el periodo histórico (1985-2014) y los periodos futuros de mediados de siglo (2040-2069) y finales de siglo (2070-2099). Extraído de Jiménez-Navarro et al. (2023).

Este fenómeno está relacionado con el aumento de la precipitación y su estacionalidad. Durante los meses cálidos (mayo a agosto), el caudal se mantendrá en niveles similares a los del período histórico o incluso podría disminuir en mayo



y junio. Sin embargo, en el resto del año, especialmente en diciembre, enero y febrero, el caudal aumentará notablemente. Esto también puede asociarse con el aumento de las temperaturas durante esos meses. A medida que la temperatura promedio supere los 0 °C, el agua de la precipitación no se retendrá como nieve en la cuenca, lo que intensificará la entrada de agua al lago durante el invierno.

En cuanto a la estimación de las condiciones del agua en los escenarios futuros (Fig. 12), se prevé un aumento significativo en las temperaturas del agua en el lago Erken, con diferencias de hasta 6 °C en la superficie y 2.5 °C en las aguas profundas. Este aumento está asociado con una mayor duración y fuerza de la estratificación térmica. La cobertura de hielo disminuiría, y en algunos escenarios, podría llegar a desaparecer al final del siglo.

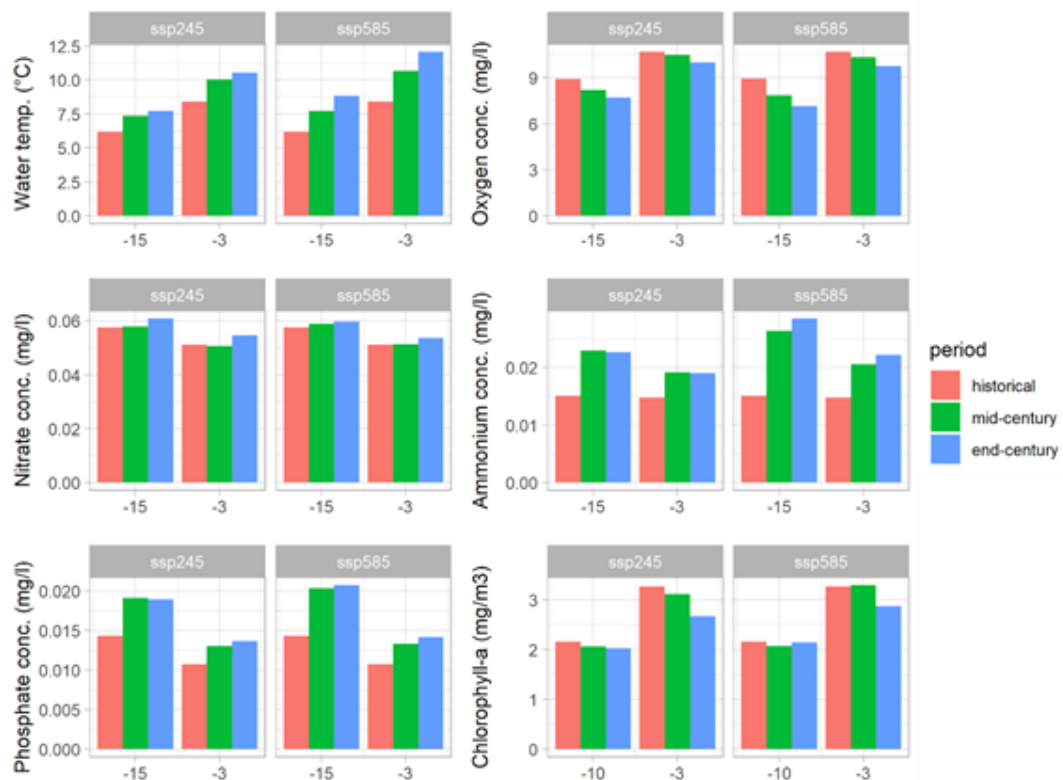


Figura 12. Valores medios de temperatura del agua y concentraciones de oxígeno, nitrato, amonio, fosfato y clorofila-a para diferentes profundidades, escenarios y periodos (histórico 1985-2014, mediados de siglo 2040-2069, finales de siglo 2070-2099).

El oxígeno en el agua disminuirá, especialmente a 15 m de profundidad, debido a la menor solubilidad a temperaturas más altas y a la mayor duración de

la estratificación, lo que lleva a una mayor prevalencia de anoxia en las aguas profundas. Las concentraciones de nitrato tienden a permanecer constantes, mientras que los niveles de amonio y fosfato aumentan. Sin embargo, hacia el final del siglo, el nitrato comienza a aumentar y el amonio y el fosfato se estancan o disminuyen. El aumento de nutrientes puede estar relacionado con una mayor carga de nutrientes o con el período prolongado de estratificación. La clorofila en el lago muestra una tendencia estable o ligeramente creciente; aunque a largo plazo se observa una disminución de la clorofila profunda.

#### **5.6.4. Predicciones en el Mar Menor**

De igual forma que en el lago Erken, se han obtenido estimaciones de cómo evolucionará el clima en el Campo de Cartagena y el Mar Menor utilizando los GCMs, y cómo esto va a afectar a las variables hidrológicas de la cuenca y a las condiciones del agua del lago en el futuro. Las predicciones abarcan dos periodos de futuro en dos escenarios climáticos distintos, como se explica en la sección 4.4.

##### *5.6.4.1. Predicción del clima*

El estudio del Campo de Cartagena con cinco GCMs indica que la temperatura general aumentará con el tiempo, especialmente en el escenario más severo (SSP 5-85), aumentando hasta 3.84 °C en el futuro lejano (Tabla 11). Este aumento, junto con la disminución de la precipitación, es preocupante porque podría llevar a la desertificación de la región (Huang et al., 2020). La disminución de la precipitación en esta área también es de esperar (Tabla 4), pudiendo alcanzar una disminución del -19% en el futuro lejano bajo el escenario más agresivo (SSP 5-85). Además, aunque la precipitación total disminuye, algunos modelos indican un aumento en la intensidad de las lluvias torrenciales. Esto se analizó considerando el número de días en cada período en los que la precipitación supera los 50 mm, el umbral sugerido por la Organización Meteorológica Mundial para definir lluvias extremas (Organización Meteorológica Mundial, 2008). La mayor parte del aumento en la intensidad se proyecta para el futuro lejano, aunque varía entre los escenarios SSP 2-45 y SSP 5-85. Es decir, se espera un incremento en la intensidad de las lluvias torrenciales en el futuro, con variaciones en el momento y la magnitud de este aumento.

*Tabla 11. Media anual de la precipitación y la temperatura y número de días con eventos extremos de precipitación en el Campo de Cartagena en los distintos periodos analizados en Jiménez-Navarro, López-Ballesteros et al. (under review).*

|                   | Temp (°C) | $\Delta$ Temp (°C) | Pcp (mm) | $\Delta$ Pcp (%) | Extreme days |
|-------------------|-----------|--------------------|----------|------------------|--------------|
| <b>Hist</b>       | 18.49     | -                  | 272.74   | -                | 2            |
| <b>SSP 2-45 M</b> | 20.17     | 1.69               | 260.45   | -4.5%            | 2            |
| <b>SSP 2-45 F</b> | 20.55     | 2.06               | 261.24   | -4.2%            | 3            |
| <b>SSP 5-85 M</b> | 21.03     | 2.54               | 254.15   | -6.8%            | 4            |
| <b>SSP 5-85 F</b> | 22.32     | 3.83               | 220.78   | -19.1%           | 4            |

#### 5.6.4.2. *Predicción de los SER en la cuenca*

Al analizar los GCMs para predecir las variables hidrológicas de la cuenca, se observan variaciones notables entre los escenarios, especialmente hacia finales de siglo (Fig. 13). Se aprecia una tendencia a la disminución de la disponibilidad de agua en el Campo de Cartagena, tanto para las plantas como para las personas, con una reducción significativa del BW, que incluye el caudal y la recarga del acuífero, y del GW, relacionada con la evapotranspiración y el contenido de agua en el suelo. También se espera una disminución en la entrada de agua a la laguna, aunque menos pronunciada. En los escenarios analizados, se prevé que el BW disminuya entre un 19% y un 43% para finales de siglo, mientras que la reducción en la entrada de agua sería de entre un 6% y un 24%, ambas debidas a la disminución de la precipitación en la cuenca. Esta diferencia podría estar relacionada con un aumento en la escorrentía debido al incremento de eventos torrenciales, lo que también provocaría un aumento en la producción de sedimentos y fósforo por erosión, que terminarían entrando en la laguna. Por otro lado, se observa una disminución en el aporte de nitrógeno, probablemente vinculada a la reducción en la recarga del acuífero, ya que el nitrógeno proviene principalmente de este. La disminución en la recarga del acuífero y la disponibilidad de agua (GW y BW) podría afectar gravemente la agricultura de riego en la zona. Todas estas predicciones anticipan una reducción en los servicios ecosistémicos relacionados con el agua, la protección contra riesgos naturales y la regulación de nutrientes.

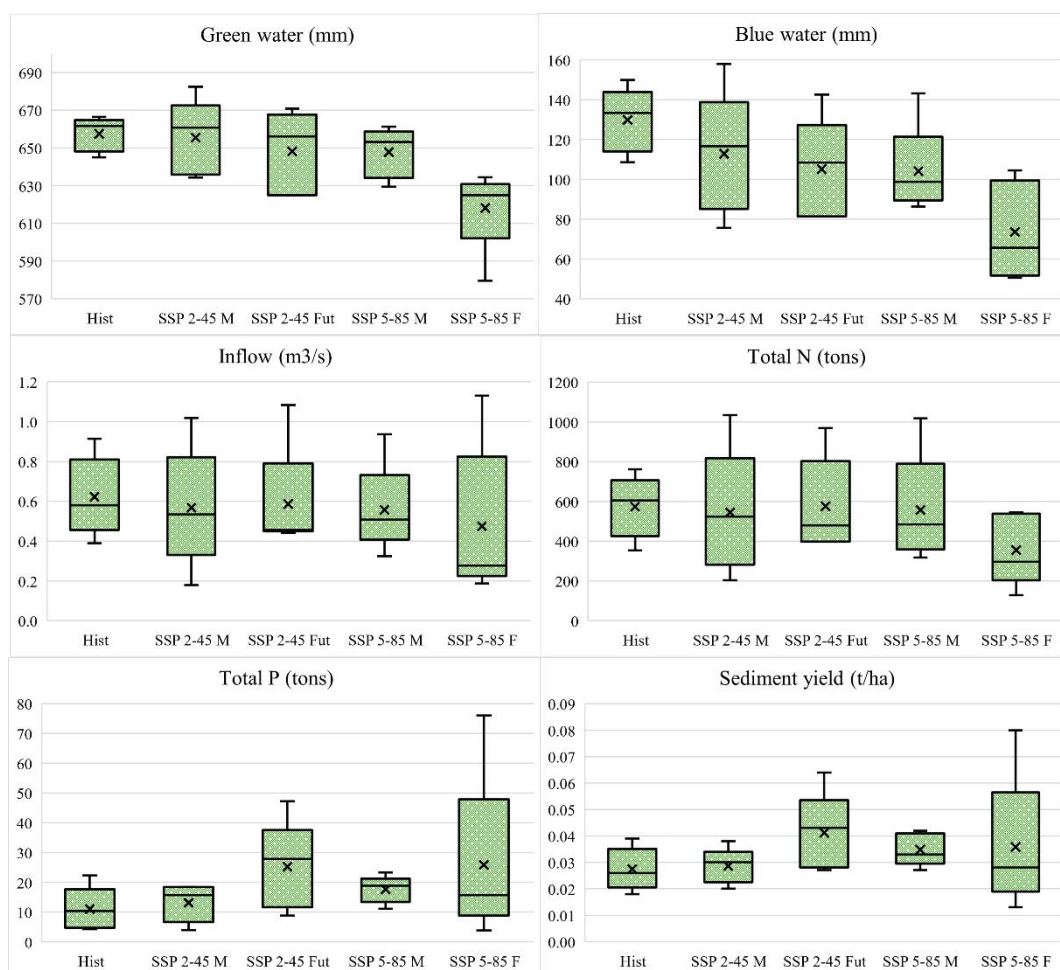
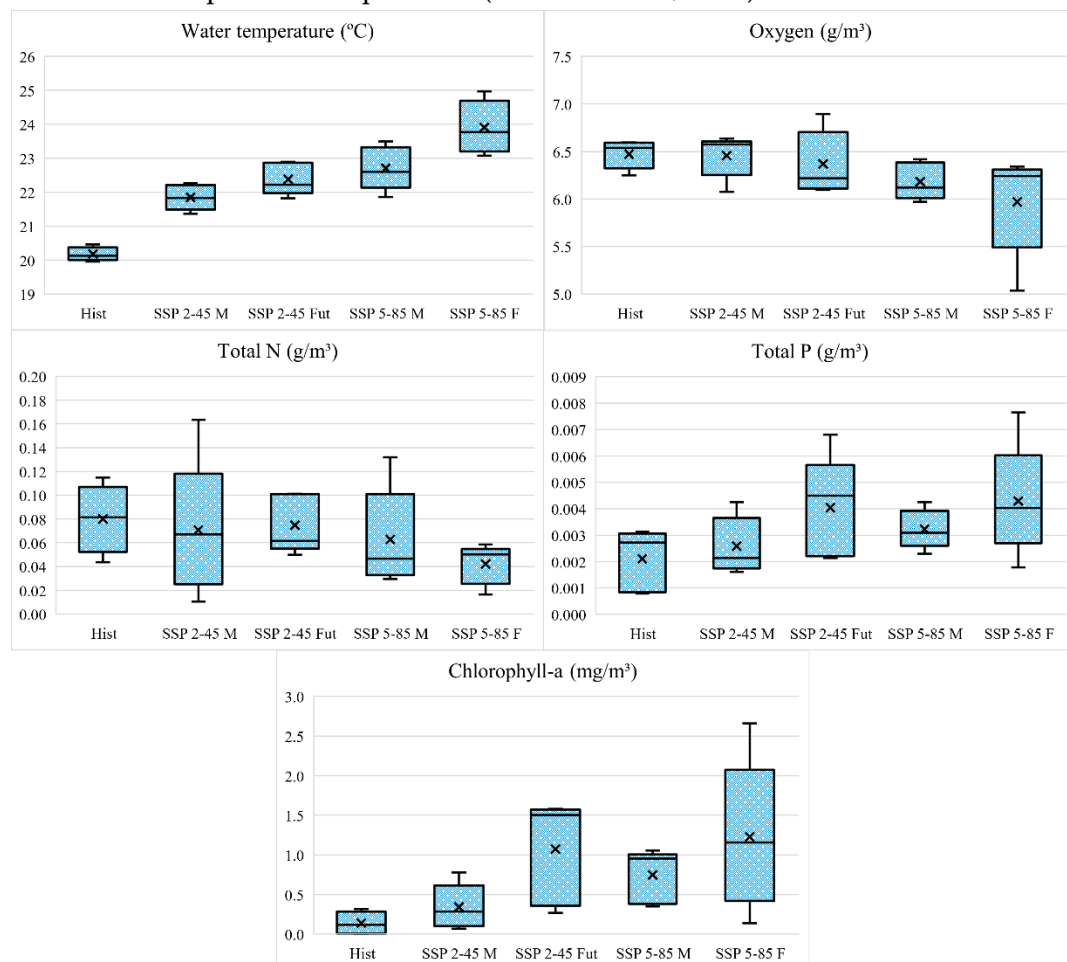


Figura 13. Predicciones de los GCMs de las variables hidrológicas medias anuales que afectan a los RES del Campo de Cartagena para cada periodo y escenario simulado en Jiménez-Navarro, López-Ballesteros et al. (under review).

#### 5.6.4.3. Predicción de los SER en la laguna

El Mar Menor experimentará cambios significativos en sus condiciones bióticas y abióticas en el futuro debido al cambio climático (Fig. 14). Se espera un aumento progresivo de la temperatura del agua, especialmente en el escenario climático más severo (SSP 5-85), impulsado por el aumento de la temperatura atmosférica en la cuenca. Las concentraciones de nutrientes, como fósforo y nitrógeno, también se verán afectadas. Se espera que la concentración de fósforo aumente, en parte debido al mayor aporte de fósforo por escorrentía en el Campo de Cartagena, con predicciones similares para los escenarios SSP 2-45 y SSP 5-85. A

finales de siglo, se proyecta que la concentración de fósforo se duplique, pasando de  $0.002 \text{ g/m}^3$  a  $0.004 \text{ g/m}^3$ . En contraste, la concentración de nitrógeno disminuirá significativamente debido a la reducción del aporte de nitratos desde el acuífero y posiblemente a cambios en el ciclo biogeoquímico de la laguna. A pesar de la disminución del nitrógeno, los niveles de clorofila-a, un indicador de la concentración de fitoplancton y, por tanto, de la producción primaria, se espera que aumenten en ambos escenarios de cambio climático. Esto podría parecer contradictorio, ya que menos nitrógeno debería llevar a una menor producción primaria, pero el aumento de fosfato y la intensificación del ciclo interno de nutrientes con temperaturas más altas pueden compensar este efecto y, de hecho, incrementar la producción primaria (Kraemer et al., 2017).



*Figura 14. Predicciones de los GCMs sobre las condiciones medias anuales del agua en la laguna del Mar Menor para cada periodo y escenario simulado en Jiménez-Navarro, López-Ballesteros et al. (under review).*



Se espera que la concentración de oxígeno en la laguna disminuya, en gran parte debido a la menor solubilidad del oxígeno a temperaturas más altas. Esto podría provocar un aumento en los eventos de hipoxia, donde el nivel de oxígeno baja a menos de 2 g/m<sup>3</sup> (según la Administración Nacional Oceánica y Atmosférica <https://oceanservice.noaa.gov/hazards/hypoxia/>). A medida que los niveles de oxígeno disminuyen y los periodos de estratificación se vuelven más frecuentes debido al calentamiento y eventos extremos, los episodios de hipoxia también se incrementarán, especialmente en el escenario SSP 5-85 (Tabla 12). Además, se proyecta que las floraciones algales, indicadas por concentraciones de clorofila-a superiores a 10 mg/m<sup>3</sup> (límite establecido por la normativa española para condiciones favorables en lagunas costeras poco profundas (Soria y Sahuquillo, 2009)), aumenten en el futuro bajo ambos escenarios (SSP 2-45 y SSP 5-85). Aunque el aumento en los días con alta clorofila-a es notable, se debe en gran parte a unos pocos eventos prolongados. Ocasionalmente, los niveles bajos de oxígeno coinciden con altas concentraciones de clorofila-a, aunque esta correlación es inconsistente. A pesar de la inconsistencia, este fenómeno se ha observado en el Mar Menor durante varios años, incluyendo los episodios de 2017 y 2019.

*Tabla 12. Número de días de cada período en los que se prevén condiciones extremas: concentración de clorofila-a superior a 10 mg/m<sup>3</sup> y concentración de oxígeno inferior a 2 g/m<sup>3</sup>. Extraído de Jiménez-Navarro, López-Ballesteros et al. (under review).*

|                       | Histórico | SSP 2-45 M | SSP 2-45 F | SSP 5-85 M | SSP 5-85 F |
|-----------------------|-----------|------------|------------|------------|------------|
| <b>Blooms (días)</b>  | 4         | 18         | 97         | 59         | 94         |
| <b>Hipoxia (días)</b> | 8         | 13         | 24         | 40         | 45         |

El estado eutrófico de la laguna la hace más vulnerable a eventos externos adicionales como tormentas más frecuentes o temperaturas más altas, que intensifican las floraciones algales y la hipoxia, amenazando los servicios ecosistémicos del Mar Menor. En general, los escenarios de cambio climático pronostican un empeoramiento de las condiciones del agua debido a cambios en los aspectos físicos, químicos y biológicos de la laguna. Esto afectará negativamente la regulación del Mar Menor y podría impactar los servicios culturales asociados, como el ecoturismo y la recreación.

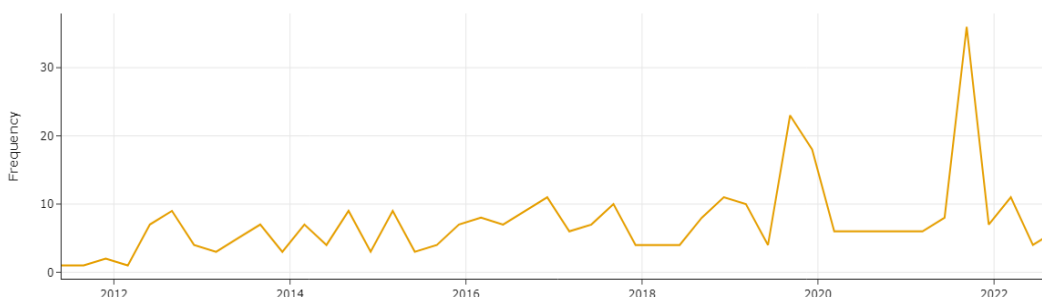
### 5.6.5. Ciencia ciudadana

Del estudio de ciencia ciudadana se obtuvieron dos resultados, estando el primero ligado con el análisis del impacto que la actividad puede tener en las redes sociales, y el segundo relacionado con la información que podemos extraer de la ciudadanía a través de actividades con los niños. La actividad en sí consistió en llevar a los niños a la playa de Los Nietos para hablarles del Mar Menor y del proyecto SMARTLAGOON. Además, se les pidió que realizaran un dibujo relacionado con el Mar Menor. Meses después se les pidió que respondieran a una encuesta para comprobar si se acordaban de la actividad.

#### 5.6.5.1. *Análisis de la percepción social sobre la crisis del Mar Menor en redes sociales*

Para este estudio se analizaron tuits sobre la crisis ambiental del Mar Menor, utilizando tres contextos geográficos progresivos. El contexto C1 se centró en tuits que solo mencionan el "Mar Menor", mientras que C2 incluye áreas cercanas a la laguna, y C3 abarca ciudades más grandes como Murcia y Cartagena. A medida que el contexto se amplía, aumenta tanto el número de tuits como el porcentaje de "falsos positivos" (mensajes no relacionados directamente con el problema). En C1, los falsos positivos alcanzan el 32.2%, mientras que en C3, con más de 27 veces más tuits que C1, el porcentaje llega al 82.6%. Se seleccionó el contexto C2, ya que incluye poblaciones adyacentes al Mar Menor sin el "ruido" de grandes ciudades como Murcia o Cartagena y porque el número de tuits relacionados con el problema ambiental es considerable y más manejable, lo que permite un análisis más preciso.

**Topics over Time**



**Figura 15.** Evolución temporal del Tema 9 (categoría infantil) analizada mediante BERTopic, en el estudio Jiménez-Navarro, Prandi et al. (under review).

Uno de los principales temas detectados en C2 fue la educación ambiental infantil (Tema 9), destacando palabras como “niños”, “escuela” y “alumnos”. Este tema presentó picos de actividad en octubre de 2019 y 2021 (Figura 15). La educación ambiental infantil en torno al Mar Menor parece ser un tema relevante en redes sociales. En octubre y noviembre de 2021, se registró un pico de actividad en redes que coincidió con las actividades en la playa con niños, las cuales tuvieron repercusión mediática. Esto refleja el interés de la población murciana en el papel de los niños para concienciar sobre la crisis ambiental del Mar Menor y refuerza la importancia de estudios como este, que captan la percepción social de las generaciones más jóvenes.

#### 5.6.5.2. *Análisis del punto de vista de los niños y sus aportaciones*

En total, 23 niños participaron en la encuesta. La mayoría fue capaz de recordar la actividad y pudo explicar detalles básicos, con solo cinco niños siendo incapaces de responder. Al preguntarles sobre lo que recordaban, 10 mencionaron la boya o el proyecto SMARTLAGOON, siete hablaron sobre las características del Mar Menor y cuatro se refirieron al dibujo que realizaron. Cuando se les interrogó directamente sobre sus dibujos y el significado detrás de ellos, la mayoría pudo recordar tanto lo que habían dibujado como el mensaje que intentaban transmitir, mientras que solo dos niños afirmaron no recordarlo. En general, la actividad parece haber tenido un impacto significativo, ya que la mayoría de los participantes pudo recordar aspectos específicos de lo aprendido. Los niños demostraron especial memoria en relación con sus dibujos y las razones detrás de ellos, lo cual no sorprende, dado que la participación activa en la actividad facilitó su retención (Rudy y Goodman, 1991).

Al preguntarles por qué es importante proteger el Mar Menor, las respuestas más comunes fueron que debía cuidarse para que las personas pudieran disfrutarlo y para garantizar la vida de los animales que habitan en él. Aunque la mayoría de los niños reconoció que la laguna y su entorno están en peligro, más de la mitad no pudo explicar las causas de esta situación, lo que sugiere que no comprenden del todo los motivos o no los conocen. Uno de los hallazgos más reveladores del estudio surgió al preguntar en qué parte del Mar Menor solían nadar, a lo que casi la mitad de los niños respondió que no se bañan en la laguna. Algunos justificaron

esta decisión argumentando que el agua es perjudicial para la piel o que puede ser dañina para los niños pequeños. Estas observaciones reflejan el impacto que el deterioro del Mar Menor tiene en las familias locales y su percepción general sobre el estado de la laguna.

Los niños también mostraron conciencia sobre las especies en peligro en el Mar Menor, como el caballito de mar. Esta especie emblemática del Mar Menor es considerado un símbolo por los residentes debido a su peligro de extinción. Sin embargo, las medusas son las más presentes en su percepción. Acostumbrados a ver muchas medusas en la laguna, su presencia se refleja en 18 de los 26 dibujos realizados, con algunos niños incluso dibujaron diferentes especies de medusas en la laguna, mostrando que las reconocen. Esto destaca el impacto que las medusas, una especie invasora desde los años 90, han tenido en el ecosistema del Mar Menor.

El estudio revela que la cercanía de los niños al Mar Menor influye en sus respuestas y dibujos, donde expresan sus experiencias y la influencia de su entorno social (Flowers et al., 2015). La mayoría dibujó escenarios positivos, mientras solo unos pocos retrataron la realidad actual de la contaminación. Aunque los niños son conscientes de los problemas del Mar Menor, la mayoría muestra una actitud optimista hacia el futuro y consideran importante proteger y recuperar la laguna. Sus dibujos reflejan este deseo, con imágenes de animales pidiendo ayuda, personas limpiando el Mar Menor o mensajes como "SOS Mar Menor", similares a los lemas vecinales. En general, los niños reflejan una actitud esperanzada hacia el futuro del Mar Menor, algo que también se ha observado en otros estudios sobre su visión del medio ambiente (Spiteri, 2022).

## **VI – CONCLUSION AND FUTURE RESEARCH**

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## VI -CONCLUSION AND FUTURE RESEARCH

Since this is an international PhD thesis, the conclusions and future research are exposed in English.

A key focus of this study has been the application of climate change scenarios to establish realistic predictions for the Mar Menor. The use of climate change scenarios has proven to be an invaluable tool in forecasting and understanding future impacts on ecosystems and watersheds. The thesis demonstrates that these scenarios allow us to model and anticipate how shifts in climatic variables, such as temperature and precipitation, influence hydrological behavior and water quality. Overall, climate change scenarios enable not only the prediction of future ecological changes but also provide critical insights for informing adaptive management strategies and policies. By understanding how various climate change mitigation strategies affect aquatic systems, the importance of mitigation efforts is highlighted, helping to develop more effective plans to address the impacts of climate change and ensure sustainable resource management.

Another important aspect of the thesis was the analysis of different calibration techniques for the SWAT+ model. In regions like the Mar Menor, where streamflow data may be scarce, SWAT model calibration can benefit from alternative techniques, including the integration of indirect data, such as satellite evapotranspiration. In **Publication 3**, our findings from Lake Erken suggest that calibrating SWAT+ with ET data can be particularly useful in data-scarce environments. The experience at Lake Erken demonstrates that, with an appropriate approach, it is possible to achieve reliable simulations even with limited data. This underscores the importance of adapting calibration strategies to maximize the use of available data and enhance model accuracy.

A further key component of the thesis was the exploration of combining hydrological models (SWAT+), hydrodynamic models (GOTM), and ecosystem models (WET) to achieve more comprehensive simulations of aquatic systems and their interactions. The coupled configuration of the SWAT+, GOTM and WET models proved effective in capturing the complex dynamics of aquatic systems. In the case of Lake Erken, coupling SWAT+ with GOTM-WET demonstrated how these tools can be integrated to model not only water flow and quality but also the

biogeochemical processes occurring within the lake. This integrated approach helps capture the intricate interactions between the water cycle and ecological processes, offering more realistic predictions of future ecosystem conditions. In both studies—Lake Erken and Mar Menor—the use of these coupled models improved the accuracy of hydrological and ecological simulations and facilitated the evaluation of how climate change affects the entire system. Additionally, this methodology can be advantageous in identifying intervention areas and assessing the effectiveness of different management strategies. Our findings suggest that future research would benefit from using coupled modeling techniques, particularly for addressing complex problems involving multiple facets of the water cycle. Furthermore, as this thesis demonstrates, such methodologies can be applied to regions with diverse climatic and hydrological characteristics, improving water resource management and ecosystem conservation.

Regarding scenario predictions, different conclusions were drawn from the studies of Lake Erken and the Mar Menor. The primary takeaway is that climate change has a substantial impact on aquatic ecosystems. In **Publication 1**, which focuses on the Lake Erken basin, we observe an increase in temperature and precipitation in Sweden, affecting the hydrological cycle and specific processes such as snow accumulation (which is expected to decrease) and flood regimes (which are projected to intensify). **Publication 2**, also examining Lake Erken, reports a rise in water temperature, greater stratification, and lower oxygen levels. These changes are accompanied by shifts in water quality and ecological processes. **Publication 5**, focused on the Mar Menor, documents rising temperatures and an increased frequency of extreme rainfall events, leading to changes in nutrient flows within the basin and a heightened risk of hypoxia and algal blooms in the lagoon. In both regions, climate change disrupts the hydrological cycle and water flow patterns. **Publication 1** notes an increase in flow and runoff in the Lake Erken basin, posing a greater risk of erosion and soil degradation. **Publication 2** supports this, indicating that water flow into the lake increases during winter and decreases in summer. **Publication 5** expands on this by projecting a future decrease in flow in the Mar Menor, along with changes in nutrient inputs due to increased runoff. The ecological consequences of these changes are concerning. In **Publication 1**, an increase in the frequency and duration of floods in Lake Erken is reported, which threatens ecosystem integrity and exacerbates soil erosion. **Publication 2** highlights

rising phosphate and ammonium concentrations in the lake, alongside decreasing oxygen levels, which could result in significant ecological degradation. Lastly, **Publication 5** describes deteriorating water quality in the Mar Menor, with a greater risk of hypoxia, algal blooms, and a general loss of ecosystem services.

**Publication 5** focused on regulating ecosystem services, but it is likely that, without climate change mitigation, degradation in the lagoon will also affect cultural ecosystem services. Since cultural services represent intangible and non-monetary benefits, they are more difficult to measure. Some authors argue that the relationship between these benefits and ecosystems is not always easy to define, making it harder to fully understand the human-ecosystem connection (Winthrop, 2014). However, cultural services are essential in conveying the value of ecosystems due to their intuitive nature. If we aim to achieve integration between research and the local population, exploring this pathway further could be a useful step toward that goal. The Mar Menor offers numerous cultural ecosystem services that are vital to the well-being of the people of Murcia. The degradation of these services would have a significant negative impact on the local population, making it crucial to involve them in the lagoon's management decisions. As highlighted in **Publication 4**, children's perspectives provide valuable insight into the broader community's concerns. For instance, nearly half of the children interviewed stated that they no longer swim in the Mar Menor because they believe it is harmful, reflecting the local population's level of concern. This study with children also highlighted other advantages of working with them: their perspectives often differ from those of adults, which can be beneficial. One example is that most children believe protecting the Mar Menor is important, primarily due to the nature and animals, indicating that they value ecosystems for their intrinsic worth, beyond their direct benefits to humans. Moreover, environmental education related to the Mar Menor is a significant topic on social media, as observed using social monitoring tools. This suggests that working with children could serve as a platform to reach the local population and establish constructive communication. Finally, another conclusion from working with children is their positive attitude toward the future and environmental restoration. Despite the current degradation of the Mar Menor, children tend to maintain an optimistic outlook on the ecosystem's potential recovery. This optimism should be harnessed to continue efforts toward this restoration without being paralyzed by future uncertainties.





## **VII - REFERENCIAS BIBLIOGRÁFICAS**

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## VIII – ANEXOS

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## VIII - ANEXOS

### ANEXO 1. Calidad de las publicaciones

1. Publicación 1: 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.
  - Índice de impacto (2021): **3,282**
  - Puesto en el JCR: **14/69**
  - Categoría: **Forestry**
  - Cuartil: **Q1**
2. Publicación 2: Jiménez-Navarro, I. C., Mesman, J. P., Pierson, D., Trolle, D., Nielsen, A., & Senent-Aparicio, J. (2023). Application of an integrated catchment-lake model approach for simulating effects of climate change on lake inputs and biogeochemistry. *Science of the Total Environment*, 885, 163946.
  - Índice de impacto (2023): **8,2**
  - Puesto en el JCR: **28/359**
  - Categoría: **Environmental Sciences**
  - Cuartil: **Q1**
3. Publicación 3: Jiménez-Navarro, I. C., Pierson, D. & Senent-Aparicio, J. (2024). The implications of the use of ET remote sensing data for calibrating hydrological models: a comparison of single and multi-criteria calibration in SWAT+. *Earth Systems and Environment*, 8, 831–847.
  - Índice de impacto (2023): **5,3**
  - Puesto en el JCR: **73/358**
  - Categoría: **Enviromental Sciences**
  - Cuartil: **Q1**

4. Publicación 4: Jiménez-Navarro, I. C., Prandi, C., Pérez-Lucia, J. G., Cecilia, J. M. & Senent-Aparicio, J. (2024). Ecological crisis from children's perspective: Lessons learned and their importance in shaking up social awareness. *Sustainability*, 16(24), 10824.
  - Índice de impacto (2024): **3,3**
  - Puesto en el JCR: **178/374**
  - Categoría: **Enviromental Sciences**
  - Cuartil: **Q2**
  
5. Publicación 5: Jiménez-Navarro, I. C., López-Ballesteros, A., Mesman, J. P., Trolle, D., Pierson, D. & Senent-Aparicio, J. Modeling Climate Impacts on Ecosystem Services in an Anthropized Coastal Lagoon for Effective Planning and Adaptation. *Climatic Change*, 178, 92 (2025).
  - Índice de impacto (2024): **4,8**
  - Puesto en el JCR: **84/374**
  - Categoría: **Enviromental Sciences**
  - Cuartil: **Q1**

## ANEXO 2: Otras publicaciones y méritos

### Otras publicaciones:

- Mesman, J. P., **Jiménez-Navarro, I. C.**, Ayala, A. I., Senent-Aparicio, J., Trolle, D., & Pierson, D. (2023). Timing of spring events changes under modelled future climate scenarios in a mesotrophic lake. *EGUsphere*, 2023, 1-22. <https://doi.org/10.5194/egusphere-2023-1679>.
- Tumedei, G., Ceccarini, C., Jiménez-Navarro, I. C., Prandi, C. (2025). From Drawings to Awareness: Exploring Narrative Visualization and AI to Teach Children About the Fragile Ecosystem of the Mar Menor Lagoon. In *Designing Interactive Systems Conference (DIS'25)*, July 5–9, 2025, Funchal, Portugal. ACM, New York, USA, 17 pages. <https://doi.org/10.1145/3715336.3735722>.

### Congresos nacionales e internacionales:

- **Jiménez-Navarro, I.**, Senent-Aparicio, J., Sáez, P. J., & Ballesteros, A. L. (2021). Análisis del impacto del cambio climático sobre las avenidas en la cuenca drenante al lago Erken (Suecia) mediante SWAT+. In Inundaciones y sequías: Análisis multidisciplinar para mitigar el impacto de los fenómenos climáticos extremos (pp. 821-832). Universidad de Alicante/Universitat d'Alacant.
- **Jimenez-Navarro, I.C.**, Senent-Aparicio, J., López-Ballesteros, A., Trolle, D., Mesman, J., Nielsen, A., Pierson, D., Colom, W. (2022). Combining SWAT+ and GOTM-WET models to simulate lake ecosystems. Case Study: Lake Erken (Sweden). International Soil and Water Assessment Tool Conference. Prague, Czech Republic.
- **Jiménez-Navarro, I.C.**, Mesman, J.P., Pierson, D., Trolle, D., Senent-Aparicio, J. (2023). Different calibration strategies with SWAT+ Toolbox using remote sensing evapotranspiration data and streamflow. International Soil and Water Assessment Tool Conference. Aarhus, Denmark.
- **Jiménez-Navarro, I.C.**, Mesman, J.P., Pierson, D., Trolle, D., Nielsen, A., Senent-Aparicio, J. (2023). Los efectos del cambio climático en un lago de Suecia a través de un modelo integrado de la masa de agua y su cuenca vertiente. IX Jornadas de Investigación y Doctorado. Murcia, Spain.
- Pierson, D. C., Mesman, J., **Jiménez-Navarro, I. C.**, Pacheco, J. P. P., Trolle, D., Nielsen, A., & Senent-Aparicio, J. (2023). A Model Based Methodology to Evaluate Future Changes in an Anthropized Coastal Lagoon. In AGU Fall Meeting Abstracts (Vol. 2023, No. 2155, pp. B31E-2155).
- **Jiménez-Navarro, I.C.**, Pierson, D., Senent-Aparicio, J. (2024). Mejora de la Calibración de Modelos Hidrológicos Utilizando Datos de Evapotranspiración Derivados de Satélites: Un Estudio de Caso del Lago Erken, Suecia. X Jornadas de Investigación y Doctorado. Murcia, Spain.



- **Jiménez-Navarro, I.C.**, López-Ballesteros, A., Mesman, J.P., Pierson, D., Trolle, D., Nielsen, A., Senent-Aparicio, J. (2024). Analysis of future climate scenarios to assess regulatory and cultural ecosystem services using an integrated SWAT+ and GOTM-WET model. International Soil and Water Assessment Tool Conference. Strasbourg, France.
- **Jiménez-Navarro, I.C.**, López-Ballesteros, A., Senent-Aparicio, J. (2025). Modelización integrada para la gestión del agua en zonas de agricultura intensiva bajo el efecto del cambio climático. Congreso AGROALNEXT 2025, Innovación y Transferencia en el Sector Agroalimentario Español. Murcia, España.
- **Jiménez-Navarro, I.C.**, López-Ballesteros, A., Mesman, J.P., Pierson, D., Trolle, D., Nielsen, A., Senent-Aparicio, J. (2025). Mitigating Climate Change Impacts with Agricultural Practices in a Coastal Lagoon. EGU General Assembly 2025. Viena, Austria.
- López-Ballesteros, A., **Jiménez-Navarro, I.C.**, Bieger, K., Senent-Aparicio, J. (2025). Assessing Two Hydrological Models for Watersheds with Intensive Agriculture: A Focus on Hydrological Ecosystem Services modeling. 2025 International SWAT Conference. Jeju, South Korea.

#### Estancias en el extranjero:

- Universidad de Bolonia, Italia. Programa de Apoyo a la Movilidad y el Intercambio Científico, Estancias Investigadoras de Corta Duración en Centros Externos. UCAM. 01/04/2022 - 01/05/2022
- Universidad de Uppsala, Suecia. Programa de Apoyo a la Movilidad y el Intercambio Científico, Estancias Investigadoras de Corta Duración en Centros Externos. UCAM. 09/05/2022- 11/07/2022.

