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ESCUELA INTERNACIONAL DE DOCTORADO
Programa de Doctorado en Tecnologías de la Computación e Ingeniería Ambiental

Development of a holistic model for science-informed decision support in intensive agricultural areas

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El Dr. D. Javier Senent Aparicio como Director de la Tesis Doctoral titulada "Development of a holistic model for science-informed decision support in intensive agricultural areas", realizada por D. Adrián López Ballesteros 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.

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COMPENDIO DE PUBLICACIONES

Esta tesis se presenta en la modalidad de compendio de publicaciones. Los artículos publicados y aceptados que componen la tesis son los siguientes:

- **Publicación 1:** López-Ballesteros, A.; Senent-Aparicio, J.; Srinivasan, R.; Pérez-Sánchez, J. (2019). Assessing the impact of best management practices in a highly anthropogenic and ungauged watershed using the SWAT model: A case study in the El Beal Watershed (Southeast Spain). Agronomy, 9 (10), 576. https://doi.org/10.3390/agronomy9100576

- **Publicación 2:** Senent-Aparicio, J.; López-Ballesteros, A.; Nielsen, A.; Trolle, D. (2021). A holistic approach for determining the hydrology of the Mar Menor coastal lagoon by combining hydrological & hydrodynamic models. Journal of Hydrology, 603, 127150. https://doi.org/10.1016/j.jhydrol.2021.127150

- **Publicación 3:** López-Ballesteros, A.; Trolle, D.; Srinivasan, R.; Senent-Aparicio, J. (2023). Assessing the effectiveness of potential best management practices for science-informed decision support at the watershed scale: The case of the Mar Menor coastal lagoon, Spain. Science of the Total Environment, 859 (1), 160144. https://doi.org/10.1016/j.scitotenv.2022.160144

AGRADECIMIENTOS

Mi mayor agradecimiento a todas las personas que me han acompañado a lo largo de estos años de trabajo y esfuerzo, desde el corazón: gracias.

Sinceramente creo que el éxito no está solo en alcanzar los resultados marcados, sino en aprender también a disfrutar del camino. Mi carrera investigadora se inició gracias a la confianza depositada en mí por parte del Dr. Javier Senent Aparicio, al cual le estoy enormemente agradecido. Su sinceridad y pragmatismo me han impulsado más lejos de lo que inicialmente hubiera imaginado, por lo que me gustaría reconocerle gran parte de mis méritos.

También me gustaría agradecer a mis compañeros de investigación el apoyo mostrado, tanto a los que han estado siempre (Patricia y Julio) como a las nuevas incorporaciones (Fran, Inma y Gerardo). Todos somos buenos, pero juntos somos mejores.

Agradecer también a mi familia, cuyo apoyo incondicional me ha ayudado a seguir adelante día a día. En especial a mi padre, mi mayor ejemplo de tenacidad y sacrificio. Gracias por indicarme siempre el camino correcto.

I would also like to acknowledge the international SWAT community, I really appreciate for letting me be part of this family. I look forward to continue meeting amazing people and working together on future research.

Por último pero no menos importante, agradecer a Laura, mi compañera de vida, por acompañarme desde el principio en este camino. Siempre tendré en cuenta la difícil decisión de tener que cambiar de vida para poder perseguir este sueño juntos. Gracias.

“Somos lo que hacemos día a día. La excelencia no es un acto, sino un hábito"
Aristóteles (384 a.C. - 322 a.C.)

ÍNDICE GENERAL

SIGLAS Y ABREVIATURAS

BMP	Mejores prácticas de gestión agrícola; Best Management Practice
CE ratio	Ratio de Coste-Efectividad
CN	Método del número de curva; Curve Number method
DANA	Depresión Aislada en Niveles Altos
ECMWF	Centro europeo de previsión del tiempo a medio plazo; European Centre for Medium-range Weather Forecasts
ETP	Evapotranspiración Potencial
FABM	Marco de modelos biogeoquímicos acuáticos; Framework for Aquatic Biogeochemical Models
GLEAM	Global Land Evaporation Amsterdam Model
GOTM	Modelo general de turbulencia oceánica; General Ocean Turbulence Model
HRU	Unidades de respuesta hidrológica; Hydrologic Response Units
HWSD	Base de datos armonizada de los suelos del mundo; Harmonized World Soil Database
IGN	Instituto Geográfico Nacional
IMIDA	Instituto Murciano de Investigación y Desarrollo Agrario y medioambiental
JCR	Informe de citas de revistas; Journal Citation Report
KGE	Coeficiente de eficiencia de Kling–Gupta
MDT	Modelo Digital del Terreno
NSE	Coeficiente de eficiencia de Nash-Sutcliffe
PBIAS	Porcentaje del sesgo
R^2	Coeficiente de determinación
RMSE	Error cuadrático medio; Root Mean Square Error
S	Sedimento total
SCS	Servicio de Conservación del Suelo
SIG	Sistema de Información Geográfica
SUFI-2	Algoritmo de ajuste de incertidumbre secuencial; Sequential Uncertainty Fitting algorithm
SWAT	Soil and Water Assessment Tool

SWAT-CUP	Programas de calibración e incertidumbre de SWAT; SWAT Calibration and Uncertainty Programs
TN	Nitrógeno total; Total Nitrogen
TP	Fosforo total; Total Phosphorus
USDA	Departamento de Agricultura de los Estados Unidos
WET	Water Ecosystems Tool
ZEC	Zonas Especiales de Conservación
ZEPA	Zonas de Especial Protección para las Aves
ZEPIM	Zona Especialmente Protegida de Importancia para el Mediterráneo

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RESUMEN

Lograr un equilibrio entre la sostenibilidad ambiental y el desarrollo económico es un objetivo prioritario. Este objetivo gana importancia en zonas de agricultura intensiva, donde converge una importante labor socioeconómica y el gran impacto de las actividades humanas sobre los ecosistemas. Por ello, el objetivo principal de esta tesis doctoral ha sido desarrollar un modelo que permita evaluar posibles soluciones a los problemas ambientales que afrontan las zonas de agricultura intensiva. Un caso muy representativo es la cuenca hidrográfica del Mar Menor, conocida como "Campo de Cartagena". Esta zona, altamente antropizada y no aforada, vierte sus aguas al Mar Menor, una de las mayores lagunas costeras saladas de la región mediterránea y un lugar de gran valor ambiental. Sin embargo, en los últimos años su estado ecológico se ha visto degradado debido a problemas de eutrofización, provocados por el exceso de nutrientes procedentes de la actividad humana local. La presente tesis se presenta por compendio de publicaciones, por tanto tres artículos científicos fueron desarrollados para la misma. Todos estos estudios se llevaron a cabo dentro de la zona de influencia del Mar Menor, siguiendo una metodología común basada en la modelización hidrológica. A lo largo los mismos, se desarrollaron varios modelos hidrológicos con SWAT (Soil and Water Assessment Tool) así como una combinación de SWAT con la parte hidrodinámica del modelo WET (Water Ecosystems Tool). Dos de los estudios publicados se centraron en la evaluación de la eficacia de mejores prácticas de gestión agrícola (BMP, en inglés) en la reducción de sedimentos y nutrientes entrantes al Mar Menor. Aunque algunas de estas BMPs aplicadas de forma individual mostraron una gran efectividad, se demostró que su combinación es la solución más efectiva. Además, esta tesis supone una mejora del conocimiento científico sobre el funcionamiento hidrológico del Campo de Cartagena y sobre el balance hídrico de la laguna costera. Los resultados de estos estudios pueden servir de guía a los responsables de la toma de decisiones para seleccionar las mejores estrategias de control de la contaminación difusa en zonas altamente antropizadas.

Palabras clave: Modelo SWAT, laguna costera, prácticas de gestión agrícola, Mar Menor; balance hídrico.

[Esta tesis doctoral ha recibido financiación del Ministerio de Universidades a través del Programa Estatal de Promoción del Talento y su Empleabilidad - Subprograma de Formación de Profesorado Universitario (FPU), con referencia FPU17/00923]

ABSTRACT

Reaching a balance between environmental sustainability and economic development is a major goal for society. This objective becomes relevant in intensive agricultural areas, where an important socioeconomic task and a significant impact of human activities in the ecosystems converge. Therefore, the main objective of this PhD thesis was developed a model to assess potential solutions for the environmental issues faced by intensive agricultural areas. A very representative case is the Mar Menor watershed, known as "Campo de Cartagena". This highly anthropogenic and ungauged area drains into the Mar Menor, one of the largest hypersaline coastal lagoons of the Mediterranean region and a site of great environmental value. However, its ecological status have been degraded in recent years due to eutrophication problems, triggered by excess of nutrients from local human activities. This PhD thesis is presented by compendium of publications, therefore three research papers have been published to achieve that requirement. All these studies were carried out within the area of influence of the Mar Menor, following a common methodology based on hydrological modeling. Throughout them, several hydrological models were developed with SWAT (Soil and Water Assessment Tool) as well as a combination of SWAT with the hydrodynamic part of the WET (Water Ecosystems Tool) model. Two of the published studies were focus on assessing the effectiveness of best management practice (BMP) scenarios in reducing sediment and nutrient inputs to the Mar Menor coastal lagoon. Although some BMPs applied individually showed a high effectiveness, it was demonstrated that a combination of BMPs is the most effective solution. Moreover, this PhD thesis supposed an improvement in the scientific knowledge about the hydrological processes of the Campo de Cartagena and the water balance of the coastal lagoon. The outcomes of these studies can guide to decision-makers to select the best strategies to control non-point source contamination in highly anthropogenic areas.

Keywords: SWAT model; Mar Menor; coastal lagoon; best management practices; water balance.

[This PhD thesis has been funded by Ministry of Universities of Spain through the State Program of the Promotion of Talent and its Employability – University Professor Training Subprogram (FPU), with reference FPU17/00923]

I - INTRODUCCIÓN

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1.1 JUSTIFICACIÓN DE LA INVESTIGACIÓN

El uso de suelo agrícola es el más extendido en Europa, ocupando casi el 50% de todo el territorio. La agricultura intensiva nace de la necesidad de aumentar la producción de acuerdo a la, cada vez mayor, demanda socioeconómica. Sin embargo, esta explotación agrícola intensiva puede desembocar en graves problemas ambientales si no se controla. La sobreexplotación de los recursos hídricos y el uso excesivo de fertilizantes son algunas de las prácticas que pueden llevarse a cabo ante la falta de regulación, lo cual puede provocar la contaminación de las aguas y su consecuente pérdida de biodiversidad. Por tanto, alcanzar una agricultura sostenible que permita la conservación de los recursos naturales, tanto a corto como a largo plazo, es uno de los objetivos fundamentales propuestos por la Unión Europea (EU Regulation 1306/2013). Además, la agricultura sostenible gana una mayor importancia cuando afecta directamente a zonas con gran valor ecológico. Este puede ser el caso de algunas cuencas costeras mediterráneas, la cuales se caracterizan por abarcar zonas de importante valor ecológico y zonas con un alto grado de antropización debido al turismo o la agricultura (Martínez-Fernández & Esteve-Selma, 2000). Por todo ello, la evaluación del impacto de la actividad humana sobre los recursos naturales de zonas altamente antropizadas es de vital importancia para poder implementar medidas que permitan contrarrestar los efectos negativos de las distintas actividades llevadas a cabo en estas regiones y conservar un buen estado ecológico de las mismas (López-Ballesteros et al., 2019).

Un ejemplo representativo de la situación anteriormente descrita es la cuenca hidrográfica vertiente al Mar Menor, conocida como Campo de Cartagena, la cual ha sufrido en las últimas décadas grandes cambios tanto socioeconómicos como medioambientales y soporta una gran presión antrópica (Senent-Aparicio et al., 2021). Esta zona de estudio, además de verter sus aguas a la mayor laguna salada costera de Europa (135 km^2), posee un gran valor ecológico tal y como indican las diferentes figuras de protección ambiental bajo las que se clasifican algunas de sus zonas: Humedal de Importancia Internacional (sitio Ramsar), Zona Especialmente Protegida de Importancia para el Mediterráneo (ZEPIM), Zonas de Especial Protección para las Aves (ZEPA) y Zonas Especiales de Conservación (ZEC) (Boletín Oficial del Estado [BOE], 2020). El Campo de Cartagena, situado al sureste de la península ibérica presenta un alto grado de antropización, además del clima semiárido típico de la zona mediterránea caracterizado por escasas precipitaciones y cauces efímeros. Sin embargo, este hecho no ha impedido que la zona sea considerada uno de los principales productores hortícolas de Europa (Álvarez-Rogel et al., 2006). La agricultura intensiva de esta región se encuentra principalmente sostenida por el uso de recursos hídricos procedentes de aguas subterráneas y del trasvase Tajo-Segura, y ayudada por el alto grado de tecnificación de su sistema de regadío. Por tanto, como puede observarse, el Mar Menor y su cuenca vertiente forman un sistema complejo que requiere de un enfoque holístico e integral para poder llevar a cabo soluciones eficaces contra los numerosos problemas ambientales que enfrenta. Entre estos problemas ambientales el que más preocupa en la actualidad es la eutrofización de la laguna costera, siendo una de sus principales causas la entrada masiva de nutrientes procedentes del Campo de Cartagena. En los últimos años, el gobierno central y regional han desarrollado varias normativas (BOE, 2020; Boletín Oficial de la Región de Murcia [BORM], 2019, 2018, 2017) con el objetivo de frenar la degradación ambiental de la laguna costera. Para ello se propone la aplicación de una serie de medidas correctoras y de prevención. Sin embargo, la falta de evaluación de la eficacia de estas medidas y la complejidad de la zona de estudio hacen necesaria la apertura y desarrollo de una línea de investigación en esta dirección. Una mejora del conocimiento científico en zonas con agricultura intensiva es necesaria para una toma de decisiones efectiva, la cual permita un equilibrio entre la sostenibilidad ambiental y el desarrollo económico de la zona.

Los motivos anteriormente descritos, las características particulares de la zona de estudio y la grave problemática ambiental bajo la que se encuentra en la actualidad, hacen que la cuenca hidrográfica vertiente al Mar Menor sea una zona de estudio idónea para aplicar y comprobar los avances de la presente tesis. Además, para poder mejorar el conocimiento científico con respecto a la problemática del Mar Menor y evaluar sus posibles soluciones, la metodología principal de la tesis se basa en la simulación hidrológica e hidráulica mediante modelos de base física. La modelización hidrológica ofrece una herramienta de gran utilidad para la gestión de los recursos hídricos (Molina-Navarro et al., 2017) y la evaluación del impacto de las diferentes prácticas agrícolas a escala de cuenca. Los modelos hidrológicos se han convertido, en los últimos años, en una herramienta ampliamente utilizada para la simulación de posibles escenarios de actuación ante problemas medioambientales relacionados con la cantidad y calidad de las aguas (Upadhyay et al., 2022). Conseguir una modelización fiable y representativa de la zona de estudio es una difícil tarea que requiere la consecución de una serie de procesos como puede ser la parametrización, calibración y validación del modelo, así como de la toma de decisiones acertada por parte del modelador. Sin embargo, cuando se logra una modelización aceptable de la zona de estudio, se abre ante los modeladores un amplio abanico de posibilidades de simulación y permite a los encargados de la toma de decisiones llevar a cabo su trabajo con base científica. Por tanto, teniendo en cuenta las incertidumbres de la modelización, la presente tesis pretende ofrecer un modelo integrado que permita la toma de decisiones respaldadas por la ciencia en zonas de agricultura intensiva. Pudiendo estas decisiones estar enfocadas tanto a la gestión de los recursos hídricos como a la aplicación de soluciones ante problemas ambientales relacionados con la contaminación de las aguas de la zona de estudio.

1.2 Objetivos

Esta investigación parte de la necesidad por encontrar soluciones ante la degradación ambiental que afrontan algunas zonas con agricultura intensiva, concretamente la cuenca vertiente al Mar Menor, además del gran reto que supone encontrar un equilibrio entre la sostenibilidad ambiental y el desarrollo económico de estas zonas. Por tanto el objetivo principal de esta tesis es la realización de un modelo integrado de ayuda a la decisión que permita dar respuestas a los diferentes retos que afrontan las zonas con agricultura intensiva.

En relación a la consecución del objetivo principal se establecen los siguientes objetivos específicos:

1. Desarrollar un modelo hidrológico del Campo de Cartagena que permita la búsqueda de soluciones efectivas para contrarrestar la problemática ambiental de la laguna costera del Mar Menor.

2. Analizar la efectividad y coste-eficacia de las distintas medidas propuestas por la legislación actual con el objetivo de reducir la entrada de sedimentos y nutrientes al Mar Menor e identificar las soluciones prioritarias.

3. Desarrollar un modelo hidrodinámico de la laguna costera del Mar Menor que permita estimar la magnitud de los componentes de su balance hídrico y así lograr una mejor comprensión de la relación causa-efecto con su cuenca vertiente.

1.3 Organización del documento

El documento de tesis se divide en seis capítulos principales y dos anexos, los cuales incluyen la siguiente información:

- **Capítulo I:** consiste en la introducción de la tesis e incluye los apartados de justificación de la investigación, objetivos generales y específicos, y estructura del documento.

- **Capítulo II:** muestra el estado del arte actual y el contexto teórico sobre el que se apoya la presente tesis. En este capítulo se describe de forma detallada la problemática ambiental bajo la que se encuentra la laguna costera del Mar Menor y su entorno, y se amplía información sobre el uso de la modelización como herramienta de toma de decisiones.

- **Capítulo III:** presenta los materiales y métodos empleados para el desarrollo de la investigación. En primer lugar, se describen las características principales de la zona de estudio modelizada. A continuación, se incluye información detallada sobre el funcionamiento del modelo SWAT y el modelo WET. Y por último, se muestra el proceso llevado a cabo para la modelización de las prácticas agrícolas así como para el cálculo de su efectividad y coste-eficacia.

- **Capítulo IV:** aglutina los tres artículos científicos desarrollados y seleccionados para la presentación de la tesis por compendio de publicaciones y presenta una síntesis global de los resultados de los mismos.

- **Capítulo V:** expone las conclusiones globales obtenidas de la investigación y presenta posibles líneas futuras de investigación que podrían seguirse como continuación de la tesis.

- **Capítulo VI:** recoge todas las referencias bibliográficas utilizadas para la escritura del documento de tesis.

- **Anexo I:** presenta los criterios de calidad de las publicaciones, incluyendo el índice de impacto de la revista, el puesto y el cuartil en el que se posicionaba por área de conocimiento en el Journal Citation Report (JCR) el año de publicación.

- **Anexo II:** recoge otras publicaciones y méritos logrados durante el desarrollo de la presente tesis.

II – ANTECEDENTES Y ESTADO DEL ARTE

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2.1 EL MAR MENOR Y SU ENTORNO

La laguna costera del Mar Menor y su entorno poseen un gran valor tanto ecológico como socioeconómico, el cual se encuentra amenazado por un grave problema ambiental que está degradando el estado de la laguna y afectando significativamente a la economía de la zona.

2.1.1 La laguna costera del Mar Menor

El Mar Menor (Figura 1) es una de las mayores lagunas costeras saladas de Europa y de la zona mediterránea occidental, lo cual le confiere una gran importancia a nivel nacional e internacional (López-Ballesteros et al., 2023). La laguna costera del Mar Menor tiene una superficie total de 135 km^2 y una línea de costa de 73 km, siendo su profundidad máxima de 7 m y la profundidad media de 4,4 m (Umgiesser et al., 2014). La laguna del Mar Menor se encuentra separada del Mar Mediterráneo por una barra de arena de unos 22 km de longitud y ancho variable entre 100 y 1200 m conocida como "La Manga" (Carreño, 2015). Esta banda de arena mantiene al Mar Menor prácticamente aislado, excepto por varias golas que la atraviesan y a través de las cuales se produce el intercambio de aguas entre el Mar Mediterráneo y la laguna costera, siendo la más importante la gola del Estacio. Sin embargo, pese a esta mínima conexión, el Mar Menor posee una características singulares de salinidad y temperatura la cuales han favorecido el desarrollo de hábitats y especies únicas y de gran valor ecológico.

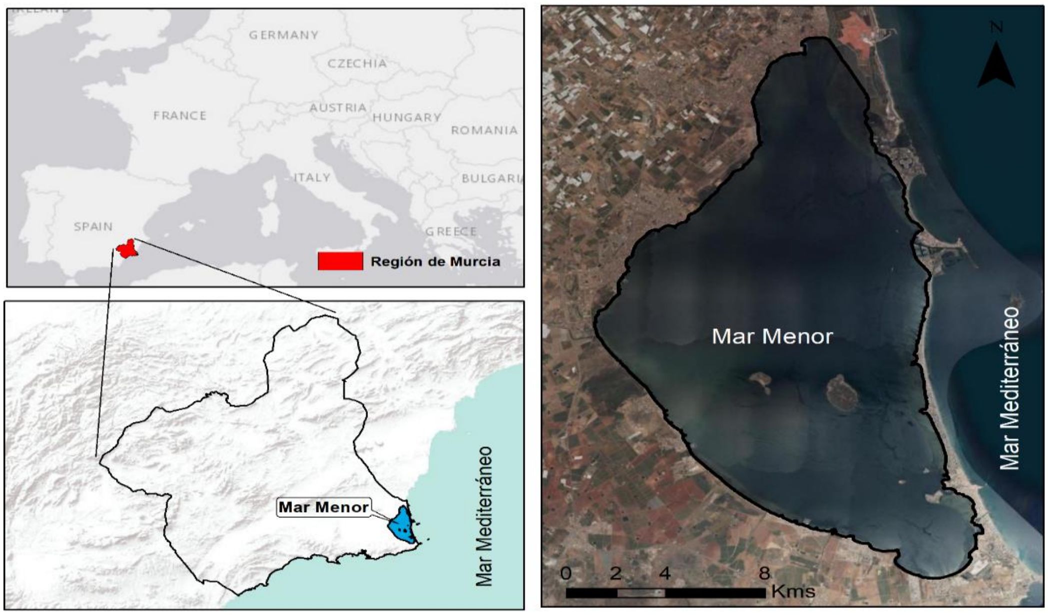

Figura 1. Localización de la laguna costera del Mar Menor.

La laguna costera del Mar Menor se encuentra incluida en la lista Ramsar de Humedales de Importancia Internacional y clasificada como Zona Especialmente Protegida de Importancia para el Mediterráneo (ZEPIM). Además, el Mar Menor es uno de los principales espacios naturales de la Región de Murcia y un importante elemento de identificación sociocultural de la zona (BOE, 2020). Las actividades pesqueras, turísticas y recreativas son las principales actividades humanas que se desarrollan en la laguna, ganando las dos últimas una especial relevancia durante los meses de verano. Sin embargo, cabe destacar que la mayor potencia económica de la zona es la agricultura que se produce de forma intensiva en la cuenca vertiente del Mar Menor, conocida como Campo de Cartagena, de la cual sus principales características se describen en el capítulo III. La minería es otra actividad económica que se llevó a cabo en las zonas adyacentes al Mar Menor durante varios años y, aunque hoy en día se encuentra abandonada, su impacto todavía perdura. Todas estas actividades antrópicas han tenido un efecto negativo en el estado de la laguna costera, desencadenando el grave problema ambiental bajo en que se encuentra el Mar Menor en los últimos años.

2.1.2 La problemática ambiental del Mar Menor

Los antecedentes al grave problema ambiental bajo el que se encuentra la laguna costera del Mar Menor son descritos en detalle en el informe integral sobre el estado ecológico del Mar Menor (Comité de Asesoramiento Científico del Mar Menor, 2017). Sin embargo a continuación, a modo de síntesis, se enumeraran algunas de las causas principales que han llevado al Mar Menor a su situación actual de grave desequilibrio ambiental.

1. A principios de los años 60, la zona costera del Mar Menor sufrió una importante transformación urbanística debido al incremento del turismo. Esta intensificación del turismo provoco un aumento, sobretodo en la época estival, de la generación de aguas residuales y de la demanda de recursos hídricos. Todo ello se tradujo en una alta presión antrópica sobre la laguna que ha ido incrementando hasta nuestros días.

2. Las explotaciones mineras localizadas en la zona sur de la laguna costera (aunque se encuentran ya en desuso), también han tenido y tienen un impacto negativo en la calidad de las aguas del Mar Menor debido al arrastre de metales pesados procedentes de las zonas no regeneradas.

3. A finales de los 70, la agricultura de la zona sufrió un gran cambio. El uso de suelo agrícola predominante hasta ese momento era la agricultura de secano, sin embargo debido a la construcción del trasvase Tajo-Segura en 1979 este uso de suelo se transformó a agricultura intensiva de regadío. Este aumento en la disponibilidad de recursos hídricos provocó una expansión exponencial del regadío, incrementando considerablemente los flujos de agua y nutrientes que desembocan al Mar Menor.

Como puede observarse, son varias las causas que han provocado el deterioro ecológico de la laguna costera del Mar Menor. Pudiéndose llegar a la conclusión de que el principal motivo de esta problemática ambiental es la entrada de contaminantes y nutrientes procedentes de las actividades humanas que se desarrollan en la zona. Por tanto, se considera que la solución a este problema ambiental requiere de un enfoque holístico e integrado que abarque el mayor ámbito de actuación posible.

Hoy en día, la principal preocupación social e institucional de este problema ambiental es la eutrofización de la laguna costera. La entrada masiva de aguas cargadas de nutrientes al Mar Menor ha desencadenado ya varios episodios de eutrofización, hipoxia y anoxia, principalmente tras eventos de precipitaciones extremas. Estas precipitaciones extremas se produjeron tanto en diciembre de 2016 como en septiembre y diciembre de 2019 debido a una situación meteorológica extrema conocida como DANA (Depresión Aislada en Niveles Altos), la cual provoca lluvias muy intensas en cortos periodos de tiempo. Estas lluvias torrenciales provocan la entrada de grandes cantidades de agua, nutrientes y sedimentos al Mar Menor (Figura 2), lo que suele provocar una estratificación de las aguas de la laguna, una proliferación masiva de algas y la consecuente mortalidad de la fauna y flora de la laguna costera debido a la falta de oxígeno.

Figura 2. Entrada de sedimentos y nutrientes al Mar Menor tras las lluvias torrenciales de septiembre 2019. Fuente: satélite Sentinel-2 de Copernicus

La recuperación del Mar Menor es un proceso largo y complejo (Álvarez-Rogel et al., 2020), el cual requiere de actuaciones y medidas eficaces para poder revertir el proceso de degradación ambiental bajo el que se encuentra inmerso. La entrada de contaminantes y nutrientes ha sido identificada como una de las presiones prioritarias de actuación, desarrollándose en los últimos años diversas normativas en esta línea (BOE, 2020; BORM, 2019, 2018, 2017) para conseguir que el Mar Menor recupere un buen estado ambiental. La implementación en la zona de mejores prácticas de gestión agrícolas (BMP, en inglés) puede jugar un papel importante en la reducción de los contaminantes y nutrientes entrantes a la laguna costera. Sin embargo, en estas BMPs, pese a haber sido propuestas como medidas a implementar, su eficacia no ha sido aún comprobada y validada por la comunidad científica. Por tanto, uno de los objetivos de la presente tesis consiste en evaluar la eficacia de estas medidas mediante su simulación en un modelo integrado de la zona de estudio.

2.2 La modelización como herramienta para la toma de decisiones

El desarrollo de modelos para lograr un mejor entendimiento de la realidad y evaluar posibles escenarios de cambio se ha convertido en una práctica habitual en la comunidad científica. La modelización hidrológica e hidráulica es con frecuencia utilizada por científicos de todo el mundo, para tratar de buscar soluciones a los problemas relacionados con los recursos hídricos y la calidad de las aguas en ecosistemas acuáticos (Gassman et al., 2014). Esta modelización abarca un amplio abanico de posibilidades que puede ir desde la estimación del impacto del cambio climático sobre los recursos hídricos hasta la evaluación del efecto de las BMPs sobre la calidad de las aguas. Además en los últimos años, la modelización ha experimentado mejoras importantes que permiten desarrollar modelos con un mayor nivel de detalle así como la combinación entre ellos para conseguir un enfoque más holístico (Rouholahnejad et al., 2014). La modelización proporciona una herramienta útil de base científica, la cual permite a los responsables de la toma de decisiones realizar un análisis más exhaustivo, de la problemática a afrontar, con una menor incertidumbre y tomar decisiones más significativas y eficaces.

Todo proceso de modelización conlleva seguir una serie de pasos necesarios para poder lograr una representación fiable de la realidad. En primer lugar, la elección del tipo de modelización a aplicar y la selección del modelo a utilizar es un punto clave. Esta selección se suele llevar a cabo en función de los objetivos que se persiguen y la complejidad del problema a estudiar. En segundo lugar, es necesaria una búsqueda exhaustiva de todos los datos de entrada al modelo, necesarios para su aplicación en la zona de estudio. Y por último, se requiere de una calibración y validación del modelo que permita reducir las incertidumbres del mismo y alcanzar una simulación significativa de la realidad mediante el uso de datos medidos y observados. Lograr la consecución satisfactoria de todos estos pasos es una tarea compleja que requiere de una toma de decisiones efectivas por parte del modelador y la inclusión de todos los condicionantes externos que afecten a la zona de estudio durante el proceso de modelización, como pueden ser las actividades antrópicas llevadas a cabo en la zona. Para el desarrollo de esta tesis se seleccionó como metodología principal la modelización hidrológica, la cual fue combinada a posteriori con un modelo hidrodinámico con el objetivo de lograr un enfoque holístico de toda la zona de estudio. A continuación se describen las características generales de los dos tipos de modelización seleccionadas.

2.2.1 La modelización hidrológica

Los modelos hidrológicos permiten reproducir el funcionamiento de los principales procesos que componen el ciclo hidrológico de una cuenca (Figura 3). Estos procesos incluyen: la precipitación del agua y su intercepción por la naturaleza, la evapotranspiración, la infiltración y recarga del acuífero, y la generación de escorrentía superficial y subterránea. La gran complejidad de estos fenómenos hidrológicos hace necesaria una simplificación de la realidad para poder modelizar la respuesta hidrológica del sistema de estudio. Esta simplificación se lleva a cabo mediante la aplicación de una serie de ecuaciones físicas y matemáticas que permiten reproducir el comportamiento del ciclo hidrológico de la cuenca.

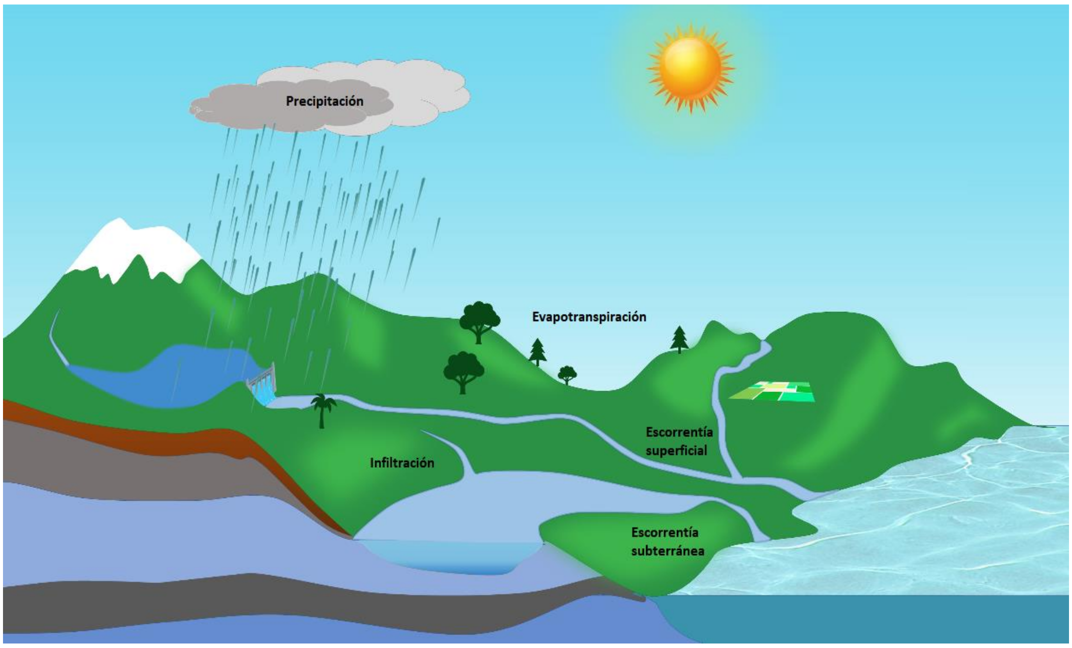

Figura 3. Componentes principales del ciclo hidrológico.

La modelización hidrológica puede llevarse a cabo a distintas escalas temporales y espaciales así como bajo diferentes condiciones de contorno. Este tipo de modelización combina componentes climáticas, características físicas y actividades antrópicas desarrolladas en la zona de estudio, proporcionando un enfoque integral que permite simular con mayor precisión los procesos hidrológicos de la cuenca de estudio.

Los modelos hidrológicos pueden clasificarse en dos grandes grupos: los modelos estocásticos y los modelos determinísticos. Los modelos estocásticos se basan en las leyes de la probabilidad y el azar mientras que los modelos determinísticos están basado en formulaciones y procesos físicos descritos mediantes ecuaciones matemáticas. De forma paralela, los modelos hidrológicos pueden ser a su vez clasificados en función del grado de discretización espacial de sus parámetros y variables. Siguiendo con la clasificación anterior, los modelos hidrológicos se consideran agregados si sus parámetros no varían espacialmente y distribuidos si se produce una variación espacial de los parámetros dentro de la zona de estudio. Una clasificación intermedia entre ambos serían los modelos semidistribuidos, los cuales poseen una variación espacial de los parámetros pero a escala de subcuenca.

2.2.2 La modelización hidrodinámica

Un modelo hidráulico es un modelo matemático que permite simular y analizar el comportamiento mecánico de un fluido. La mecánica de fluidos se divide en dos grandes áreas de conocimiento: la hidrodinámica y la hidrostática. Mientras que hidrodinámica es la parte de la hidráulica que se encarga de estudiar el movimiento del agua en un sistema físico, la hidrostática se encarga de estudiar el comportamiento del agua en reposo. Por tanto para el caso de estudio que concierne a la presente tesis, la modelización hidrodinámica fue seleccionada para poder estimar y cuantificar con precisión los componentes del balance hídrico de la laguna costera estudiada. Conocer con exactitud el volumen de los principales flujos de agua que rigen el comportamiento hidrodinámico del Mar Menor, supone un gran avance en el entendimiento de la dinámica fisicoquímica y biológica de la laguna. Además, la combinación del modelo hidrodinámico con el modelo hidrológico es necesaria para mejorar la calidad de los resultados, ya que son las aguas procedentes de la cuenca vertiente la que poseen una mayor influencia en estos procesos hidrodinámicos.

III – MATERIALES Y MÉTODOS

III – MATERIALES Y MÉTODOS

3.1 ÁREA DE ESTUDIO

3.1.1 La cuenca vertiente al Mar Menor: El Campo de Cartagena

La cuenca hidrográfica que vierte sus aguas al Mar Menor es conocida como Campo de Cartagena. El Campo de Cartagena se encuentra localizado al sureste de la península ibérica entre la latitud 38° 00′ - 37° 00′ N y la longitud 1° 50′ - 0° 40′ O, dentro de la cuenca hidrográfica del rio Segura (Figura 4).

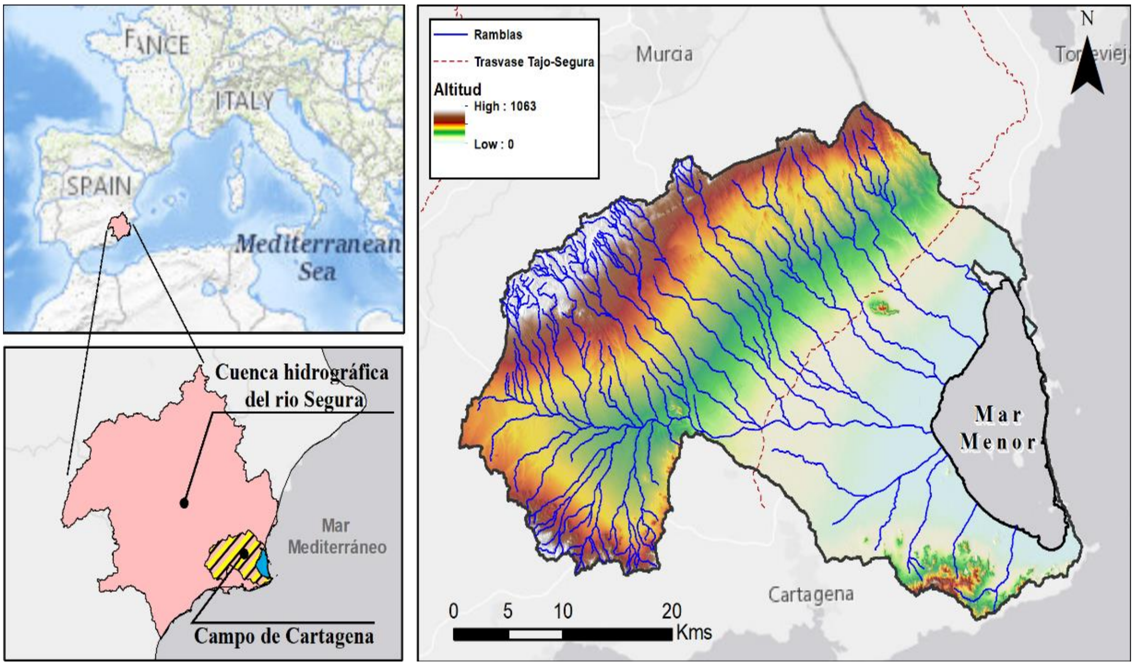

Figura 4. Mapa de ubicación y características físicas del Campo de Cartagena.

Esta región se caracteriza por ser una de las áreas con mayor estrés hídrico de Europa (Senent-Aparicio et al., 2016). Sin embargo, a pesar de su déficit de agua estructural, el cual le obliga a obtener agua de otras zonas o emplear recursos hídricos no convencionales como son las desoladoras o aguas reutilizadas, el Campo de Cartagena es considerado uno de los mayores productores agrícolas tanto a nivel nacional como internacional, principalmente de hortalizas y cítricos.

La agricultura intensiva del Campo de Cartagena se encuentra sostenida mayoritariamente por el agua procedente del trasvase Tajo-Segura y los recursos hídricos subterráneos disponibles en la zona ya que no dispone de cursos permanentes de agua. Además, esta agricultura presenta una alta tecnificación de sus sistemas de regadío lo cual le permite una gran eficiencia de riego y un máximo aprovechamiento de los recursos hídricos. El Campo de Cartagena abarca un área total de 1,244 km^2, con un uso de suelo principalmente agrícola de aproximadamente el 75% de toda la cuenca, como puede verse en la Tabla 1.

Tabla 1. Principales usos del suelo en el Campo de Cartagena.

Uso del suelo	Área (km^2)	Porcentaje de Ocupación (%)
Cultivos herbáceos en regadío	449	36.1
Frutales en secano	200	16.1
Matorrales	141	11.3
Cítricos en regadío	114	9.2
Tierras de labor en secano	103	8.3
Improductivo	100	8
Huerta	29	2.3
Frutales en regadío	28	2.3
Bosques de coníferas	25	2
Matorral asociado a coníferas	20	1.6
Otros usos	35	2.8

En cuanto a la topografía, cabe destacar que aproximadamente el 40% de la zona de estudio posee una pendiente inferior al 2% lo cual clasifica este área como una zona llana de pendientes suaves. Como puede observarse en la Figura 4, la altitud varía desde 1,063 metros hasta el nivel del mar, encontrándose las zonas de menor pendiente en las proximidades a la laguna costera y las zonas de mayor altitud en la cabecera de la cuenca hidrográfica. Con respecto a la tipología del suelo predomina una textura limosa compuesta principalmente por sílice y arena, clasificada según la FAO-ISRIC (1990) como Cambisol Calcárico.

3.1.1.1 Principales características climáticas

El Campo de Cartagena posee un clima semiárido caracterizado por inviernos suaves y altas temperaturas en verano, rasgo característico del clima mediterráneo. La temperatura media anual de aproximadamente 17 °C y la precipitación media en torno a los 300 mm/año. Esta precipitación posee una gran variabilidad interanual (Figura 5), produciéndose principalmente en otoño y primavera, y suele caer de forma torrencial (García-Pintado et al., 2007). La evapotranspiración potencial media se encuentra alrededor de los 1,300 mm/año y las horas de sol superan las 3,000 al año.

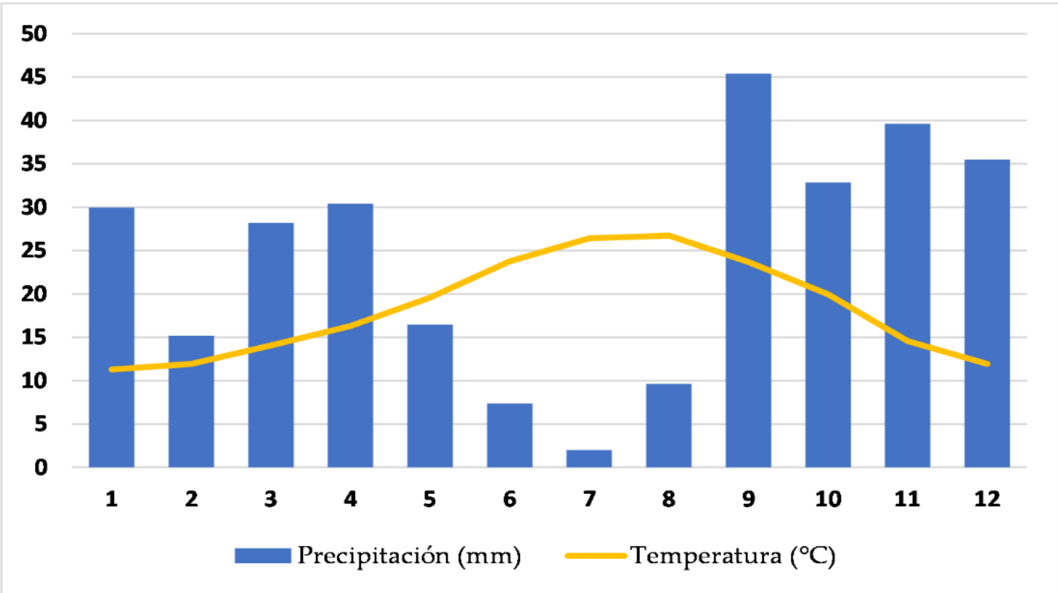

Figura 5. Variación interanual de la de la precipitación y temperatura media del Campo de Cartagena.

La características climáticas anteriormente descritas hacen que el Campo de Cartagena no presente cauces permanentes de agua y su red de drenaje este compuesta por ramblas de poca pendiente y sección amplia, las cuales permanecen secas la mayor parte del año excepto durante los eventos de precipitaciones extremas (Alcolea et al., 2019). Estos eventos de lluvias torrenciales, cada vez más frecuentes, son los principales causantes de la entrada masiva de nutrientes y sedimentos al Mar Menor a través de las aguas que recogen las ramblas.

3.1.1.2 Principales actividades antrópicas

La actividades antrópicas que se han desarrollado a lo largo del tiempo en el Campo de Cartagena son la agricultura, el turismo y antiguamente la minería. Hoy en día, el turismo de costa y la agricultura intensiva son los principales motores económicos de la zona. Las extracciones de metales pesados de la sierra minera de Cartagena-La Unión, localizada en la parte sur del CC, cesaron su actividad de forma definitiva en 1990. Sin embargo, graves problemas ambientales debido a la explotación continua de los recursos mineros se arrastran hasta nuestros días. En cuanto al turismo, cabe destacar que se concentra en la zona costera del Mar Menor, la cual se vio afectada por un fuerte desarrollo urbanístico y ve multiplicada su población durante los meses de verano. Además, el Campo de Cartagena es una zona de crecimiento demográfico continuo desde los años 80, debido principalmente al efecto llamada del sector agrícola y turístico. Sin embargo, es la agricultura de regadío la principal actividad antrópica de la zona. Como ya se ha comentado anteriormente el uso del suelo agrícola ocupa casi el 75% del Campo de Cartagena, debido a la buenas condiciones térmicas y edáficas de la zona, siendo en torno al 50% cultivos bajo sistemas de riego. Fue a partir de 1979, cuando se puso en marcha el trasvase Tajo-Segura, y por tanto cuando comenzó la intensificación del regadío en la zona media – baja de la cuenca. Los cultivos hortícolas, los cítricos y los invernaderos son los principales usos agrícolas de regadío. Este regadío presenta una alta tecnificación, con más del 90% del sistema de riego llevado a cabo por goteo (Alcon et al., 2011). Esta agricultura intensiva presenta cultivos de gran variación estacional según la demanda del mercado, que pueden llegar hasta tres rotaciones anuales. La Tabla 2 muestra un esquema estándar de cultivo hortícola con tres rotaciones anuales llevado a cabo en el Campo de Cartagena y las prácticas agrícolas comunes empleadas para ello.

Tabla 2. Esquema estándar de cultivo hortícola y sus prácticas agrícolas en el Campo de Cartagena.

Año	Fecha		Practica agrícola	Cantidad aplicada	Cultivo
	Mes	Día			
1	Enero	1	Plantación		Bróculi
1	Enero	1	Riego	~28 mm/mes	Bróculi
1	Enero	1	Fertilización[1]	245 KgN/ha/año 100 KgP/ha/año	Bróculi
1	Abril	30	Cosecha		Bróculi
1	Mayo	1	Plantación		Melón
1	Mayo	1	Riego	~48 mm/mes	Melón
1	Mayo	1	Fertilización[1]	225 KgN/ha/año 105 KgP/ha/año	Melón
1	Agosto	31	Cosecha		Melón
1	Septiembre	1	Plantación		Lechuga
1	Septiembre	1	Riego	~25 mm/mes	Lechuga
1	Septiembre	1	Fertilización[1]	100 KgN/ha/año 58 KgP/ha/año	Lechuga
1	Diciembre	31	Cosecha		Lechuga

[1] Cantidad total aplicada por fertirrigación a lo largo de todo el cultivo

En cuanto a los cítricos, el cultivo predominante es el naranjo o limonero mientras que en los invernaderos es el pimiento. El uso de invernaderos o acolchados es una práctica habitual en el Campo de Cartagena que permite la reducción de las perdidas por evaporación. Sin embargo, la alta intensidad de cultivo hace que las demandas hídricas sigan siendo altas.

3.2 Soil and Water Assessment Tool (SWAT)

SWAT (Soil and Water Assessment Tool) es un modelo hidrológico determinístico y semidistribuido desarrollado por el Servicio de Investigación Agrícola del Departamento de Agricultura de los Estados Unidos (USDA; Arnold et al., 1998). SWAT es un modelo de simulación continua que trabaja a escala diaria y ha sido diseñado para evaluar el impacto de las prácticas agrícolas y cambios del uso del suelo sobre los componentes del ciclo hidrológico y el transporte de sedimentos y nutrientes a escala de cuenca. Entre otros, el modelo SWAT permite simular escenarios de cambio climático, de gestión de recursos hídricos y de calidad de las agua. SWAT es uno de los modelos hidrológicos más utilizados a nivel mundial y que cuenta con más de 30 años de utilización y mejoras continuas. La gran aceptación del modelo SWAT por la comunidad científica internacional puede ser atribuida a su carácter de software libre y gratuito además de a su alta eficiencia computacional, su intuitiva interfaz apoyada en herramientas de Sistema de Información Geográfica (SIG) y su amplia comunidad de usuarios y desarrolladores (Gassman et al., 2014). Los principales componentes del modelo SWAT son el clima, la hidrología, la erosión del suelo, el ciclo de los nutrientes y las prácticas agrícolas.

Los procesos simulados por SWAT incluyen la generación de escorrentía superficial y subterránea, la evapotranspiración, la infiltración y recarga de acuíferos, y la circulación de las aguas, sedimentos y nutrientes a través de la red de drenaje. Para llevar a cabo esta simulación, SWAT divide la cuenca hidrográfica en varias subcuencas, las cuales son a sus vez divididas en Unidades de Respuesta Hidrológica (HRU, en inglés), agrupando para ello zonas con características homogéneas, es decir con un mismo uso del suelo, tipo de suelo y rango de pendientes. Los procesos del ciclo hidrológico son simulados en SWAT mediante la aplicación de la ecuación del balance hídrico (Ecuación 1) en cada HRU.

$$SW_{t\,i} = SW_{o\,i} + \sum\left(R_{day\,i} - Q_{surf\,i} - ET_i - W_{seep\,i} - Q_{gw\,i}\right) \qquad (1)$$

donde SWt es el contenido de agua final en el día i (mm); SWo es el contenido de agua inicial en el día i (mm); Rday es la precipitación en el día i (mm); Qsurf es la escorrentía superficial en el día i (mm); ET la evapotranspiración en el día i (mm); Wseep es la infiltración en el día i (mm) y Qgw is la escorrentía subterránea en el día i (mm).

Este balance hídrico tiene una gran influencia tanto en la parte ecológica del modelo (vegetación) como en los procesos de generación y transporte de sedimentos y nutrientes. Una vez estimado el balance hídrico de cada HRU, sus resultados son agregados a escala de subcuenca y llevados a la red de drenaje para la simulación de su comportamiento hidráulico. El proceso de simulación hidrológica del modelo SWAT se divide en dos fases: una primera fase terrestre que se encarga de estimar la cantidad de agua, sedimentos y nutrientes arrastrados hasta la red de drenaje principal y una segunda fase de circulación de aguas, la cual se centra en el movimiento del agua, sedimentos y nutrientes desde la red de drenaje hasta el punto de salida de la cuenca de estudio (Arnold et al., 2012).

3.2.1 Datos de entrada y preparación del modelo SWAT

El modelo SWAT requiere de un gran número de datos de entrada para su aplicación tales como datos climáticos, mapas de usos y tipos de suelo, mapas topográficos e información sobre prácticas agrícolas llevadas a cabo en la zona (Neitsch et al., 2011). Los datos climáticos necesarios en SWAT son: la precipitación, la temperatura máxima y mínima, la humedad relativa, la radiación solar y la velocidad del viento, todos ellos a escala diaria. La Tabla 3 muestra información detallada sobre los datos de entrada utilizados para el desarrollo del modelo SWAT en las zonas de estudio de la presente tesis. La resolución espacial y temporal de los datos de entrada es función de su disponibilidad.

Tabla 3. Datos de entrada utilizados del modelo SWAT.

Dato de entrada	**Descripción**	**Fuente**
Modelo Digital del Terreno (MDT)	MDT 1ª Cobertura con resolución espacial de 25 m MDT 1ª Cobertura con resolución espacial de 5 m	Instituto Geográfico Nacional (IGN) de España
Mapa de usos del suelo	Mapa de cultivos y aprovechamientos de España escala 1:50,000	Ministerio de medio ambiente, y medio rural y marino (2000–2010)
Mapa de tipos de suelo	Mapa raster con resolución espacial de 1 km	Base de Datos Armonizada de los Suelos del Mundo (HWSD)
Datos climáticos	Precipitación, temperatura, humedad relativa, radiación solar y velocidad del viento a escala diaria de las estaciones MU62, CA21, CA42, CA91, CA52 y TP42	Instituto Murciano de Investigación y Desarrollo Agrario y Medioambiental (IMIDA)

Para la obtención de la escorrentía superficial, el modelo SWAT proporciona dos métodos de cálculo distintos: el método del número de curva (CN) desarrollado por el Servicio de Conservación del Suelo de los Estados Unidos (SCS) (USDA-SCS, 1972) y el método de Green & Ampt (1911). En todas las zonas de estudio de la presente tesis, el método seleccionado para el cálculo de la escorrentía fue el CN del SCS. Del mismo modo, SWAT permite el uso de tres métodos distintos para la estimación de la evapotranspiración potencial (ETP): Penman-Monteith (Monteith, 1965), Priestley-Taylor (Priestley & Taylor, 1972), y Hargreaves (Hargreaves et al., 1985). Debido a la disponibilidad de todos los datos climáticos necesarios para su aplicación, la metodología de cálculo de la ETP seleccionada fue Penman-Monteith. Todos los modelos de SWAT fueron desarrollados a partir de su versión para QGIS conocida como QSWAT (Dile et al., 2016). Las principales masas de agua presentes en las zonas de estudio fueron introducidas al modelo mediante la herramienta SWAT2lake (Molina-Navarro et al., 2018), la cual permite modelizar con SWAT el área total de drenaje que afecta a la masa de agua estudiada.

3.2.2 Calibración y validación del modelo SWAT

El proceso de calibración y validación del modelo se realizó mediante la comparación de los valores simulados por SWAT con los valores observados. Este proceso permite realizar un ajuste de los parámetros del modelo y así conseguir una simulación más precisa de la realidad. El proceso de calibración puede llevarse a cabo de forma manual o de forma automática. En el desarrollo de la presente tesis ambas formas de calibración fueron utilizadas. Con respecto a los valores observados, debido a la ausencia de datos de aforo medidos en el Campo de Cartagena, se utilizaron datos de teledetección, concretamente datos satelitales de evapotranspiración obtenidos de GLEAM (Global Land Evaporation Amsterdam Model). GLEAM es una base de datos desarrollada por la Universidad de Amsterdam (Miralles et al., 2011), la cual incluye varios algoritmos encargados de estimar la evaporación y humedad del suelo a partir de datos de teledetección. La Tabla 4 muestra información de todos los parámetros de SWAT utilizados para la calibración de los modelos desarrollados en esta tesis.

Tabla 4. Parámetros modelo SWAT utilizados para la calibración.

Parámetro	Descripción	Unidades	Valores limite
CN2.mgt	Número de curva inicial del método CN del SCS		35 - 98
ESCO.hru	Factor de compensación de la evaporación del suelo		0 - 1
EPCO.hru	Factor de compensación de la captación de agua por la vegetación		0 - 1

SOL_AWC.sol	Contenido de agua disponible en el suelo	mm/mm	0 - 1
RCHRG_DP.gw	Factor de recarga del acuífero profundo		0 - 1
SOL_BD.sol	Densidad del suelo húmedo	mg/m^3	0.95 – 2.5
SOL_K.sol	Conductividad hidráulica del suelo saturado		0 - 2000
CANMX.hru	Almacenamiento máximo de agua en la cobertura vegetal	mm	0 - 100
Alpha_BF.gw	Coeficiente de recesión del flujo base	días	0 - 1

Los parámetros de la Tabla 4 fueron seleccionados basándose en la aplicación de un análisis de sensibilidad durante el proceso de calibración automática y en la experiencia adquirida sobre las zonas de estudio durante la modelización. Para la calibración automática, se utilizó el algoritmo SUFI-2 (Sequential Uncertainty Fitting) incluido en el programa SWAT-CUP (SWAT Calibration and Uncertainty Programs) (Abbaspour, 2012). Durante este proceso automático, se realizó un total de 1000 simulaciones divididas en dos lotes de 500. La función objetivo utilizada para la calibración de la ET fue el coeficiente de eficiencia de Kling–Gupta (KGE) (Gupta et al., 2009) (Ecuación 2). Otros estadísticos, tal como el coeficiente de eficiencia de Nash-Sutcliffe (NSE) (Nash & Sutcliffe, 1970) (Ecuación 3), el coeficiente de determinación (R^2) (Ecuación 4) y el porcentaje del sesgo (PBIAS) (Ecuación 5), fueron también utilizados para la determinación de la bondad del ajuste durante el proceso de calibración y validación.

$$KGE = 1 - \sqrt{(\alpha - 1)^2 + (\beta - 1)^2 + (\gamma - 1)^2} \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Yobs_i - Ysim_i)^2}{\sum_{i=1}^{n}\left(Yobs_i - \overline{Yobs}\right)^2} \quad (3)$$

$$R^2 = \frac{\sum_{i=1}^{n}\left(Yobs_i - \overline{Yobs}\right)\left(Ysim_i - \overline{Ysim}\right)}{\sqrt{\sum_{i=1}^{n}\left(Yobs_i - \overline{Yobs}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Ysim_i - \overline{Ysim}\right)^2}} \quad (4)$$

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Yobs_i - Ysim_i\right)}{\sum_{i=1}^{n} Yobs_i} * 100 \quad (5)$$

Donde $Yobs_i$ e $Ysim_i$ son los datos observados y simulados, $\overline{Yobs}$ e $\overline{Ysim}$ es el valor medio de los datos observados y simulados, n es el número total de datos, α es el coeficiente de correlación de Pearson, β es el factor de desviación estandar y γ es la media de los valores simulados entre la media de los valores observados. NSE y KGE varían desde -∞ hasta 1, siendo 1 el valor óptimo. R^2 varía entre 0 y 1, produciendo los valores más cercanos a 1 la mejor simulación y el PBIAS, el cual estima la infra o sobre estimación del valor total del modelo, es 0 su valor óptimo.

3.3 Water Ecosystems Tool (WET)

El modelo WET (Nielsen et al., 2017) es una versión actualizada del acoplamiento del modelo hidrodinámico unidimensional GOTM (General Ocean Turbulence Model) y el modelo de ecosistemas acuáticos FABM (Framework for Aquatic Biogeochemical Models). Por tanto, WET es un modelo hidrodinámico y ecosistémico unidimensional el cual permite la evaluación de distintos escenarios de cambio, tanto climáticos como de carga de nutrientes, y su impacto sobre los ecosistemas acuáticos. La parte del modelo GOTM se encarga de la simulación de la estratificación termal y del cálculo de las turbulencias mediante las ecuaciones de transporte de la energía cinética y de su ratio de disipación. La Figura 6 muestra el mapa conceptual del ecosistema acuático modelado con WET.

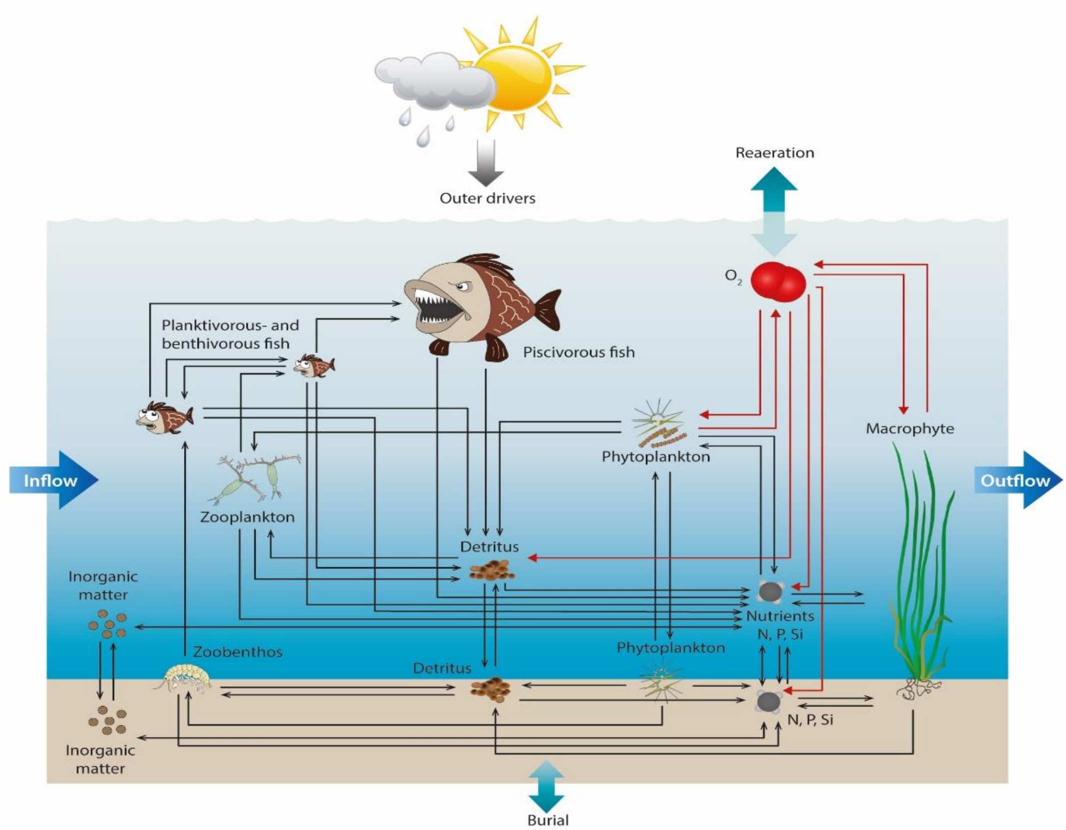

Figura 6. Mapa conceptual del ecosistema acuático en WET. Fuente: https://projects.au.dk/wet.

En la presente tesis el modelo WET fue utilizado a través de su interfaz para QGIS conocida como QWET (QGIS Water Ecosystems Tool). QWET es una herramienta de código abierto la cual proporciona una interfaz gráfica de fácil entendimiento para el usuario y permite la simulación tanto hidro como termodinámica de masas de agua. Además, QWET puede utilizar los datos de salida del modelo SWAT como datos de entrada, lo que permite una combinación rápida y eficaz entre ambos modelos.

3.3.1 Datos de entrada y preparación del modelo WET

El modelo WET requiere de la introducción de datos de características físicas de la masa de agua, tales como la relación área y profundidad, y datos climáticos como la precipitación directa sobre la masa de agua, la dirección y velocidad del viento, la temperatura del aire, la presión del aire, el punto de rocío y el factor de cobertura de las nubes. Para la presente tesis, los datos climáticos fueron obtenidos a escala horaria de la estación del IMIDA más cercana y de la base de datos ERA5 creada por el centro europeo de previsión del tiempo a medio plazo (ECMWF). Esta base de datos presenta una resolución espacial de 31 km. Además, como dato de entrada de caudales a la masa de agua modelizada se utilizó las serie de caudales simuladas por el modelo SWAT.

3.3.2 Validación del modelo WET

El proceso de calibración del modelo WET no fue necesario debido a la calibración previa de los datos de entrada de caudales obtenidos en SWAT. Sin embargo, sí que se llevó a cabo un proceso de validación utilizando para ello datos diarios de temperatura del agua proporcionados por el gobierno regional de la Comunidad Autónoma de Murcia a través de la página web https://canalmarmenor.carm.es/. Como estadísticos de comprobación de la bondad del ajuste del modelo WET se empleó NSE y PBIAS así como el error cuadrático medio (RMSE).

3.4 PRÁCTICAS DE GESTIÓN AGRÍCOLA (BMP)

En este apartado se muestran las distintas BMPs simuladas con el modelo SWAT. Entre ellas se encuentran la plantación siguiendo las curvas de nivel, la implantación de barreras vegetales, los cambios de usos del suelo, la reducción de la aplicación de fertilizantes, la construcción de diques, la restauración de la vegetación de los cauces, el cambios en la rotación anual de cultivos, la recolección de aguas de lluvia en los invernaderos y las distintas combinaciones entre cada una de ellas.

3.4.1 Descripción de las BMPs y su simulación con SWAT

3.4.1.1 Plantación siguiendo las curvas de nivel

Esta BMP consiste en la plantación, arado y cosecha de los cultivos siguiendo las líneas de contorno del terreno. La plantación siguiendo las curvas de nivel provoca un aumento de la infiltración del suelo, y por tanto una reducción de la escorrentía superficial. Este descenso de la escorrentía provoca a su vez una reducción de la erosión del terreno y de los fertilizantes arrastrados fuera de la zona de cultivo durante los episodios de lluvias intensas (Liu et al., 2013). Para llevar a cabo su simulación, se activó la opción de "Contouring" en el módulo de operaciones de SWAT (.ops). Esta opción permite la modificación de los parámetros CONT_CN y CONT_P, cuyos valores se ajustaron siguiendo las recomendaciones de Arnold et al. (2012) para la plantación de cultivos siguiendo las curvas de nivel.

3.4.1.2 Implantación de barreras vegetales

Las barreras vegetales son bandas de vegetación instaladas siguiendo los bordes de los cultivos, con el objetivo de interceptar y reducir la escorrentía superficial, y atrapar los sedimentos y nutrientes presentes en ella. Para su simulación, SWAT utiliza la ecuación 6 de eficiencia de atrapamiento ($trap_{ef}$) de sedimentos y nutrientes, la cual es función del ancho de la barrera vegetal (FILTERW).

$$trap_{ef} = 0.367 \cdot FILTERW^{0.2967} \quad (6)$$

3.4.1.3 Cambios de usos del suelo

El cambio en los usos del suelo consiste en la modificación de las actividades llevadas a cabo en zonas específicas de la cuenca con el objetivo de mejorar la situación ambiental de toda la cuenca hidrográfica y su área de influencia. Existen dos formas de llevar a cabo este cambio de usos del suelo en SWAT. Una de ella es la utilización del módulo de actualización de usos del suelo de SWAT (.lup) y la otra es la transformación de los mapas de uso de suelo mediante herramientas SIG. La Tabla 5 muestra los diferentes cambios de usos del suelo simulados durante el desarrollo de la tesis.

Tabla 5. Cambios de usos del suelo simulados con SWAT.

BMP	**Descripción**
Reforestación	Restauración a su estado natural de los bosques en las zonas de explotación minera
Buffer 500 m	Eliminación de toda la agricultura de regadío existente dentro de un área de 500 m alrededor del Mar Menor
Buffer 1500 m	Eliminación de toda la agricultura de regadío existente dentro de un área de 1500 m alrededor del Mar Menor
Buffer Zona 1	Eliminación de toda la agricultura de regadío existente dentro del área de protección conocida como Zona 1 según BOE (2020).
Agricultura ilegal	Eliminación de la agricultura sin derecho a regadío dentro del área de estudio

3.4.1.4 Reducción de la aplicación de fertilizantes

La calidad de las aguas puede mejorar mediante la reducción de la cantidad total de nutrientes aplicados a los cultivos (Risal & Parajuli, 2022). Para llevar a cabo esta BMP en SWAT, se redujo la cantidad de nitratos y fosfatos aplicados a los cultivos en un 20%, tal y como recomiendan el Código de Buenas Prácticas Agrarias de la Región de Murcia (BORM, 2018) y la comisión europea (EC, 2020). Este porcentaje de reducción fue aplicado a los ratios de fertilización del esquema estándar de cultivo (Tabla 2).

3.4.1.5 Construcción y restauración de diques

La construcción de diques a lo largo de la red de drenaje permite la interceptación de los sedimentos y nutrientes transportados en los cauces y reduce la erosión de los mismos. Estos diques requieren de un mantenimiento continuo para evitar su colmatación, por lo que a veces es necesaria su restauración. La simulación de diques en SWAT se realizó utilizando su módulo de estanques (.pnd), mediante la modificación del parámetro PND_FR el cual representa el porcentaje de la subcuenca que drena al dique.

3.4.1.6 Restauración de la vegetación de los cauces

La restauración de cauces consiste en la recuperación de la vegetación autóctona de la red de drenaje para la reducción de la velocidad del agua y de la erosión del canal. Para su simulación en SWAT se utilizó el módulo de operaciones (.ops), en concreto la opción de vegetación en los cauces. En esta opción se modificaron los parámetros GWATN y GWATL correspondientes al número de Manning en el cauce y a la longitud total del cauce afectado por la restauración, respectivamente.

3.4.1.7 Cambios en la rotación anual de cultivos

Llevar a cabo una buena gestión de los cultivos es necesario para poder lograr una reducción de la cantidad de sedimentos y nutrientes arrastrados fuera de los mismos. Mediante el cambio del esquema de cultivo se puede lograr un mejor control del exceso de fertilizantes y la perdida de suelo. Además, es recomendable un cultivo de cobertura durante los meses de no cultivo para evitar dejar al suelo sin protección. Para simular esta BMP con SWAT, se modificó el esquema de cultivo utilizado de tres a dos cultivos anuales desde el módulo de agricultura (.mgt) de SWAT y se introdujo vegetación de cobertura durante los meses de no cultivo.

3.4.1.8 Recolección de aguas de lluvia en los invernaderos

La recolección de aguas de lluvia es una práctica común que permite el uso de aguas de lluvia para riego y reduce la escorrentía superficial durante estos episodios (Waidler et al., 2009). El módulo de estanques (.pnd) de SWAT ha sido utilizado para implementar esta BMP. En este módulo se consideró la superficie total de los invernaderos dentro de cada subcuenca mediante el parámetro PND_FR y se modificaron los valores de los parámetros del volumen de agua almacenado (PND_PVOL) y la superficie de agua con el depósito lleno (PND_PSA) para asemejarlos a los depósitos de almacenamiento de aguas de lluvia.

3.4.1.9 Combinación de BMPs

La combinación de diferentes BMPs suele provocar un efecto sinérgico, el cual proporciona mejores resultados que la aplicación individual de las mismas. Las BMPs pueden clasificarse en estructurales o agrícolas en función de la zona de aplicación de las mismas. Si se aplican a escala de parcela se consideran agrícolas, mientras que si se aplican fuera de ella suelen ser consideradas estructurales. Esta clasificación también puede realizarse en función de quien sea el responsable de su implantación, siendo normalmente las BMP agrícolas responsabilidad de los agricultores y las estructurales responsabilidad de las entidades públicas. La simulación en SWAT de la combinación de BMPs se llevó a cabo siguiendo el criterio de clasificación anterior y simulando de forma paralela todas las BMPs.

3.4.2 Evaluación del impacto de las BMPs sobre los sedimentos y nutrientes

Para la evaluación de la eficacia de las BMPs en la reducción de sedimentos y nutrientes se extrajeron del modelo SWAT las cargas medias anuales de sedimento total (S), nitrógeno total (TN) y fosforo total (TP) para cada uno de los escenarios de BMP simulados. Una vez obtenidas las cantidades simuladas por cada uno de los escenarios, estos resultados fueron comparados con los obtenidos en el escenario base mediante la aplicación de la ecuación 7.

$$Efectividad = \frac{(Y_{base} - Y_{BMP})}{Y_{base}} \cdot 100 \tag{7}$$

Donde Y_{base} e Y_{BMP} son las cargas medias anuales de sedimentos y nutrientes (t/año) estimados en el escenario base y en los escenarios de BMP, respectivamente.

3.4.3 Análisis de coste-eficacia

La implantación de BMPs tiene un impacto económico tanto a corto como a largo plazo (Ricci et al., 2020). Por tanto, la evaluación de su coste-eficacia es necesaria para poder priorizar las BMP que generen una mayor reducción de los sedimentos y nutrientes a un menor costo. Este análisis de coste-eficacia se llevó a cabo mediante el uso del ratio de coste-efectividad (CE ratio) representado por la ecuación 8, la cual compara el coste total de la implantación del escenario de BMPs simulado con la eficacia mostrada por dicho escenario en la reducción de S, TN y TP.

$$CE\ ratio = \frac{Coste\ Total}{Efectividad} \tag{8}$$

El CE ratio representa el coste por unidad de porcentaje de cambio de las cargas contaminantes. Por tanto, un valor bajo de CE ratio representa una mayor coste-eficacia del escenario BMP.

IV – PUBLICACIONES

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De la presente tesis se derivaron tres artículos científicos con el objetivo de realizar un compendio de publicaciones para su presentación. Todos los artículos fueron corregidos por revisores anónimos y aprobados para su publicación en revistas indexadas en JCR. A continuación se muestra un breve resumen de cada uno de los artículos.

- **Publicación 1:** La primera publicación que compone la tesis fue titulada "Assessing the Impact of Best Management Practices in a Highly Anthropogenic and Ungauged Watershed Using the SWAT Model: A Case Study in the El Beal Watershed (Southeast Spain)". Este artículo se centra en la evaluación de BMPs con el objetivo de controlar la cantidad de sedimentos y nutrientes que se vierten a la laguna costera del Mar Menor desde una pequeña cuenca situada en la parte sur de la laguna. Esta pequeña cuenca hidrográfica conocida como "Cuenca de la rambla del Beal" se caracteriza por su alto nivel de antropización, debido a la existencia de agricultura intensiva y antiguas explotaciones mineras dentro de la misma. Además, esta zona de estudio no cuenta con mediciones de aforo, lo que hizo necesario aplicar el novedoso enfoque de utilización de datos de evapotranspiración satelital para la calibración y validación de su modelo hidrológico. Siguiendo con la metodología general de la presente tesis, la modelización hidrológica se realizó con el modelo SWAT en el cual cinco BMPs diferentes fueron simuladas y evaluadas bajo un total de diez escenarios individuales y combinados. Los resultados mostraron un buen ajuste del modelo tanto en el periodo de calibración como en el de validación. También se observó que a nivel individual, la restauración o construcción de diques y el cambio de uso del suelo minero a uso forestal presentaban los mejores resultados de reducción de sedimentos y nutrientes exportados al Mar Menor. Además, los resultados mostraron una mayor efectividad cuando se realizó una combinación de las

BMPs. Este estudio supuso un primer acercamiento a la evaluación de posibles soluciones para afrontar la problemática medioambiental del Mar Menor.

- **Publicación 2:** El siguiente artículo científico de la tesis se tituló "A holistic approach for determining the hydrology of the mar menor coastal lagoon by combining hydrological & hydrodynamic models". En esta segunda publicación se llevó a cabo una combinación del modelo hidrológico SWAT con la parte hidrodinámica del modelo WET. Mediante el uso de SWAT, se modelizó toda la cuenca vertiente a la laguna costera del Mar Menor, conocida como Campo de Cartagena, y con el modelo WET se simularon los procesos hidrodinámicos de la laguna costera. Primeramente, se llevó a cabo el proceso de calibración y validación del modelo SWAT del Campo de Cartagena siguiendo el enfoque de uso de datos de teledetección utilizado en la primera publicación de esta tesis, debido a la ausencia de datos aforados en la zona de estudio. Lograda una modelización satisfactoria, se realizó el acoplamiento de ambos modelos SWAT y WET, con la herramienta QWET, mediante la utilización de los datos de salida del modelo hidrológico como datos de entrada de WET. Este acoplamiento permitió simular las componentes del balance hídrico de la laguna costera del Mar Menor. La bondad del ajuste del modelo WET fue verificada mediante el uso de datos de temperatura del agua y evaporación de la laguna a escala diaria. Por último, mediante la combinación de ambos modelos se consiguió cerrar el balance hídrico de la laguna costera, observándose una entrada generalizada de agua desde el Mar Mediterráneo al Mar Menor. El acoplamiento de ambos modelos proporciono un enfoque novedoso y de gran utilidad para mejorar el entendimiento de los procesos hidrológicos e hidrodinámicos que gobiernan la laguna costera del Mar Menor. Este mejor entendimiento permite desarrollar estrategias más efectivas para conseguir la sostenibilidad ambiental en zonas altamente antropizadas.

- **Publicación 3:** El último artículo de la tesis es el titulado "Assessing the effectiveness of potential best management practices for science-informed decision support at the watershed scale: The case of the Mar Menor coastal lagoon, Spain". Este artículo es una ampliación de la publicación anterior y fue desarrollado en base al modelo SWAT del Campo de Cartagena mediante la aplicación de una serie de mejoras, sobretodo de la parte agrícola. En este artículo se llevó a cabo la simulación de ocho BMPs evaluadas en un total de 16 escenarios tanto individuales como combinados. Esta evaluación se centró en conocer la efectividad de la implantación de los distintos escenarios, extraídos de normativas y leyes de aplicación en la zona de estudio, sobre el control de la contaminación de la laguna a escala de toda la cuenca. Los resultados del estudio permitieron conocer el porcentaje de reducción de sedimentos y nutrientes vertidos a la laguna costera del Mar Menor bajo cada uno de los escenarios simulados. Por tanto, este estudio proporciona una base científica sobre la efectividad de las BMPs evaluadas y sirve de ayuda a los responsables de la toma de decisiones para seleccionar y priorizar las BMPs más apropiadas a escala de cuenca con el objetivo de contrarrestar de manera eficaz la problemática ambiental del Mar Menor.

4.1 RESEARCH PAPER 1: ASSESSING THE IMPACT OF BEST MANAGEMENT PRACTICES IN A HIGHLY ANTHROPOGENIC AND UNGAUGED WATERSHED USING THE SWAT MODEL: A CASE STUDY IN THE EL BEAL WATERSHED (SOUTHEAST SPAIN)

López-Ballesteros, A.; Senent-Aparicio, J.; Srinivasan, R.; Pérez-Sánchez, J. (2019). Assessing the impact of best management practices in a highly anthropogenic and ungauged watershed using the SWAT model: A case study in the El Beal Watershed (Southeast Spain). Agronomy, 9(10), 576.
https://doi.org/10.3390/agronomy9100576

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Assessing the Impact of Best Management Practices in a Highly Anthropogenic and Ungauged Watershed Using the SWAT Model: A Case Study in the El Beal Watershed (Southeast Spain)

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Received: 22 July 2019; Accepted: 14 September 2019; Published: 24 September 2019

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Abstract: Best management practices (BMPs) provide a feasible solution for non-point source pollution problems. High sediment and nutrient yields without retention control result in environmental deterioration of surrounding areas. In the present study, the soil and water assessment tool (SWAT) model was developed for El Beal watershed, an anthropogenic and ungauged basin located in the southeast of Spain that drains into a coastal lagoon of high environmental value. The effectiveness of five BMPs (contour planting, filter strips, reforestation, fertilizer application and check dam restoration) was quantified, both individually and in combination, to test their impact on sediment and nutrient reduction. For calibration and validation processes, actual evapotranspiration (AET) data obtained from a remote sensing dataset called Global Land Evaporation Amsterdam Model (GLEAM) were used. The SWAT model achieved good performance in the calibration period, with statistical values of 0.78 for Kling–Gupta efficiency (KGE), 0.81 for coefficient of determination (R^2), 0.58 for Nash–Sutcliffe efficiency (NSE) and 3.9% for percent bias (PBIAS), as well as in the validation period (KGE = 0.67, R^2 = 0.83, NS = 0.53 and PBIAS = −25.3%). The results show that check dam restoration is the most effective BMP with a reduction of 90% in sediment yield (S), 15% in total nitrogen (TN) and 22% in total phosphorus (TP) at the watershed scale, followed by reforestation (S = 27%, TN = 16% and TP = 20%). All effectiveness values improved when BMPs were assessed in combination. The outcome of this study could provide guidance for decision makers in developing possible solutions for environmental problems in a coastal lagoon.

Keywords: hydrological modelling; soil and water assessment tool (SWAT) model; evapotranspiration; GLEAM; non-point source pollution; best management practices; Mar Menor coastal lagoon

1. Introduction

Highly anthropogenic regions commonly have serious environmental problems, due to the impact of such human activities as intensive agriculture and mining extractions, among others. Environmental impact intensifies when extreme climate conditions characterize the affected area [1]. Surrounding areas that have high ecological value can also aggravate the problem. All of the conditions described above characterize the El Beal watershed, which drains into the coastal lagoon Mar Menor. A site of special environmental significance, Mar Menor has been classified as one of the most valuable and threatened sites in the European Natura 2000 network and included in the list of Wetlands of

International Importance (RAMSAR) and Specially Protected Areas of Mediterranean Importance (SPAMI) [2]. Historically, external nutrient inputs into Mar Menor occurred primarily via atmospheric deposition and groundwater, mainly due to the high ratio of sediment surface area to water volume and lack of major watercourses. Recently, as is the case for many other Mediterranean coastal zones, the area surrounding Mar Menor has experienced an intensification of agricultural practices and a marked increase in tourist activities, resulting in increased nutrient inputs into the lagoon. In 2016, the eutrophication process caused an important reduction in water turbidity, affecting the tourism industry and regional economy. The local government reacted by creating the Scientific Advisory Committee of Mar Menor [3] and approving, by decree law, some urgent measures to ensure environmental sustainability of the Mar Menor area [2,4]. These measures include fertilizer application control and the implementation of best management practices (BMPs). Such requirements are applied mainly in the surrounding areas of the coastal lagoon to mitigate the problems with water quality. The implementation of these measures promises to impact both the private and public sectors, with clear socioeconomic consequences: Recent studies appraised the economic impact of farmers' implementing these measures at over 500 million euros [5]. However, the effectiveness of the measures proposed have not yet been evaluated.

BMPs are established to ensure the environmental sustainability of a particular area. BMPs refer to the soil and water conservation practices, management techniques and social actions that protect the environment [6]. Reduction of sediment and nutrients in the incoming watercourses is a central requirement of the applied regulations in the Mar Menor coastal lagoon. BMPs are an effective mechanism to reduce sediment and nutrients from non-point sources [7]. However, there is a remarkable lack of knowledge concerning the extent to which the required BMPs can effectively reduce the sediment and nutrient yields in the application area. Given that the effectiveness of BMPs cannot be tested across all situations, watershed managers depend on models to provide an estimate of their impact on improving water quality at the watershed scale [8]. It is important to estimate the pollution reduction efficiency of these BMPs to help policymakers guide future resource allocations [9]. To estimate pollution and determine the effectiveness of BMPs, use of the Soil and Water Assessment Tool (SWAT) [10] is proposed. This is the most widely used hydrological model in the world [11]. Many studies use SWAT to evaluate the water quality benefits of agricultural conservation practices [12]. Such studies usually focus on fertilizer application control, changes in land use and other management practices, such as tillage management, filter strips or contour farming [13]. However, SWAT applications evaluating BMPs in Spain are scarce in the scientific literature. Such studies have been conducted mostly in the north of the country [14,15], where streams are perennial and water resources are in a natural regime.

The SWAT model is usually calibrated using stream gauging stations. However, in ungauged catchments, where discharge measurements are not available, calibration based on remotely-sensed data may provide an alternative solution [16]. Actual evapotranspiration (AET) is a key process in the hydrologic cycle and one of the most difficult components to evaluate [17]. In the present study, satellite AET data from the Global Land Evaporation Amsterdam Model (GLEAM) [18] was used to calibrate and validate the SWAT model. AET calibration and validation is less common, because evapotranspiration data are usually unavailable. However, recent studies have demonstrated that the SWAT model can be calibrated and validated with AET data [17,19–21]. Moreover, the use of AET data entails the incorporation of actual agricultural practices carried out in the watershed, which supposes an improvement in the accuracy of the model.

Therefore, the main objectives of this study were as follows: (1) to obtain a high-performance calibrated and validated SWAT model for El Beal watershed, using remote-sensing AET data and (2) to implement individual and combined BMPs in SWAT to evaluate their effectiveness in controlling non-point source pollutants. To the best of our knowledge, no studies have used the approach proposed in this study of using remote-sensing data to calibrate the SWAT model in an ungauged watershed to assess the effectiveness of BMPs.

2. Materials and Methods

2.1. Study Area

The Segura River Basin, in the southeast of Spain, lies between latitude 39°00′–37°00′ N and longitude 2°50′–0°40′ W. The study site, El Beal watershed, is located in the southeast part of Segura River Basin within the area known as Campo de Cartagena (Figure 1), which is one of the main horticultural producers in Europe [22] and is characterized by an intensive agriculture and torrential rainfall regime. Water scarcity has resulted in the use of drip irrigation and the need to make efficient use of water [23]. Moreover, the southern portion of Campo de Cartagena was a very active mining region for hundreds of years, although the area is currently abandoned [24].

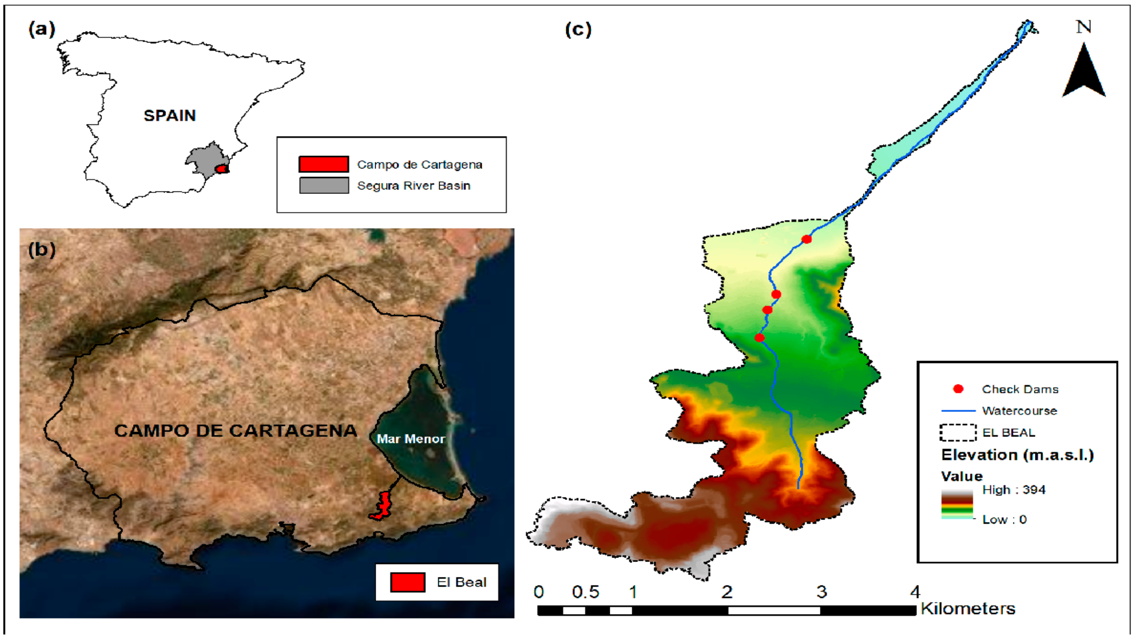

Figure 1. (**a**) Location map of Campo de Cartagena watershed as part of the Segura River Basin (Spain); (**b**) Situation map of El Beal within the Campo de Cartagena basin and Mar Menor coastal lagoon location; (**c**) Digital elevation model (DEM) and check dam location of El Beal watershed.

The region is one of the most arid in the Mediterranean region, with an average annual temperature of 16 °C and average annual precipitation of 300 mm distributed across a few intensive events, mainly in spring and autumn. The drainage system of El Beal watershed is an ephemeral watercourse. The Campo de Cartagena watercourses flow into the Mar Menor coastal lagoon, bringing great quantities of sediment and nutrients [22]. In the study area, intensive agriculture is possible through a water transfer known as the Tagus–Segura transfer, in operation since 1979. This hydraulic infrastructure changed the traditional unirrigated agricultural activities, without significant influence on sediment and nutrient yields [25], to intensively irrigated crops.

The total area of El Beal basin is around 6 km^2, with an average elevation of 152 m above sea level (m.a.s.l.). The main land uses of El Beal watershed are abandoned mineral extraction sites (37%), scrubland (27%), urban (12%), cropland (11%) and forest (6%). Moreover, the soil cover is mainly Calcaric Cambisols [26], which is characterized by high sand and silt content.

2.2. *SWAT Model*

The SWAT is a semi-distributed and physically based model developed by the United States Department of Agriculture [10] to predict the impact of land management practices on sediment yield and water quality. It can be used to model the water cycle and crop yields in a river catchment and to assess the effects of agricultural practices and water resource management [27]. The SWAT model divides the catchment into sub-basins composed of hydrologic response units (HRUs), which are characterized by unique combinations of land use, soil and slope characteristics. The water and sediment processes are simulated at individual HRUs, the outputs of which are summed up and routed through the sub-basin to the stream network [28].

The main components of the model include weather, surface runoff, percolation, groundwater flow, nutrient and sediment loads, reach routing, crop growth and irrigation, water transfer and evapotranspiration. A detailed SWAT model component description is given in the theoretical documentation [10,28].

In the SWAT model, the hydrologic cycle is based on the water balance equation of soil water content:

$$SW_t = SW_o + \sum (R - Q_s - ET - W_{seep} - Q_{gw}) \quad (1)$$

where SWt is the final soil water content (mm), SWo the initial water content on day i (mm), R the precipitation on day i (mm), Qs the surface runoff on day i (mm), ET the evapotranspiration on day i (mm), Wseep the amount of water entering the vadose zone on day i (mm) and Qgw the return flow on day i (mm).

In this study, the Soil Conservation Service (SCS) curve number method was used to estimate surface runoff and the Penman–Monteith method, to determine potential evapotranspiration values; these are generally acknowledged to be the most rigorous and physically realistic approaches [20]. Once potential evapotranspiration is obtained, the SWAT model determines the AET for each HRU, calculating the amount of sublimation and evaporation from the soil surface and from water intercepted by the plant canopy [28]. The soil erosion process is simulated for each HRU using the Modified Universal Soil Loss Equation (MUSLE), and the transformation and movement of nitrogen and phosphorus are computed through a function of nutrient cycles [8]. Additionally, in the SWAT model, BMPs can be defined by simulating the management parameters for each HRU.

2.2.1. Model Inputs

In the present study, the SWAT model was developed with the input data listed in Table 1.

Table 1. List of input datasets used for model setup.

Data	Description	Source
DEM	5 m × 5 m resolution map	Spanish National Geographic Institute (IGN)
Land use map	Vector database	Corine Land Cover programme of year 2012 (CLC2012)
Soil map	1 km × 1 km resolution map	Harmonized World Soil Map (HWSD)
Climate data	Daily meteorological station called TP42	Murcian Institute of Agrarian and Food Research and Development (IMIDA)

The DEM of a 5-m spatial resolution, obtained from the Spanish National Geographic Institute (IGN), was used to calculate the physical watershed characteristics in the SWAT: slope lengths, stream network, as well as flow direction and accumulation. The land use map, downloaded from the Corine Land Cover project (CLC2012), was rasterized and reclassified into 12 classes, included in the land use SWAT database. In the agricultural land uses, the management practices regarding planting, irrigation, fertilization and harvesting were simulated, according to the criteria of Francés et al. (2018) [29]. The Harmonized World Soil Map (HWSD) dataset includes the physical properties of soil required for soil map in the SWAT: texture, bulk density, soil depth and organic carbon, sand, silt, clay and rock content. The daily climate data (precipitation, temperature, wind speed, solar radiation and relative humidity) was obtained from the closest meteorological station (TP42) to the centroid of the watershed, for the period 1999 to present.

GLEAM is a remote-sensing evapotranspiration dataset developed by the Vrije University of Amsterdam [18], and used in this study. GLEAM includes a set of algorithms that estimate the different components of terrestrial evaporation (i.e., transpiration, bare soil evaporation, sublimation, interception loss and open-water evaporation) and root-zone soil moisture from satellite data. The last version of GLEAM (v3) has been globally validated through 91 eddy-covariance towers and 2325 in situ sensors [30]. In this study, the AET data of version 3.2b of GLEAM was implemented. This dataset is available on a 0.25°-latitude-longitude regular grid.

2.2.2. Model Setup, Sensitivity Analysis, Calibration and Validation

The Quantum Geographic Information System interface for SWAT (QSWAT 1.7) was used to configure and parameterize the SWAT model. Based on the distribution of the land use classes, soil types and slopes ($< 8\%$, 8–30%, $> 30\%$), the watershed is divided into 2 basins and 42 HRUs. The simulation period was from 2000 to 2015 (16 years) at a monthly time step. To balance the initial soil water conditions, a three-year warm-up period (2000–2003) was established.

Although the SWAT model operates on a daily scale, the model calibration process was carried out at a monthly time-step, pursuant to the Split Sample Test hierarchical scheme proposed by Klemes (1986) [31]. The simulation period was split 70/30. AET data from 2003 to 2011 (a 9-year period) was selected for calibration of the model and from 2012 to 2015 (a 4-year period) for the validation process.

In the SWAT model, there is a multitude of calibration parameters, and, to avoid over-parameterization and identify the most sensitive parameters in the AET process of our study area, a sensitivity analysis was executed [32] before the calibration and validation processes. The sensitivity analysis and automatic calibration were carried out using the Sequential Uncertainty Fitting procedure (SUFI-2) included in the SWAT Calibration and Uncertainty Programs (SWAT-CUP) [33]. Based on the literature reviewed [17,19,20,34], 12 of the most frequently used parameters for AET calibration (Table 2) were selected for a global sensitivity analysis. Parameter sensitivity was calculated on the basis of the significance of the sensitivity (p-value); the lower the p-value, the more sensitive the parameter [33]. After sensitivity analysis, ALPHA_BF and the seven most sensitive parameters (ESCO, CN2, EPCO, SOL_BD, CANMX, SOL_AWC and SOL_K) and were chosen for automatic calibration.

Table 2. Ranking of selected SWAT parameters with their p-values, based on sensitivity analysis.

Parameter	Description	p-Value	Rank
ESCO.hru	Soil evaporation compensation factor	0.00	1
CN2.mgt	Initial SCS runoff curve number	0.00	2
EPCO.hru	Plant uptake compensation factor	0.00	3
SOL_BD.sol	Moist bulk density (g/cm^3)	0.01	4
CANMX.hru	Maximum canopy storage (mm)	0.08	5
SOL_AWC.sol	Soil available water content (mm/mm)	0.19	6
SOL_K.sol	Saturated hydraulic conductivity (mm/h)	0.25	7
GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (m)	0.27	8
GW_DELAY.gw	Groundwater delay (days)	0.30	9
GW_REVAP.gw	Groundwater revap coefficient	0.41	10
ALPHA_BF.gw	Base flow recession constant (days)	0.88	11
REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur (m)	0.99	12

Tobin and Bennett (2017) [20] and Odusanya et al. (2019) [17] proved that the AET GLEAM product can be an alternative approach to calibrate the SWAT model. Therefore, due to the unavailability of recorded discharge measurements in El Beal watershed, the satellite-derived AET data from GLEAM were selected as observed inputs. For the automatic calibration process, the Kling–Gupta efficiency index (KGE) (Gupta et al., 2009) (Eq. 2) was set as the objective function. A total of 1000 simulations were run, divided into two iterations of 500 simulations, and the parameter ranges were adjusted after the first iteration.

$$KGE = 1 - \sqrt{(\alpha - 1)^2 + (\beta - 1)^2 + (\gamma - 1)^2} \quad (2)$$

where α is the Pearson correlation coefficient between the observed and simulated AET data, β is the fraction of standard deviation of the simulated AET data over the observed AET data and γ is the average simulated AET value over the average observed value. KGE ranges from $-\infty$ to 1, with 1 being the optimal value.

The validation process involved introduction of the fitted parameters obtained during the calibration process to the SWAT model and the comparison between the satellite-derived AET data and SWAT-simulated AET data. To assess the performance of the SWAT model, three of the most commonly used statistical indices in the calibration and validation procedures were selected: the coefficient of determination (R^2), the percent bias (PBIAS) and the Nash–Sutcliffe efficiency (NSE) [35], as shown in Equations (3)–(5), respectively.

$$R^2 = \frac{\sum_{i=1}^{n}\left(Y_{obs\ i} - \overline{Y_{obs}}\right)\left(Y_{sim\ i} - \overline{Y_{sim}}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_{obs\ i} - \overline{Y_{obs}}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_{sim\ i} - \overline{Y_{sim}}\right)^2}} \quad (3)$$

where $Y_{obs\ i}$ and $Y_{sim\ i}$ are the observed and simulated AET values, $\overline{Y_{obs}}$ and $\overline{Y_{sim}}$ are the average observed and simulated AET values and n is the total number of observations. R^2 ranges from 0 to 1, with 1 being the optimal value.

$$PBIAS = \frac{\sum_{i=1}^{n}(Y_{obs\ i} - Y_{sim\ i})}{\sum_{i=1}^{n} Y_{obs\ i}} * 100 \quad (4)$$

where $Y_{obs\ i}$ and $Y_{sim\ i}$ are the observed and simulated AET values. PBIAS is the mass balance error in percent, with 0 being the optimal value.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Y_{obs\ i} - Y_{sim\ i})^2}{\sum_{i=1}^{n}\left(Y_{obs\ i} - \overline{Y_{obs}}\right)^2} \quad (5)$$

where $Y_{obs\ i}$ and $Y_{sim\ i}$ are the observed and simulated AET values, $\overline{Y_{obs}}$ is the average observed AET value and n is the total number of observed data. NSE ranges from -∞ to 1, where 1 is the optimal value.

2.3. Best Management Practice Scenarios

Based on the different controlling non-point source pollutant strategies applied in Campo de Cartagena [2], five management practices were selected and implemented in the SWAT model: contour planting, filter strips, reforestation, fertilizer application and check dam restoration. These BMP scenarios were assessed individually and in combination, to test their impact on reduction of sediment and nutrient loadings.

The effectiveness of these BMP scenarios was quantified by comparing each one with the baseline scenario to obtain a percent of reduction. This effectiveness was computed using Equation (6):

$$Effectiveness\ (\%) = \frac{(Y_{Baseline} - Y_{BMP})}{Y_{Baseline}} \times 100, \quad (6)$$

where $Y_{Baseline}$ and Y_{BMP} are the average annual sediment or nutrient yields in the baseline scenario and in the BMP scenario, respectively.

2.3.1. Baseline Scenario

The baseline scenario was obtained by running the SWAT model on an annual basis with the calibrated parameters and the current management and crop rotation practices of the agricultural land use (Table 3).

Table 3. Schedule of management and rotation practices in agricultural land use.

Year	Date		Operation	Application Rate	Crop
	Month	Day			
1	January	1	Planting begin		Broccoli
1	January	1	Irrigation	~36 mm/month	Broccoli
1	January	1	Auto fertilization	Max. 250 KgN/ha	Broccoli
1	April	30	Harvest and kill		Broccoli
1	June	1	Planting begin		Cantaloupe
1	June	1	Irrigation	~72 mm/month	Cantaloupe
1	June	1	Auto fertilization	Max. 130 KgN/ha	Cantaloupe
1	August	31	Harvest and kill		Cantaloupe
1	October	1	Planting begin		Lettuce
1	October	1	Irrigation	~25 mm/month	Lettuce
1	October	1	Auto fertilization	Max. 130 KgN/ha	Lettuce
1	December	31	Harvest and kill		Lettuce

2.3.2. Contour Planting

Contour planting practices entail tilling and planting crops, delineating the contour of the field to increase soil infiltration capacity, intercept surface runoff and reduce sediment and nutrient losses. In the present study, contour planting was simulated by activating the contouring option in the scheduled management operations tool (.ops) for the non-woody agricultural land uses in the SWAT. The main parameters for simulating contour planting in the SWAT model are curve number (CONT_CN) and USLE Practice factor (CONT_P), the values of which were set to 65 and 0.8, respectively, following Arnold et al. (2012) [32].

2.3.3. Filter Strips

Dense vegetation is installed along the perimeter of the field to intercept and filter surface runoff. Sediment and nutrient loads are trapped in the strip vegetation. The SWAT calculates trapping efficiency ($trap_{ef}$) for sediment and nutrients, using Equation (7) and the parameter FILTERW, which reflects the width of the vegetation strip.

$$trap_{ef} = 0.367 \times FILTERW^{0.2967}, \tag{7}$$

Based on the recent laws enforced in the study area [2,4], the efficiency of 2 m, 3 m and 5 m filter strips applied in agricultural land uses was assessed.

2.3.4. Reforestation

Reforestation requires the conversion of land to its historically natural conditions. Mineral extraction sites are highly prone to soil erosion due to a general scarcity of vegetation [24]. In the present study, the conversion of mining sites (SHRB) to forest (FRST) was carried out by applying the Land Use Update module in the SWAT.

2.3.5. Fertilizer Application

The SWAT includes a management module for the representation of crop practices (.mgt), where fertilizer can be adjusted. Maximum doses of fertilizer were established in the context of agricultural land use, based on the guidelines provided by a regional regulation known as the Code of Good Agricultural Practices of Murcia [2], which entails a reduction of about 15%–25% of the maximum amount of elemental nitrogen applied to each crop per year.

2.3.6. Check Dam Restoration

Check dam practice requires the construction of rock dams across a watercourse to intercept sediment and nutrient loads and reduce erosion of the stream. However, the siltation due to sediment loads suppose a serious problem in check dam performance. In the study area, there are four filled dams (Figure 1), which were simulated in their original conditions (without saturation) by the SWAT. According to Waidler et al.'s (2009) [36] guidelines, check dams were introduced as ponds. Ponds were simulated in the ponds module (.pnd), using the parameter PND_FR, which represents the fraction of the sub-basin area that drains into ponds.

2.3.7. BMP Combination

The combination of BMPs can be more effective than individual BMPs [37]. Based on the action scale, three combinations of BMPs were implemented in the SWAT to assess their effectiveness to reduce sediment and nutrients (Table 4).

Table 4. Selected Best management Practices (BMPs) combinations.

BMP Combination	Description	BMPs
1	Structural BMPs	Reforestation Check dam restoration
2	Agricultural BMPs	Contour planting 3 m filter strips Fertilizer application
3	All BMPs	Reforestation Check dam restoration Contour planting 3 m filter strips Fertilizer application

Combination 1 includes all structural BMPs, which encompass management practices that require a significant investment, because of their application process. Combination 2 includes contour planting, 3 m filter strips and fertilizer application, which are grouped under a classification of agricultural BMPs, because they are applied mainly at the cropland scale. Additionally, among the filter strip widths evaluated, 3 m filter strips were selected for combination with other BMPs, because they were considered the most representative for the study area. Finally, Combination 3 was conducted to assess the application of all BMPs.

3. Results and Discussion

3.1. Sensitivity Analysis

In the global sensitivity analysis, eight parameters were identified as the most influential to the AET process: CN2, ALPHA_BF, SOL_BD, SOL_AWC and SOL_K, which control the amount of water in soil layers; and ESCO, EPCO and CANMX, which are related to the soil water evaporation processes. Overall, the ESCO was the most sensitive parameter, because it relates closely to soil evaporation, followed by CN2 and EPCO. Similar sensitivity results were achieved in other AET calibration reports [20,34]. Table 5 shows the initial maximum and minimum range, default values and calibrated values applied in the SWAT model.

Table 5. Optimized SWAT parameters for calibration of AET.

Parameter	Value Range	Default Value	Fitted Value
ESCO.hru	0–1	0.95	0.86
CN2.mgt	±20%	-	−7.24%
EPCO.hru	0–1	1	0.14
SOL_BD.sol	±20%	-	−8.2%
CANMX.hru	0–100	0	12.1
SOL_AWC.sol	±20%	-	+14.84%
SOL_K.sol	±20%	-	−5.32%
ALPHA_BF.gw	0–1	0.048	0.16

3.2. Model Calibration and Validation

The model performance was satisfactory in both periods: calibration (2003–2011) and validation (2012–2015). Figure 2 shows the simulated and observed AET in El Beal watershed over the total period. The SWAT model simulated the trend of the observed AET data with high accuracy, with R^2 values of 0.81 for calibration and 0.83 for validation. The other statistical indices also showed good performance for calibration (KGE = 0.78, NS = 0.58 and PBIAS = 3.9%) and validation (KGE = 0.67, NS = 0.53 and PBIAS = −25.3%). The higher values of KGE relative to NSE are due to overemphasis of peak values in NSE [38]. The PBIAS value for the validation period was higher than for the calibration period because, in the last years of the study period, the amount of available water for irrigation in El Beal watershed decreased, due to water constraints in the Tagus–Segura transfer. As a result, the observed AET was less than the simulated AET.

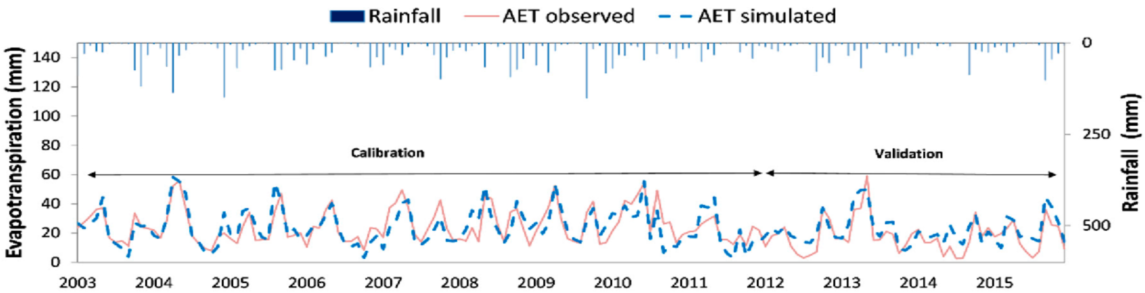

Figure 2. Comparison of simulated and observed actual evapotranspiration of the El Beal watershed for the calibration and validation periods.

As can be seen in the monthly distribution of observed and simulated AET (Figure 3), the model's over/under prediction is acceptable. The simulated average annual precipitation, potential evapotranspiration, total flow and AET were 301.9 mm, 1283.8 mm, 46.2 mm and 270.5 mm, respectively. Similar results were reported in other work on the study area [39]. Ninety percent of the annual precipitation was lost due to evapotranspiration, which is fairly common in semiarid areas. The model estimated an annual sediment yield of 2.64 Tn/ha. This result fell within the range 0–5 Tn/ha/year of sediment yield estimated by the National Soil Erosion Inventory of Murcia for the study area [40]. A calibrated SWAT model simulation was established as the base scenario to assess the impacts of BMPs on sediment and nutrients.

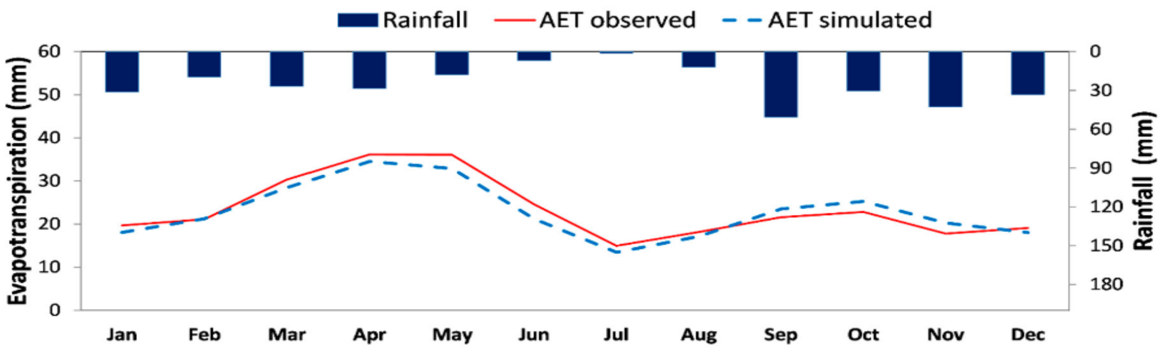

Figure 3. Comparison of average monthly simulated and observed AET for the calibration and validation periods.

3.3. BMP Effectiveness

The assessment of BMPs was performed individually and in combination for the total period. The simulation results showed an effective reduction of sediment yield, total nitrogen (TN) and total phosphorus (TP) by application of individual BMPs (Figure 4) and a higher effectiveness when they were combined.

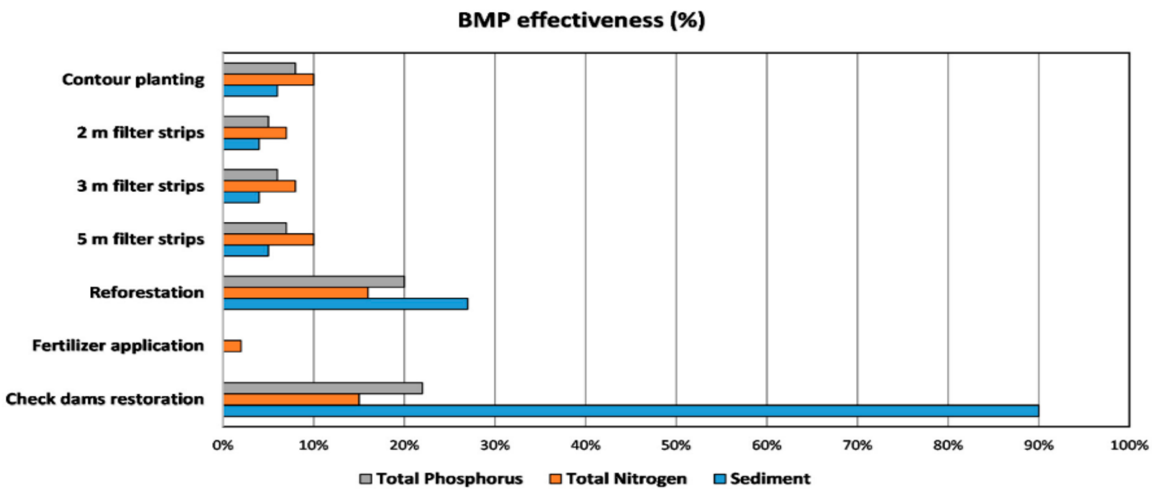

Figure 4. Effectiveness of individual BMPs in sediment and nutrient loadings at the watershed scale.

3.3.1. Individual BMPs

Contouring practice is highly recommended to avoid soil erosion during extreme weather events in Mediterranean regions [41]. The results showed that contour planting simulation reduced sediment yield by 6%, TN by 10% and TP by 8% at the watershed scale. However, contouring was found to improve the percent of sediment reduction to 71% at the cropland level. Filter strips with a width of 2 m achieved a reduction of 4%, 7% and 5% for sediment yield, TN and TP, respectively. Increasing the filter strip width to 3 m improved all the effectiveness values by 1%, and for 5 m of width, there was a 5% enhancement in the reduction of sediment, 10% for TN and 7% for TP. These findings indicate that increasing the width of filter strips results in an insignificant improvement in the effectiveness at the basin scale. Notwithstanding these results, at the cropland scale, the improvement rate ranged from 45% to 60%, with the improvement rate increasing as the widths increased. Other studies have reported finding similar trends related to filter strips [42,43]. Reforestation entails a land use conversion from

SHRB to FRST. The results showed that reforestation was one of the most effective practices for reducing sediment and nutrients in El Beal watershed. Sediment yield generated from the basin was reduced by up to 27%, and TN and TP reduction were 16% and 20%, respectively. These results are consistent with the findings of other research carried out in the study area [29]. According to the agricultural practice guidelines of Murcia [2], the maximum annual amount of elemental nitrogen applied in agricultural land use was reduced. As a result of fertilizer application BMP, the nitrogen decreased by 20% at the cropland level. However, at the basin scale, the percent of reduction was 2%. Regarding the check dam restoration, almost 90% of the sediment was found to be retained at the dams. Mtibaa et al. (2018) [37] proved that the highest sediment yield reductions were achieved by structural BMPs. Check dams also reduced the TN by 15% and the TP by 22%. Although check dam restoration was found to be the most effective individual practice, this BMP requires special maintenance to avoid saturation. The relatively lower results at the watershed level for contour planting, filter strips and fertilizer application are attributable to the small proportion of the agricultural area in the El Beal watershed.

3.3.2. Combination BMPs

Combinations of BMPs achieved better results than individual BMPs (Table 6). Similar studies, using the SWAT model, in different regions of the world corroborate these results [37,44–46].

Table 6. Effectiveness of combination BMPs in sediment and nutrient loadings at the watershed scale.

BMP Combination	Description	Average Annual Reduction (%)		
		Sediment	TN	TP
1	Structural BMPs	92%	18%	23%
2	Agricultural BMPs	7%	14%	10%
3	All BMPs	93%	32%	33%

Combination 1 involved testing the percent of reduction by applying the structural BMPs. High reductions were achieved for all yields at the watershed scale, although with a particularly level of effectivity in sediment reduction. The effectiveness was 92% for sediment loads, 18% for TN and 23% for TP. Combination 2 was used to check the effectiveness of BMPs applicable only in agricultural land use. A greater percent of reduction was achieved when agricultural BMPs were implemented simultaneously, relative to their being implemented individually, at both the watershed and cropland levels. This combination achieved an effectiveness of 7% for sediment reduction, 14% for TN and 10% for TP at the watershed scale. However, at the cropland scale, these results reached values higher than 80% for sediment reduction and nutrient yields. Similar scale patterns were obtained by Uribe et al. (2018) [47] in an agricultural watershed in Colombia. When all evaluated BMPs were applied in El Beal watershed at the same time, the effectiveness reached the highest values. Predictably, Combination 3 was the most effective, with reduction values of 93%, 32% and 33% for sediment, TN and TP, respectively. With respect to sediment reductions, the structural BMPs obtained the best results. Although BMP Combination 1 produced an important reduction of TN and TP at the watershed scale, when structural BMPs were combined with agricultural BMPs, meaningfully greater effectiveness was achieved. These results provide useful information on how to assess which BMPs better fit current conditions of El Beal watershed. They may be feasible future solutions to reduce the sediment and nutrient loadings that flow into the Mar Menor coastal lagoon.

3.4. Cost-Effective BMP Simulation

The total costs for BMPs implementation are listed in Table 7. Unit costs related to reforestation, check dam restoration and fertilizer application were obtained from the Spanish Ministry for the Ecological Transition [48] while unit costs related to filter strips and contour planting were obtained from Cuttle et al. (2007) [49]. Agricultural BMPs are the most cost-effective strategies to remove sediments, N and TP in El Beal watershed. Taking into account that the environmental restoration of Mar Menor to good ecological status has the potential to generate a total economic value of more than 45 million euros per year [50], the implementation of structural BMPs is also recommended. The results presented aim to facilitate decision-making for cost-effective management of pollution by stakeholders.

Table 7. Analysis of cost-effective BMPs.

BMP	Cost per Hectare	Land Use	Total Cost (€)	Cost per Ton of Reduction		
				Sediment	TN	TP
Reforestation	46000 €	Abandoned mineral extraction sites	10212000	24898	33594	85331
Check dam restoration	200000 € [1]	-	800000	575	2790	5885
Fertilizer application	100 €	Cropland	10800	-	267	-
3 m filter strips	30 €	Cropland	3240	48	21	91
Contour planting	10 €	Cropland	1080	11	6	24
Structural BMPs	-	-	11012000	7693	32124	79397
Agricultural BMPs	-	-	15120	132	57	257
All BMPs	-	-	11027120	7640	18109	55922

[1] This cost is per dam.

4. Conclusions

A SWAT model for El Beal watershed was developed to evaluate the effectiveness of selected BMPs. The SWAT model achieved good performance in calibration and validation processes with satellite-derived AET data from GLEAM on a monthly basis. The applicability of the assessed BMPs was tested in a semiarid and highly anthropogenic watershed in the southern region of Spain. Among the individual BMPs simulated, check dam restoration and reforestation were found to be the most effective to reduce the loads of sediment and nutrients that flow into the Mar Menor coastal lagoon. All effectiveness values improved when BMPs were assessed in combination. Despite the model's uncertainties and taking into account the high socioeconomic impact of the implementation of these measures, this study may provide guidance for decision makers to implement the best BMPs to reduce nutrient and sediment inputs. The results can be extended to similar watersheds.

Author Contributions: A.L.-B. and J.S.-A. conceived and developed the study; A.L.-B., J.S.-A. and R.S. analyzed the input and output data; A.L.-B. wrote the paper; J.S.-A., R.S. and J.P.-S. revised the paper.

Funding: This research was funded by the Region of Murcia Government.

Acknowledgments: This research was supported by the Ministerio de Educación y Formación Profesional of Spain under an FPU grant (FPU17/00923). The authors gratefully acknowledge support from the Region of Murcia Government through the project "Modelización hidrológica distribuida de la cuenca de la rambla del Albujón mediante el uso de datos de teledetección". We acknowledge Papercheck Proofreading and Editing Services.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Herman, M.R.; Nejadhashemi, A.P.; Abouali, M.; Hernandez-Suarez, J.S.; Daneshvar, F.; Zhang, Z.; Anderson, M.C.; Sadeghi, A.M.; Hain, C.R.; Sharifi, A. Evaluating the role of evapotranspiration remote sensing data in improving hydrological modeling predictability. *J. Hydrol.* **2018**, *556*, 39–49. [CrossRef]
2. Comunidad Autónoma de la Región de Murcia. *Ley 1/2018, de 7 de Febrero, de Medidas Urgentes Para Garantizar la Sostenibilidad Ambiental en el Entorno Del Mar Menor*; Boletín Oficial de la Región de Murcia: Murcia, Spain, 2018. (In Spanish)

3. Comunidad Autónoma de la Región de Murcia. *Orden de 29 de Julio de 2016 Por la Que se Crea el Comité de Asesoramiento Científico Del Mar Menor*; Boletín Oficial de la Región de Murcia: Murcia, Spain, 2016. (In Spanish)
4. Comunidad Autónoma de la Región de Murcia. *Decreto-Ley n° 1/2017, de 4 de abril, de Medidas Urgentes Para Garantizar la Sostenibilidad Ambiental en el Entorno Del Mar Menor*; Boletín Oficial de la Región de Murcia: Murcia, Spain, 2017. (In Spanish)
5. La Opinión de Murcia. Available online: https://www.laopiniondemurcia.es/comunidad/2018/01/13/pasando/889517.html (accessed on 10 July 2019).
6. Sharpley, A.N.; Daniel, T.; Gibson, G.; Bundy, L.; Cabrera, M.; Sims, T.; Stevens, R.; Lemunyon, J.; Kleinman, P.; Parry, R. *Best Management Practices to Minimize Agricultural Phosphorus Impacts on Water Quality*; Agricultural Research Service of the United States Department of Agriculture (USDA-ARS): Washington, DC, USA, 2006.
7. Bosch, N.S.; Allan, J.D.; Selegean, J.P.; Scavia, D. Scenario-testing of agricultural best management practices in Lake Erie watersheds. *J. Great Lakes Res.* **2013**, *39*, 429–436. [CrossRef]
8. Arabi, M.; Frankenberger, J.R.; Engel, B.A.; Arnold, J.G. Representation of agricultural conservation practices with SWAT. *Hydrol. Process.* **2008**, *22*, 3042–3055. [CrossRef]
9. Tuppad, P.; Kannan, N.; Srinivasan, R.; Rossi, C.G.; Arnold, J.G. Simulation of agricultural management alternatives for watershed protection. *Water Resour. Manag.* **2010**, *24*, 3115–3144. [CrossRef]
10. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modeling and assessment Part I: Model development. *J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [CrossRef]
11. Mannschatz, T.; Wolf, T.; Hülsmann, S. Nexus Tools Platform: Web-based comparison of modelling tools for analysis of water-soil-waste nexus. *Environ. Modell. Softw.* **2016**, *76*, 137–153. [CrossRef]
12. Park, J.Y.; Yu, Y.S.; Hwang, S.J.; Kim, C.; Kim, S.J. SWAT modeling of best management practices for Chungju dam watershed in South Korea under future climate change scenarios. *Paddy Water Environ.* **2014**, *12*, 65–75. [CrossRef]
13. Xie, H.; Chen, L.; Shen, Z. Assessment of agricultural best management practices using models: Current issues and future perspectives. *Water* **2015**, *7*, 1088–1108. [CrossRef]
14. Cerro, I.; Antigüedad, I.; Srinivasan, R.; Sauvage, S.; Volk, M.; Sánchez-Pérez, J.M. Simulating land management options to reduce nitrate pollution in an agricultural watershed dominated by an alluvial aquifer. *J. Environ. Qual.* **2014**, *43*, 67–74. [CrossRef]
15. Epelde, A.M.; Cerro, I.; Sánchez-Pérez, J.M.; Sauvage, S.; Srinivasan, R.; Antigüedad, I. Application of the SWAT model to assess the impact of changes in agricultural management practices on water quality. *Hydrolog. Sci. J.* **2015**, *60*, 825–843. [CrossRef]
16. Immerzeel, W.W.; Droogers, P. Calibration of a distributed hydrological model based on satellite evapotranspiration. *J. Hydrol.* **2008**, *349*, 411–424. [CrossRef]
17. Odusanya, A.; Mehdi, B.; Schürz, C.; Oke, A.O.; Awokola, S.O.; Awomeso, J.A.; Adejuwon, J.O.; Schulz, K. Multi-site calibration and validation of SWAT with satellite-based evapotranspiration in a data sparse catchment in southwestern Nigeria. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 1113–1144. [CrossRef]
18. Miralles, D.G.; Holmes, T.H.R.; de Jeu, R.A.M.; Gash, J.H.; Meesters, A.G.C.A.; Dolman, A.J. Global land-surface evaporation estimated from satellite-based observations. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 453–469. [CrossRef]
19. Ha, L.; Bastiaanssen, W.G.M.; van Griensven, A.; van Dijk, A.I.J.M.; Senay, G.B. Calibration of spatially distributed hydrological processes and model parameters in SWAT using remote sensing data and an auto-calibration procedure: A case study in a Vietnamese river basin. *Water* **2018**, *10*, 212. [CrossRef]
20. Tobin, K.; Marvin, E.B. Constraining SWAT calibration with remotely sensed evapotranspiration data. *J. Am. Water Resour. Assoc.* **2017**, *53*, 593–604. [CrossRef]
21. Cheema, M.J.M.; Immerzeel, W.W.; Bastiaanssen, W.G.M. Spatial quantification of groundwater abstraction in the irrigated indus basin. *Groundwater* **2014**, *52*, 25–36. [CrossRef] [PubMed]
22. Velasco, J.; Lloret, J.; Millán, A.; Marín, A.; Barahona, J.; Abellán, P.; Sánchez-Fernández, D. Nutrient and particulate inputs into the Mar Menor Lagoon (SE Spain) from an intensive agricultural watershed. *Water Air Soil Pollut.* **2006**, *176*, 37–56. [CrossRef]
23. Senent-Aparicio, J.; Pérez-Sánchez, J.; García-Aróstegui, J.L.; Bielsa-Artero, A.; Domingo-Pinillos, J.C. Evaluating groundwater management sustainability under limited data availability in semiarid zones. *Water* **2015**, *7*, 4305–4322. [CrossRef]

24. Navarro, M.C.; Pérez-Sirvent, C.; Martínez-Sánchez, M.J.; Vidal, J.; Tovar, P.J.; Bech, J. Abandoned mine sites as a source of contamination by heavy metals: A case study in a semi-arid zone. *J. Geochem. Explor.* **2008**, *96*, 183–193. [CrossRef]
25. Pérez-Rufaza, A.; Navarro, S.; Barba, A.; Marcos, C.; Cámara, M.A.; Salas, F.; Gutiérrez, J.M. Presence of pesticides through trophic compartments of the food web in the Mar Menor lagoon (SE Spain). *Mar. Pollut. Bull.* **2000**, *40*, 140–151. [CrossRef]
26. Food and Agriculture Organization of the United Nations–International Soil Reference and Information Centre (FAO–ISRIC). *Guidelines for Profile Description*, 3rd ed.; FAO–ISRIC: Roma, Italy, 1990.
27. Krysanova, V.; White, M. Advances in water resources assessment with SWAT—An overview. *Hydrol. Sci. J.* **2015**, *60*, 771–783. [CrossRef]
28. Neitsch, S.; Arnold, J.; Kiniry, J.; Williams, J.; King, K. *Soil and Water Assessment Tool: Theoretical Documentation, version 2009*; Texas Water Resources Institute: College Station, TX, USA, 2011.
29. Francés, F. *Informe Sobre el Análisis de Afecciones de Diferentes Actuaciones en la Zona Sur Del Mar Menor Sobre Aportaciones a la Laguna de Agua, Sedimentos y Nitrógeno*; Comunidad Autónoma de la Región de Murcia: Murcia, Spain, 2018. (In Spanish)
30. Martens, B.; Miralles, D.G.; Lievens, H.; Fernández-Prieto, D.; Verhoest, N.E.C. GLEAMv3: Satellite-based land evaporation and root-zone soil moisture. *Geosci. Model Dev.* **2017**, *10*, 1903–1925. [CrossRef]
31. Klemes, V. Operational testing of hydrological simulation models. *Hydrolog. Sci. J.* **1986**, *31*, 13–24. [CrossRef]
32. Arnold, J.G.; Moriasi, D.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, R.D.; Griensven, A.V.; Liew, M.; et al. SWAT: Model use, calibration, and validation. *Trans. ASABE* **2012**, *55*, 1491–1508. [CrossRef]
33. Abbaspour, K.C. *SWAT-CUP-2012: SWAT Calibration and Uncertainty Program—A User Manual*; Swiss Federal Institute of Aquatic Science and Technology: Dubendorf, Switzerland, 2012.
34. Sun, C.; Ren, L. Assessment of surface water resources and evapotranspiration in the Haihe River basin of China using SWAT model. *Hydrol. Process.* **2013**, *27*, 1200–1222. [CrossRef]
35. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models. Part I: A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [CrossRef]
36. Waidler, D.; White, M.; Steglich, E.; Wang, S.; Williams, J.; Jones, C.A.; Srinivasan, R. *Conservation Practice Modeling Guide for SWAT and APEX*; Texas Water Resources Institute: College Station, TX, USA, 2009.
37. Mtibaa, S.; Hotta, N.; Irie, M. Analysis of the efficacy and cost-effectiveness of best management practices for controlling sediment yield: A case study of the Joumine watershed, Tunisia. *Sci. Total Environ.* **2018**, *616*, 1–16. [CrossRef]
38. Gupta, H.V.; Kling, H.; Yilmaz, K.K.; Martinez, G.F. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *J. Hydrol.* **2009**, *377*, 80–91. [CrossRef]
39. Contreras, S.; Hunink, J.E.; Baille, A. Building a Watershed Information System for the Campo de Cartagena basin (Spain) integrating hydrological modeling and remote sensing. *Report Future Water* **2014**, *125*. [CrossRef]
40. Dirección General de Conservación de la Naturaleza. *Inventario Nacional de Erosión de Suelos 2002–2012*; Ministerio de Medio Ambiente: Murcia, Spain, 2002; ISBN 84-8014-483-1. (In Spanish)
41. Durán-Zuazo, V.H.; Rodríguez-Pleguezuelo, C.R. Soil-erosion and runoff prevention by plant covers. *Agron. Sustain. Dev.* **2008**, *28*, 65–86. [CrossRef]
42. Yuan, Y.; Bingner, R.A.; Locke, M.A. Review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. *Ecohydrology* **2009**, *2*, 321–336. [CrossRef]
43. Parajuli, P.B.; Mankin, K.R.; Barnes, P.L. Applicability of targeting vegetative filter strips to abate fecal bacteria and sediment yield using SWAT. *Agric. Water Manag.* **2008**, *95*, 1189–1200. [CrossRef]
44. Briak, H.a.; Mrabet, R.; Moussadek, R.A.; Aboumaria, K. Use of a calibrated SWAT model to evaluate the effects of agricultural BMPs on sediments of the Kalaya river basin (North of Morocco). *Int. Soil Water Conserv. Res.* **2019**, *7*, 176–183. [CrossRef]
45. Leh, M.; Sharpley, A.N.; Singh, G.; Matlock, M. Assessing the impact of the MRBI program in a data limited Arkansas watershed using the SWAT model. *Agric. Water Manag.* **2018**, *202*, 202–219. [CrossRef]
46. Wagena, M.; Zachary, M.E. Agricultural conservation practices can help mitigate the impact of climate change. *Sci. Total Environ.* **2018**, *635*, 132–143. [CrossRef]

47. Uribe, N.; Corzo, G.; Quintero, M.; van Griensven, A.; Solomatine, D. Impact of conservation tillage on nitrogen and phosphorus runoff losses in a potato crop system in Fuquene watershed, Colombia. *Agric. Water Manag.* **2018**, *209*, 62–72. [CrossRef]
48. Ministerio de Agricultura y Pesa, Alimentación y Medio Ambiente (2018). Análisis de Soluciones Para el Objetivo Del Vertido Cero al Mar Menor Proveniente Del Campo de Cartagena. Available online: https://www.chsegura.es/chs/servicios/informacionpublica/vcerommenor/ (accessed on 4 September 2019).
49. Cuttle, S.; Macleod, C.; Chadwick, D.; Scholefield, D.; Havgarth, P.; Newell-Price, P.; Harris, D.; Sepherd, M.; Chambers, B.; Humphrey, R. An Inventory of Methods to Control Diffuse Water Pollution from Agriculture (DWPA). User Manual. Defra Report, Project ES0203 2007. Available online: http://www.cost869.alterra.nl/UK_Manual.pdf (accessed on 2 September 2019).
50. Perni, A.; Martínez-Carrasco, F.; Martínez-Paz, J.M. Economic valuation of coastal lagoon environmental restoration: The Mar Menor (Spain). *Cienc. Mar.* **2011**, *37*, 175–190. [CrossRef]

4.2 RESEARCH PAPER 2: A HOLISTIC APPROACH FOR DETERMINING THE HYDROLOGY OF THE MAR MENOR COASTAL LAGOON BY COMBINING HYDROLOGICAL & HYDRODYNAMIC MODELS

Senent-Aparicio, J.; López-Ballesteros, A.; Nielsen, A.; Trolle, D. (2021). A holistic approach for determining the hydrology of the mar menor coastal lagoon by combining hydrological & hydrodynamic models. Journal of Hydrology, 603, 127150.
https://doi.org/10.1016/j.jhydrol.2021.127150

Journal of Hydrology 603 (2021) 127150

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A holistic approach for determining the hydrology of the mar menor coastal lagoon by combining hydrological & hydrodynamic models

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ARTICLE INFO

This manuscript was handled by S. Sally Elizabeth Thomson, Editor-in-Chief, with the assistance of Tara Troy, Associate Editor

Keywords:
SWAT
QWET
Water balance
Mar Menor
Coastal lagoons

ABSTRACT

A combination of hydrological and hydrodynamic modelling can be applied to understand the hydrology and key water balance components of lakes and lagoons. In this research, the Soil and Water Assessment Tool (SWAT) model and the QGIS Water Ecosystems Tool (QWET) were applied for the Mar Menor coastal lagoon and its watershed known as Campo de Cartagena. First, the SWAT model was calibrated and validated based on remote sensing evapotranspiration data. Results showed an acceptable performance of the SWAT model in both calibration ($R^2 = 0.63$, NSE = 0.62, PBIAS = 2.91%) and validation ($R^2 = 0.68$, NSE = 0.68, PBIAS = 2.47%) periods on a monthly basis. The SWAT simulated streamflow was fed into the QWET model to simulate the water balance of the lagoon. The hydrodynamic model performance was evaluated based on a comparison between simulated and observed water temperatures and also the model estimated evaporation. Simulated daily temperatures showed a good agreement with observed data by capturing the timing and inter-annual variations, with an NSE of 0.98, and a BIAS of 2.7%. Our water balance estimation, using the reference period 2003–2019, yields a mean annual rainfall over the lake of 301 mm and a mean annual evaporation of 1325 mm. The average surface runoff and groundwater discharge to the lagoon are 49 hm^3/year and 11 hm^3/year, respectively. Extreme storm events cause annual surface runoff to vary between 8 hm^3/year and 202 hm^3/year. The water balance was closed with the water exchange with the Mediterranean Sea, resulting in an overall positive flow from the Mediterranean Sea of 82 hm^3/year. Our study showed that during summer months, in particular, there is considerable inflow of Mediterranean water to the lagoon, whereas for some autumn and winter months (November, December and January) there is a net outflow from the lagoon to the Mediterranean. This novel approach by combining the SWAT hydrological model and QWET hydrodynamic model complex provides a useful tool for understanding the hydrology of the lagoon and may also play a role for decision makers when developing strategies for mitigating eutrophication.

1. Introduction

Coastal lagoons are shallow water bodies partially or totally isolated from the open sea by sedimentary or anthropic barriers but linked to the sea by one or more inlets (Kjerfve, 1994). These types of lagoons are recognised as one of the most valuable ecosystems for the fishing and aquaculture industries in the world (Nixon, 1982) with ideal conditions for the development of recreational and tourism services, which are often concentrated in these areas (De Pascalis et al., 2012; Velasco et al., 2018). However, these natural systems are particularly at risk from increasing anthropogenic pressures, such as intensive agriculture and urbanization pressures associated with tourism development (Viaroli et al., 2005). Among other threats, eutrophication is one of the main causes of water quality deterioration in coastal lagoons (Le Moal et al., 2019).

Developed countries are generally exposed to a greater number of anthropogenic activities, making the accurate modelling of these systems much more complex. Such modelling allows the analysis and simulation of different measures, helping to make decisions focused on the cohabitation between human activity and the preservation of the environmental values of these territories (García-Ayllón, 2017). In the Mediterranean Sea, more than a hundred of these coastal lagoons have been identified (Pérez-Ruzafa et al., 2011) and, in addition to the previously mentioned activities, there will also be a negative impact on

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https://doi.org/10.1016/j.jhydrol.2021.127150
Received 22 October 2020; Received in revised form 24 September 2021; Accepted 29 October 2021
Available online 6 November 2021

these lagoons as a consequence of climate change (Ferrarin et al., 2014). It is necessary to understand the different components of the system, how they are connected and the cause-effect relationships between the drainage basin and the coastal lagoon. This paper proposes an integrated approach to modelling such systems that can be used as a first step to improve the management of any of the coastal lagoons that are currently undergoing eutrophication processes around the world.

From this perspective, this research is focused on the Mar Menor coastal lagoon (Spain) as a representative case of a highly anthropized area experiencing environmental pressures that have emerged over the last few decades. As in many other coastal areas of the Mediterranean, the surroundings of the Mar Menor, which are catalogued as a wetland site of international importance under the Ramsar Convention and is integrated in the Nature 2000 network, has suffered from an expansion of farming activities in the watershed and a significant increase in the tourism, which led to an increase in nutrient inputs to the Mar Menor. In recent years, the process of eutrophication has resulted in a considerable reduction in water transparency, affecting the tourism sector and the local economy (Jimeno-Sáez et al., 2020). The regional government has responded with a series of legislative actions to guarantee a sustainable development of the Mar Menor environment (CARM, 2017; CARM, 2018; CARM, 2019). Some of these measures are fertilizer application control and adaptation of best management practices (BMPs) in the watershed draining into the Mar Menor called Campo de Cartagena. However, no evaluation of the effectiveness of the proposed measures has yet been carried out due to the complexity of this highly anthropized system and the uncertainty associated with the quantification of certain components of the lagoon's water balance such as the water exchanges with the Mediterranean sea and not least the surface runoff and groundwater discharges to the lagoon. Given this situation, a comprehensive understanding of the processes that govern the water balance of the lagoon is an essential foundation to ensure suitable management of this fragile ecosystem.

In recent years, several studies have tried to evaluate the components of the Mar Menor lagoon water balance, but these studies have been characterized by addressing only certain components of the water balance, and not taking a holistic approach where all the key water balance components and their relations are quantified in a global framework. These studies provide some valuable key individual pieces of the hydrological puzzle, but do not provide the full picture of the dynamics and hydrological functioning of the lagoon. Hence, there is a need for a holistic approach, which combine hydrological and hydrodynamic models to better understand the big picture, and for reducing uncertainties related to the water balance.

For instance, previous studies on the Mar Menor included hydrodynamic modelling of the coastal lagoon (Martínez-Álvarez et al., 2011; De Pascalis et al., 2012; Baudron et al., 2015; García-Oliva et al., 2018; García-Oliva et al., 2019) obtaining estimates of certain components of the water balance like the evaporation or the water exchange with the Mediterranean sea. However, these studies disregarded the connection to the Campo de Cartagena area (watershed and aquifer) with the Mar Menor, or at best, in a very simplified manner. For instance, De Pascalis et al. (2012), García-Oliva et al. (2018) and García-Oliva et al. (2019) adopted a homogeneous runoff coefficient of 6.5% for the entire drainage watershed to proxy surface runoff.

The contribution of water from Campo de Cartagena aquifer has also recently been studied (e.g., CHS, 2015; Jiménez-Martínez et al., 2016; Domingo-Pinillos et al., 2018; Alcolea et al., 2019) obtaining very different results, which may be attributed to the complexity of the aquifer. For example, discharges to the Mar Menor from the aquifer varies from 6.2 Mm^3/yr (CHS, 2015) to 68 Mm^3/yr (Jiménez-Martínez et al., 2016). This large variability is influenced by the extreme anthropogenic activity (e.g. groundwater abstractions) and the complex relation between the different aquifer compartments. For example, more than 2000 wells exist in the area (i.e. 1.18 wells/km^2) many of which exploit several aquifers through internal connections – thus connections between the aquifers, which is subject to increasing concern (Jiménez-Martínez et al., 2016).

Hydrological modelling studies of the Campo de Cartagena watershed, however, are scarce (Martínez-Álvarez et al., 2011). This is mainly due to the ephemeral character of the rivers and the lack of reliable data of daily discharge. Alcolea et al. (2019) combined the Modular Groundwater Flow (MODFLOW) model (Harbaugh, 2005) with the hydrological model SPHY (Terink et al., 2015) using available hydraulic head measurements to calibrate the groundwater model. López-Ballesteros et al. (2019) applied the Soil and Water Assessment Tool (SWAT) model in El Beal watercourse, one of the ephemeral streams that drains to the Mar Menor, using actual evapotranspiration data (AET) from remote sensing data to calibrate and validate the model. However, the total surface runoff that drains into the Mar Menor coastal lagoon has not yet been assessed.

To be able to simulate the hydrology of the Mar Menor watershed, the SWAT model has been chosen for this study because it is a public domain model that run on inputs that can be easily gathered for most watersheds (Blanco-Gómez et al., 2019). In addition, and despite not being the goal of this work, the SWAT model can evaluate the effectiveness of agricultural practices on a watershed scale, which could be a future line of research beyond this study. SWAT is usually calibrated using stream discharge stations (Senent-Aparicio et al., 2017; Jimeno-Sáez et al., 2018). However, when discharge data are not available, remotely sensed data is an alternative solution for calibration purposes (Herman et al., 2020). Recent studies proved that the SWAT model can be calibrated using AET data (Tobin and Bennett, 2017; Ha et al., 2018; Odusanya et al., 2019; López-Ballesteros et al., 2019).

To simulate the hydro- and thermodynamics of the Mar Menor lagoon, the QGIS Water Ecosystems Tool (QWET) has been chosen. QWET is an open source tool that provides a graphical user interface for the coupled one-dimensional hydrodynamic-ecosystem model GOTM-WET (Nielsen et al., 2017; Nielsen et al. 2020). The model simulates mixing processes, the vertical distribution of temperature and evaporation. QWET also provide a link to the SWAT watershed model, whereby SWAT output can be utilized as input to the QWET model setup. To the best of our knowledge, none of the recent studies in the Mar Menor area have combined hydrological and hydrodynamic models, and only a few similar studies like this have been carried out world-wide (Inoue et al., 2008; Dargahi & Setegn, 2011; Zhang et al., 2017; Wu et al., 2017; Munar et al., 2018; Lopes et al., 2018; Coppens et al., 2020), of which none of them combined WET and SWAT models. The modelling approach proposed in this research could guide decision makers in the development of an integrated environmental management of the Mar Menor coastal lagoon and is of great interest to similar coastal lagoons. The objectives of this study were to conduct a holistic, integrated analysis of the different components of the lagoon water balance, and to identify aspects that should be a research priority in order to further advance the quantification of the water balance. Since water flows are one of the main controlling forces of the physical–chemical and biological dynamics of the lagoon, their study and characterization must be considered as a key task to advance the scientific knowledge of this case study.

2. Study area

Due to the complexity of the integrated watershed - lagoon hydrosystem, we have separated the description of the case study in (1) the basin that drains into the Mar Menor coastal lagoon, called Campo de Cartagena; (2) the multilayer aquifer under this watershed and (3) the Mar Menor coastal lagoon. An extensive review of human pressures and impacts on the whole Campo de Cartagena – Mar Menor system can be found in Conesa & Jiménez-Cárceles (2007) and Jiménez-Martínez et al. (2016).

2.1. Campo de Cartagena basin

Located in the Segura river basin (SE Spain), which is characterized as one of the most water-stressed areas in Europe (Senent-Aparicio et al., 2016), the Campo de Cartagena watershed covers an area of around 1400 km^2 and is characterized by its ephemeral streams, usually running dry, but which can carry large quantities of water and sediment when torrential rain falls (García-Pintado et al., 2007). This watershed ranks as one of Europe's leading vegetable producers (Velasco et al., 2006) mainly due to the construction of the Tagus-Segura Water Transfer Channel (TSWTC). The TSWTC was completed in 1980 and can provide a flow rate of up to 122 million cubic meters per year (hm^3/year) although, in recent years and due to water shortages at the headwaters of the Tagus river, the flow rate has decreased, elevating the pressure on groundwater resources and promoting the use of desalination and wastewater reuse (Rupérez-Moreno et al., 2017). Shortage of water has led to the implementation of drip irrigation and generally a need to make good use of the limited water available (Senent-Aparicio et al., 2015). Tourism on the coast of the Mar Menor lagoon is also a major contributor to the local economy (Jimeno-Sáez et al., 2020) and mining in the southern part of the basin was one of the main activities in the past, although it has now ceased (Navarro et al., 2008).

According to the weather data used in this study, this basin is one of the most arid of the Mediterranean area, with an annual precipitation amount (from 2000 to 2019) that ranges from 166 mm to 469 mm, where average precipitation is less than 300 mm per year, and the annual averages for maximum and minimum daily temperatures were 23.7 °C and 13.0 °C, respectively. The precipitation is unevenly distributed into a few high-intensity events mainly in spring and autumn. Regarding topography, the altitude ranges from sea level to 1063 m a.s.L., but most of the area is flat, with over 36% of the watershed with slopes of less than 2%. The primary land use of the Campo de Cartagena watershed is intensive irrigated agriculture (around 50% of the total area). The dominant soil type is Calcaric Cambisols (71%), which is mainly composed of sand and silt.

2.2. Campo de Cartagena aquifer

The watershed described above is settled over the Campo de Cartagena aquifer. This aquifer is a multi-layered system composed of deep, confined aquifers and an unconfined shallow aquifer (quaternary). Groundwater is a major contributor to the sustainability of local agriculture, along with water supplied by the TSWTC and the recent increase in public desalinated seawater and private brackish water treatment plants (Senent-Aparicio et al., 2015).

2.3. Mar Menor coastal lagoon

The Mar Menor is a hypersaline coastal lagoon with an immense socio-economic and ecological value and a clear case of a severely anthropized hydroecosystem in southeastern Spain (Velasco et al., 2018). It has a surface area of 135 km^2 covering a coastline of 73 km and contains five volcanic islands. The Mar Menor is considered a shallow lagoon, with an average depth of 4.4 m, being the maximum depth around 7 m (Umgiesser et al., 2014). A 22 km long sandy coastal barrier, known as La Manga, isolates the lagoon from the Mediterranean Sea and is intersected by three inlets (Las Encañizadas, Estacio, Marchamalo), facilitating exchanges of waters between the Mediterranean Sea and the lagoon (Fig. 1.d). The most important water exchange takes place through the Estacio channel. In 1973, this channel was dredged and broadened to make it nautical navigable (Baudron et al., 2015)

Among the most significant environmental sites in the Mediterranean area is the Mar Menor, where many economic and industrial activities meet (Conesa & Jiménez-Cárceles, 2007). Its unique weather conditions and abundant natural resources have attracted tourism, recreational and fishing uses, without forgetting the relevance of farming to the local economy. The process of economic, social and urban transformation that has affected the lagoon in the past half century (and even before, in the case of mining) has led to a multitude of impacts on the physical and natural environment and makes the Mar Menor an area in need of special protection (CARM, 2019).

The situation, far from improving, has deteriorated in recent years.

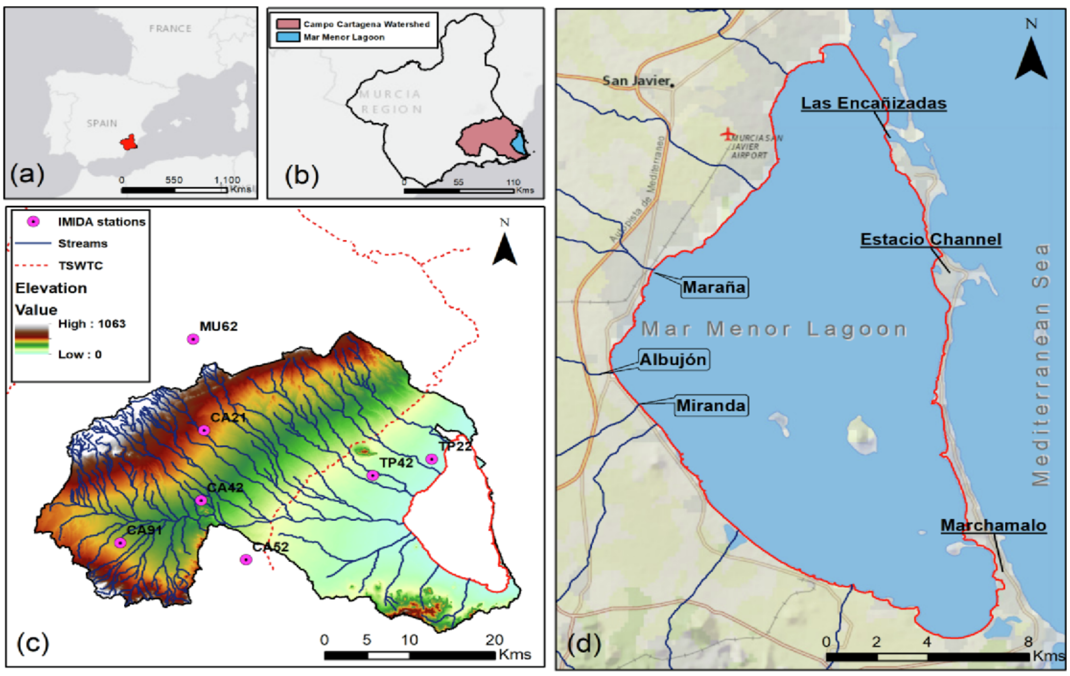

Fig. 1. (a) Location of the study area in Peninsular Spain; (b) Location of the study area in Murcia Region; (c) Campo de Cartagena watershed; (d) Mar Menor lagoon.

In 2016, profound eutrophication generated by a severe increase in the nutrients occurred. Consequently, chlorophyll concentrations rose, which was responsible for the loss of 85% of the vegetation cover and a strong public awareness not only from an ecological point of view but also in the tourism sector. (García-Ayllón, 2018; Pérez-Ruzafa et al., 2019). During 11–14 September 2019, extreme storm events corresponding to a return period of 500 years caused extensive flash flooding in the Campo de Cartagena basin, causing a strong increase in chlorophyll levels and a sudden drop in salinity that caused the death of thousands of fish.

3. Methodology

3.1. Framework for evaluating the water balance in the Mar Menor coastal lagoon.

This study combines QWET with SWAT model to assess the Mar Menor water balance for the period 2003–2019. It includes the following steps: (1) SWAT model was calibrated and validated in the Campo de Cartagena watershed on a monthly basis using remote sensing evapotranspiration data; (2) hydrodynamic component of QWET model was simulated using SWAT model outputs as an input, comparing the results obtained with the available observed temperature measurements; (3) using the calibrated SWAT and QWET models, Mar Menor water balance was simulated and all its components were analyzed and discussed.

3.2. Hydrological modelling approach

SWAT is a continuous, physically based and semi-distributed hydrological model developed for exploring the effects of agricultural management practices and climate change on hydrology, sediment, and water quality (Arnold et al., 2012). SWAT operates on a daily time step, and derives key hydrological processes based on Hydrological Response Units (HRUs), defined as unique combinations of land cover, soil, and topographic conditions (Neitsch et al., 2011). Simulations are performed at the HRU level, aggregated at the subwatershed level, and routed through the stream network to the watershed outlet. Major components of the hydrological cycle considered in SWAT include surface runoff, evapotranspiration, lateral flow, channel routing, infiltration, shallow and deep aquifer contribution and percolation into a confined deeper aquifer.

In this study, surface runoff from daily rainfall is estimated using the Soil Conservation Service (SCS) curve number approach and potential evapotranspiration is simulated using Penman-Monteith. Infiltrated water is distributed in the soil profile and water that percolates below the soil profile is assumed to recharge the shallow aquifer. This water can either percolate deeper or flow laterally towards a stream. More detailed descriptions of the SWAT model are available in the documentation provided by the authors in Neitsch et al. (2011).

Based on the availability of satellite-based remote sensing AET data, a 13-year period from 2003 to 2015 was set as the simulated period. Additionally, three first years (2000–2002) were run as a warm-up period to allow key model states (e.g. groundwater aquifers) to reach equilibrium. Based on previous studies (López-Ballesteros et al., 2019), four SWAT parameters affecting evapotranspiration were selected for manual calibration from 2003 to 2009 using monthly AET data. Graphical time series plots were used to assess qualitatively model performance. In addition, to assess quantitatively SWAT model performance, three statistical evaluation indices (coefficient of determination (R2), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and the percent bias (PBIAS)) were used in this study.

3.2.1. SWAT inputs and model setup

Hydrological modeling was performed using the QGIS interface for SWAT (QSWAT), version 1.8 (Dile et al., 2016). SWAT model requires specific meteorological, topographic, land use, and land cover data for the study area (Arnold et al., 1998). Streams and the drainage basin were derived based on a DEM of 25 m spatial resolution, obtained from the National Geographic Institute of Spain. The crops and land use map of Spain (2000–2010) at a resolution of 200 m, downloaded from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 2010), was reclassified into SWAT land uses. Related to management practices, crop rotations with different crop types and fertilizer application intensities were simulated based on the criteria of Francés (2018). The soil maps were extracted from the Harmonized World Soil Database (HWSD) (Nachtergaele et al., 2012) which includes the physical characteristics of a large number of typical profiles for each of the soils defined according to the FAO classification at a spatial resolution of 1 km.

Based on DEM analysis, Campo de Cartagena watershed was discretized into 152 sub-basins. The SWAT2lake plugin was used to assist in the watershed's delineation (Molina-Navarro et al., 2018). Afterwards, 520 Hydrological Response Units (HRUs) were defined by SWAT based on the unique combinations of land use, soil type and slope class (<2%, 2–8%, >8%). A threshold area of 100 ha was applied to optimize processing of the computational model. The required daily weather data were obtained from the weather stations of the Institute of Agriculture and Food Research and Development of Murcia Region (IMIDA) within the Campo de Cartagena watershed, for the period 2000 to 2019.

3.2.2. Data used for model validation

In this study, model calibration was conducted by comparing the SWAT simulated AET data with the Global Land Evaporation Amsterdam Model (GLEAM) (Miralles et al., 2011) remote sensing evapotranspiration dataset. GLEAM was developed by the Vrije University of Amsterdam and includes several algorithms aimed to estimate terrestrial evaporation and root-zone soil moisture from remote sensing data (Martens et al., 2017). In this research, GLEAM version 3b, spanning the period from 2003 to 2015, was used. The GLEAM evapotranspiration datasets have been widely validated and applied for many hydrometeorological applications (Peng et al., 2019; López-Ballesteros et al., 2019; Bai and Liu, 2018).

3.3. Hydrodynamic modelling approach

QWET is an interface for application of the coupled one-dimensional hydrodynamic-ecosystem model GOTM-WET (Nielsen et al., 2017; Nielsen et al., 2020). In QWET, the lake branch of the open-source General Ocean Turbulence Model (GOTM) is applied to simulate the vertical water column thermal structure (Burchard et al., 1999). GOTM is a one-dimensional, physically based turbulence closure model, which calculates the transport equations for the turbulent kinetic energy and the turbulence dissipation rate. The model thereby simulates the vertical distribution of temperatures, which are influenced by the light attenuation that is derived from the Water Ecosystems Tool (WET). The QWET model complex can be used to quantify evaporation rates, and may also be used to close the water balance, by deriving the residual water input or output required to achieve a certain water level. In our study, watershed inflows derived from SWAT were read into the QWET model complex, and the residual in the water balance for the lagoon was derived as a proxy for the net exchange rate between the Mar Menor lagoon and the Mediterranean Sea on a daily time step.

3.3.1. QWET inputs

Hydrodynamic simulations by QWET require detailed physical and meteorological input data. Hypsographic curves were obtained from Erena et al. (2020). Daily rainfall data were obtained from the IMIDA weather station named TP22 (Fig. 1) and meteorological observations (wind speed and direction, air temperatures, air pressure, dew-point temperature and cloud-cover fraction) were obtained from the newly released ERA5 global reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) that provides hourly estimates of the global atmosphere, land surface and ocean waves at a horizontal resolution of 31 km (Herbasch et al., 2020). The use of ERA5 data was driven by the unavailability of some of the meteorological variables at the TP22 station and the demonstrated good agreement of the wind values provided by ERA5 (Ramon et al., 2019). SWAT simulations were used as inflows to the Mar Menor through the use of the QWET built-in option that permits the connection with SWAT outputs.

3.3.2. Data used for model validation

In this study, the hydrodynamic model performance was assessed by comparing the QWET simulated temperature data with the observed daily temperature data provided by the Autonomous Regional Government of Murcia (http://canalmarmenor.es/). Since the monitored temperature data was only available from 2016, the period 2016–2019 was used for model evaluation, and the period 2003–2015 was defined as the initial QWET model warm-up.

4. Results and discussion

4.1. SWAT model performance

SWAT model was manually calibrated from 2003 to 2009 (7-years period) and validated from 2010 to 2015 (6-years period). Table 1 shows the initial and calibrated parameter values used for the Campo de Cartagena watershed. Some of the calibrated SWAT parameters include: CN2 and SOL_AWC that were reduced by 5% and 10%, respectively. In addition, ESCO was decreased from 0.95 to 0.75 and EPCO was decreased from 1 to 0.3, which leads to an increase in the evaporation simulated by the model. RCHRG_DP was fixed to 0.40 based on previous studies (Jiménez-Martínez et al., 2011). Similar parameter values have been found in watersheds in a Mediterranean climate (Molina-Navarro et al., 2014).

Monthly AET was satisfactorily predicted by the model. NSE value was 0.68 in calibration and 0.75 in validation, with PBIAS values of −11.43% and −7.35%, respectively. Trend of the observed AET was also simulated with accuracy, with R^2 values of 0.77 for calibration and 0.78 for validation. Fig. 2 shows that the SWAT model also performs graphically well in the simulation of the actual evapotranspiration on a monthly basis.

4.2. QWET model performance

Simulated water temperatures spanned the observed water temperature range of approximately 10–30 °C and showed (Fig. 3) an appropriate agreement with observed data during the period 2016–2019 by capturing the timing and inter-annual variations, with an RMSE of 0.8 °C, a BIAS of 2.7 %, and an NSE of 0.98, which can be considered as acceptable based on previous modeling studies (Andersen et al., 2020; Ladwig et al., 2020). Usually, as the hydro-and thermodynamics in QWET are based on the physically based GOTM model, there is little need to calibrate process-parameters in the model. Rather, scale factors for wind input data may be used if the temperature simulations are not satisfactory. In our case, the simulated water temperatures were in good agreement with observations, and therefore no further calibration was needed.

Table 1
Selected parameters for the AET calibration.

Parameter	Description	Default value	Calibrated value
CN2.mgt	Initial SCS runoff curve number for moisture condition II	–	−5%
ESCO.hru	Soil evaporation compensation factor	0.95	0.75
EPCO.hru	Plant uptake compensation factor	1	0.3
SOL_AWC.sol	Soil available water content (mm/mm)	–	−10%
RCHRG_DP.gw	Deep aquifer percolation fraction	0.05	0.4

4.3. Water balance

The annual water balance of the Campo de Cartagena watershed for the period 2003–2019 is reported in Table 2. The average annual rainfall is about 300 mm, supplemented by about 200 mm from other sources (mainly from the TSWTC) that allow crop irrigation in the area. As it was expected, the semiarid climate of the study area and their intensive agriculture make AET the main component to water loss from the basin, with average values above 400 mm. It was also found that the average surface runoff (35.1 mm) is higher than the groundwater seepage (27.0 mm) and significantly higher than the amount of groundwater discharge (4.4 mm), considering that a large part of the water that percolates into the quaternary aquifer connects to the aquifers below (Jiménez-Martínez et al., 2011). The results obtained for the different components of the water balance are in line with those obtained recently by Puertes et al. (2021) in their hydrological modelling of the ephemeral streams located to the south of the Albujón stream.

Related to the Mar Menor coastal lagoon, water balance analysis shows that 44.8% and 26.8% of annual inflows originate from water exchange with the Mediterranean Sea and from surface runoff, respectively (Fig. 4). The direct rainfall contributes around 22.4% on the lake surface, while the groundwater discharge provides 6.0% of the total inflow. Water balance results highlight that the surface runoff is significantly greater than groundwater discharge especially in wetter years.

The monthly average of simulated water balance components from 2003 to 2019, showed that higher water exchange from the Mediterranean Sea occurred during the dry season (i.e., May–August), with the highest inflow in July (Fig. 5). In other months, the net water exchange to the Mar Menor lagoon was much lower because of a higher precipitation, surface runoff, and groundwater discharge. The net water exchange was even negative during November, December and January, which means that the amount of water draining towards the Mediterranean is greater than that entering from the Mediterranean.

4.3.1. Rainfall

In general, for the years 2003–2019, the average annual amount of precipitation on the Mar Menor surface was 301 mm. Over the entire period, the maximum annual amount of precipitation in the TP22 station was observed in 2019 (567 mm), and the minimum in 2014 (124 mm). As it is characteristic of Mediterranean and semi-arid climates, on a monthly scale, 60% of the year's total precipitation is concentrated in 4 months (September–December). Another feature of the Mediterranean climate is the occurrence of high-intensity rainfall events (Castejón-Porcel et al., 2018). As examples, the torrential precipitation episode of 15–19 December of 2016 had a registration of 275 mm or 12–13 September of 2019 when more than 200 mm were registered.

4.3.2. Evaporation

During 2003–2019, annual evaporation ranged between 1293 and 1368 mm/year, with an average value of 1325 mm/year. Monthly evaporation reaches its minimum values in December, January, and February with average values below 50 mm/month. Maximum monthly evaporation occurs in July and August reaching values close to 200 mm/month. An absolute maximum daily value of over 15 mm/day occurs in summer while minimum values during winter can be even negative due to condensation (Martínez-Álvarez et al., 2011). Many authors consider that Penman-Monteith evapotranspiration estimation is a suitable approach for obtaining annual evaporation in water bodies (Cabezas, 2009; Martínez-Álvarez et al., 2011). In this study, the SWAT model estimates an average evapotranspiration value of 1305 mm/year, which is consistent with the evaporation values obtained by the QWET model.

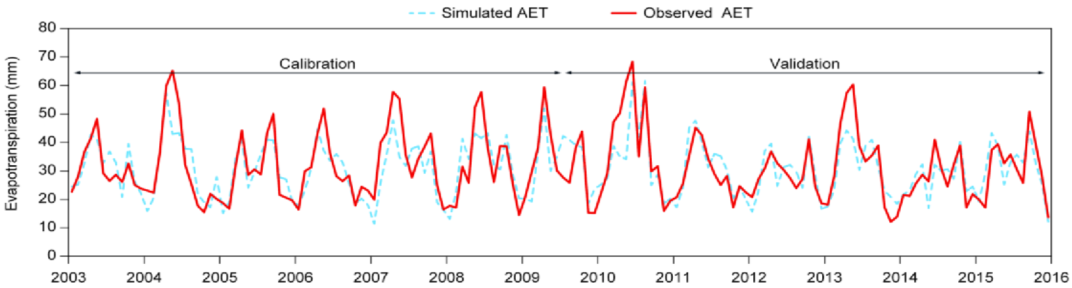

Fig. 2. Comparison of monthly observed and simulated AET for the calibration and validation periods.

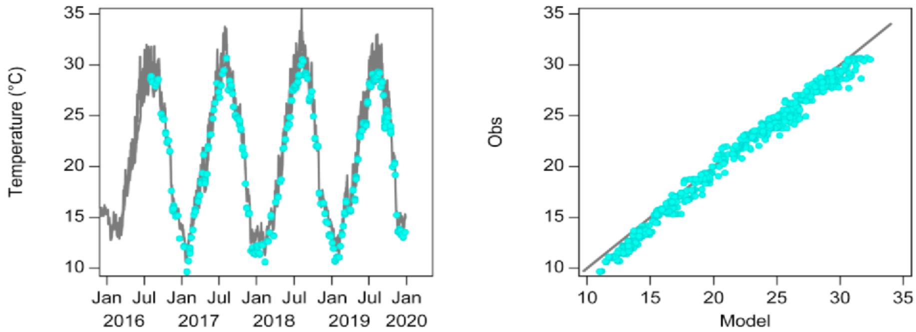

Fig. 3. a) Simulated temperature values (black lines) against observed values (blue points for the period 2016–2019); b) Scatter plot of observed and simulated temperatures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Annual average of each water balance component for the period 2003–2019.

Water balance components (mm)	
Precipitation	293.3
PET	1305.4
AET	410.8
Surface runoff	35.1
Lateral soil flow	3.4
Groundwater seepage	27.0
Groundwater discharge	4.4
Irrigation	185.3

4.3.3. *Surface runoff*

Annual average surface runoff to the Mar Menor for the 2003–2019 period is 49 hm^3/year. As expected, there is a great variability in runoff from year to year depending, not only on the amount of precipitation, but also on the intensity of precipitation events occurring in that year. Throughout the study period, surface runoff varies from 8.1 hm^3 in 2011, where annual rainfall barely exceeded 200 mm, to 202.3 hm^3 in 2019, the wettest year. This large variability is consistent with the findings of other studies performed in the Campo de Cartagena basin (Cabezas, 2009). In addition, the application of a distributed hydrological model has made it possible to quantify the amount of water draining from each of the wadis that flow into the Mar Menor. Results show that Albujón wadi represents 42% of the total drainage water, while Maraña and Miranda wadis account for 17% and 9% of the total surface runoff, respectively.

In recent years, there have been extreme rainfall events in the study area, in which significant amount of water drained into the lagoon, mobilizing in a few hours volumes of water significantly higher than the annual aquifer discharge, altering the salinity of the lagoon suddenly, equaling that of the Mediterranean, and dragging a very significant volume of sediment, with the adverse effects that this can generate. The impact of these flash floods is another component of the problem that must be taken into account when making recommendations for action, and which reaffirms the need for progress in the development of an integrated hydrological and hydrodynamic modelling system to address the problem. As an example, this study has quantified a total discharge during the isolated depression at high levels occurred in December 2016 of 162.9 hm^3 or during the most recent one occurred in September 2019 of 132.1 hm^3.

4.3.4. *Groundwater discharge*

During the last few years, several studies have been conducted to determine the volume of groundwater discharge from the aquifer into the Mar Menor, but the results obtained show a high uncertainty with differences from 8.5 hm^3/year (MITECO, 2020) to 68 hm^3/year (Jiménez-Martínez et al., 2016). The findings from the SWAT model simulations presented in our study shows an average water transfer from the aquifer to the Mar Menor lagoon of 11.1 hm^3/year for the period 2003–2019. If we focus specifically at the time period from October 2018 to September 2019 simulated by the most recent study available (MITECO, 2020), we can see that the groundwater discharge obtained in this work (8.5 hm^3) is very similar to that obtained by our model for the same period of time (8.64 hm^3). It is noteworthy that, in contrast to surface runoff, the variability of annual groundwater discharges is much lower, varying between 7.4 hm^3/year and 32.2 hm^3/year. As a result of the water transferred from the TSWT, occurring since the 1980s, there has been an increase in the aquifers piezometric levels (Senent-Aparicio et al., 2015), which probably has led to greater groundwater discharges into the Mar Menor and the generation of a certain flow in the last kilometers of the ephemeral streams, especially in Albujón stream. This study quantifies the flow in this stream to 4.8 hm^3/year as an average for the period 2003–2019, which is consistent with the observed stream flows measured by the Murcia regional government during the last year (CARM, 2020).

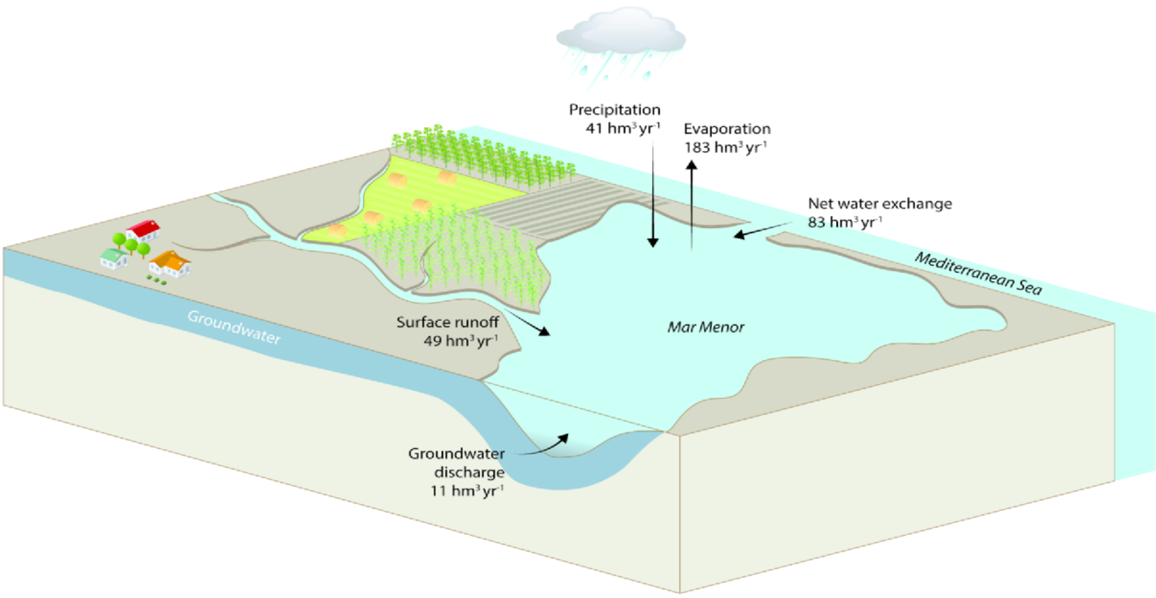

Fig. 4. Annual water balance of the Mar Menor for a period between 2003 and 2019.

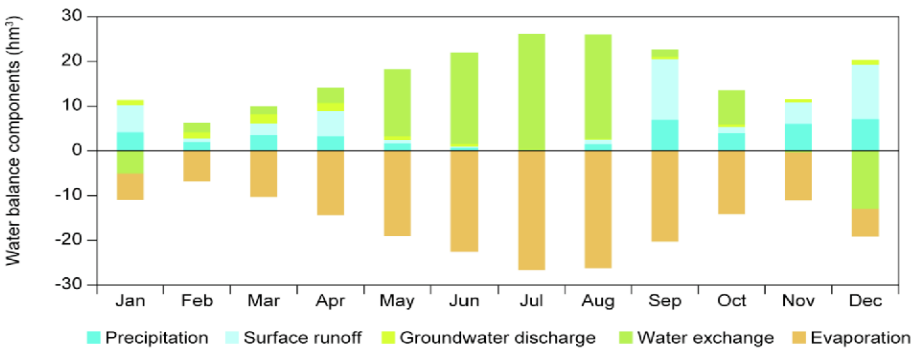

Fig. 5. Monthly average water balance components for a period from 2003 to 2019.

4.3.5. *Water exchange with the Mediterranean Sea*

The average annual water exchange with the Mediterranean Sea is estimated at 82.5 hm^3/year for the period 2003–2019. Martínez-Álvarez et al. (2011) estimated an average annual water exchange from 2003 to 2006 of around 100 hm^3/year. This estimate is lower than water exchange estimated in this study where average annual water exchange from 2003 to 2006 was assessed to be 81.8 hm^3/year. Martínez-Álvarez et al. (2011), however, did not consider surface runoff. Other authors such as De Pascalis et al. (2012) estimated using the SHYFEM hydrodynamic model for the year 1997 a net exchange of water from the Mediterranean Sea to the Mar Menor of 94 hm^3/year, values that are very close to those obtained in this work.

The water balance simulation of the Mar Menor in our study was conducted for a period of time that was much longer than what has been typical of previous studies (Martínez-Álvarez et al., 2011; García-Oliva et al., 2018; García-Oliva et al., 2019). This has allowed us to evaluate the different components in the water balance in both very dry years and in very wet years. From the results obtained, we found that in most of the simulated years the quantity of water that enters the Mar Menor from the Mediterranean Sea is greater than the one that goes out from the Mar Menor to the Mediterranean Sea. However, this does not occur in the years 2016 and 2019, due to the large storm and rainfall events that occurred in these years, resulting in a greater flow of water towards the Mediterranean than the opposite direction. Only in the wettest months, where the runoff generated is great, water exchange is greater towards the Mediterranean Sea (Table 3, see November, December, and January).

It is important to highlight that the approach for deriving the net water exchange between the Mar Menor and the Mediterranean Sea does not consider the water level differences. Compared to other lagoon systems, the Mar Menor generally have little water level fluctuations (Ferrarin et al., 2014), and consequently it has also been demonstrated that wind speed and direction, rather than water level differences, are key drivers of the water exchange between the Mar Menor and the Mediterranean (García-Oliva et al. 2018). However, low-frequency-sea-level fluctuations on a daily, monthly or seasonal scale in the Western Mediterranean are significant (Gomis et al., 2008; Bonaduce et al., 2016). When determining the average water balance over a long period, such sea-level influence diminishes, but on a monthly or seasonal basis, such a contribution can have a significant impact on the water balance. This consideration must be taken into account in the development of future models, and given its importance, it is essential to install specific instrumentation in the Mar Menor lagoon to measure these water exchanges for an accurate model calibration.

Table 3
Monthly and annual average water exchange (hm^3) with the Mediterranean Sea during the period 2003 to 2019. Positive values mean water entering into the Mar Menor.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Min	−25.3	−10.5	−16.4	−46.5	4.4	10.6	23.1	4.3	−129.8	4.6	−28.6	−178.9	−77.3
Mean	−5.1	2.1	1.7	3.4	14.9	20.5	25.8	23.3	1.6	7.6	−0.4	−13.0	82.5
Max	7.8	8.3	11.6	15.2	20.6	23.5	27.7	28.0	20.7	15.4	10.0	7.1	159.5

4.4. Limitations and relevance for policy makers and environmental managers

In recent years, and because of the serious environmental deterioration of the Mar Menor, great efforts have been made to monitor the lagoon (Erena et al., 2020; Pérez-Ruzafa et al., 2019). However, the situation in the Mar Menor watershed is totally different. Here, hardly any gauging stations are present to measure flows caused by storms, besides recently installed gauges in the Albujón streams. In all the other streams that drains into the lagoon there is no point of measurement. No systematic information is available on sediment and nutrients transport in the basins, except some occasional measures usually in low water levels (García-Pintado et al., 2007; Velasco et al., 2006). Hence, no registration of flooding episodes is carried out, despite this is when most of the load is mobilized of sediments and surface contaminants from the basin to the lagoon.

If other key elements of the water balance are examined as the water exchange with the Mediterranean Sea, the situation is similar, and systematic measurements using pressure sensors and Acoustic Doppler Currents Profiles (ADCP) have been deployed only very recently (López-Castejón, 2017). In short, the level of data monitoring is very limited and requires an important effort to improve the information needed by decision makers, especially in extreme storm events. Given the current sensitivity of the regional society to the problem of pollution in the Mar Menor, the implementation of citizen science projects could be very effective for hydrological monitoring (Njue et al., 2019). The model obtained based on the methodology presented in this study, is a good starting point, but future improvements require obtaining more data to reduce the uncertainties inherent in the modelling processes.

Nevertheless, as demonstrated in this study, the combined application of the SWAT and QWET models is an effective tool for stakeholders to estimate the components of the water balance. The ability to import the SWAT-simulated series of flows, sediments or nutrients into the QWET model provides an innovative and easy-to-use tool for decision makers, and can be utilized to simulate the impacts and land use management scenarios on the water quality of the Mar Menor lagoon.

5. Conclusions

This study is the first methodological attempt to integrate the widely used SWAT hydrological model with the QWET hydrodynamic-ecosystem model. This holistic, integrated approach has been applied to evaluate the water balance of the Mar Menor lagoon, which is one of the largest lagoon in Europe and is characterized by its high environmental value. Annual rainfall over the Mar Menor is about 41 hm^3/year, compared to evaporation from the lagoon of 183 hm^3/year and total runoff from the watershed is very variable, between 8 and 202 hm^3/year. The groundwater discharge is of little relative magnitude (about 11 hm^3/year) and variable (maximum values reached 32 hm^3/year) compared with surface runoff. The water exchange with the Mediterranean Sea varies between 160 hm^3/year coming into the Mar Menor in the driest year and 77 hm^3/year leaving from the Mar Menor to the Mediterranean Sea as a result of the extraordinary storm events in 2019. On average, the net water exchange between the Mar Menor and the Mediterranean Sea is 82 hm^3/year towards the Mar Menor lagoon.

The results of this study can be relevant for stakeholders due to its contribution to a deeper understanding of the water cycle of Mar Menor. Despite the scarcity of data and the high degree of anthropization of the study area, it has been possible to evaluate the different components of the water balance. Therefore, the model complex developed in our study, which focused on hydrology, could provide a strong basis for further development with focus on nutrient and ecosystem dynamics. Such further developed model could be used for scenario simulations and help to better understand how climate and nutrient changes affect the aquatic ecosystem. Beyond the Mar Menor study, the methodological approach applied in the present study can also be useful for many other highly anthropized sites where observed data are scarce.

CRediT authorship contribution statement

Javier Senent-Aparicio: Conceptualization, Methodology, Writing – original draft. **Adrián López-Ballesteros:** Data curation. **Anders Nielsen:** Supervision, Writing – review & editing. **Dennis Trolle:** Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements

This work has received funding from the European Unionś Horizon 2020 research and innovation programme within the framework of the project SMARTLAGOON under grant agreement No. 101017861. This work is also a result of Javier Senent-Aparicio internship (21201/EE/19) funded by the Seneca Foundation – Agency for Science and Technology in the Region of Murcia under the Jiménez de la Espada Program for Mobility, Cooperation and Internationalization. Adrián López-Ballesteros was supported by the Ministry of Education, Culture and Sport of Spain under an FPU grant (FPU17/00923). The authors would like to thank the regional government of Murcia for the data supplied through the website of the Mar Menor information service (https://www.canalmarmenor.es/).

References

Alcolea, A., Contreras, S., Hunink, J.E., García-Aróstegui, J.L., Jiménez-Martínez, J., 2019. Hydrogeological modelling for the watershed management of the Mar Menor coastal lagoon (Spain). Sci. Total Environ. 663, 901–914. https://doi.org/10.1016/j.scitotenv.2019.01.375.

Andersen, T.K., Nielsen, A., Jeppesen, E., Hu, F., Bolding, K., Liu, Z., Søndergaard, M., Johansson, L.S., Trolle, D., 2020. Predicting ecosystem state changes in shallow lakes using an aquatic ecosystem model: Lake Hinge, Denmark, an example. Ecol. Appl. 30 (7) https://doi.org/10.1002/eap.v30.710.1002/eap.2160.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2012. Soil and Water Assessment Tool: Input/Output Documentation. Texas Water Resources Institute, College Station, TX, USA, 2012, 650p.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment Part I: model development. J. Am. Water Resour. Assoc. 34, 73–89. https://doi.org/10.1111/jawr.1998.34.issue-110.1111/j.1752-1688.1998.tb05961.x.

Bai, P., Liu, X., 2018. Intercomparison and evaluation of three global high-resolution evapotranspiration products across China. J. Hydrol. 566, 743–755. https://doi.org/10.1016/j.jhydrol.2018.09.065.

Baudron, P., Cockenpot, S., López-Castejón, F., Radakovitch, O., Gilabert, J., Mayer, A., García-Aróstegui, J.L., Martínez-Vicente, D., Leduc, C., Claude, C., 2015. Combining radon, short-lived radium isotopes and hydrodinamic modeling to assess submarine

groundwater discharge from an anthropized semiarid watershed to a Mediterranean lagoon (Mar Menor, SE Spain). J. Hydrol. 525, 55–71. https://doi.org/10.1016/j.jhydrol.2015.03.015.
Blanco-Gómez, P., Jimeno-Sáez, P., Senent-Aparicio, J., Pérez-Sánchez, J., 2019. Impact of climate change on water balance components and droughts in the Guajoyo river basin (El Salvador). Water 11 (11), 2360. https://doi.org/10.3390/w11112360.
Bonaduce, A., Pinardi, N., Oddo, P., Spada, G., Larnicol, G., 2016. Sea-level variability in the Mediterranean Sea from altimetry and tide gauges. Clim. Dyn. 47, 2851–2866. https://doi.org/10.1007/s00382-016-3001-2.
Burchard, H., Bolding, K., Villarreal, M., 1999. GOTM, a general ocean turbulence model: theory, implementation and test cases. Luxembourg Rep. EUR 18745, 103 pp.
Cabezas, F., 2009. Balance hídrico del Mar Menor. In: El Mar Menor: Estado Actual del conocimiento científico. IEA Foundation, Murcia, pp. 167–206.
CARM. Comunidad Autónoma de la Región de Murcia. Decreto–Ley n° 1/2017, de 4 de abril, de Medidas Urgentes Para Garantizar la Sostenibilidad Ambiental en el Entorno Del Mar Menor; Boletín Oficial de la Región de Murcia: Murcia, Spain, 2017. (In Spanish).
CARM. Comunidad Autónoma de la Región de Murcia. Ley 1/2018, de 7 de Febrero, de Medidas Urgentes Para Garantizar la Sostenibilidad Ambiental en el Entorno Del Mar Menor; Boletín Oficial de la Región de Murcia: Murcia, Spain, 2018. (In Spanish).
CARM. Comunidad Autónoma de la Región de Murcia. Decreto–Ley n° 2/2019, de 26 de diciembre, de Protección Integral del Mar Menor; Boletín Oficial de la Región de Murcia: Murcia, Spain, 2019. (In Spanish).
CARM. Comunidad Autónoma de la Región de Murcia. Canal Mar Menor. https://www.canalmarmenor.es/monitorizacion/aforos (accessed 25 July 2020).
Castejón-Porcel, G., Espín-Sánchez, D., Ruiz-Álvarez, V., García-Marín, R., Moreno-Muñoz, D., 2018. Runoff water as a resource in the Campo de Cartagena (Region of Murcia): current possibilities for use and benefits. Water 10, 456. https://doi.org/10.3390/w10040456.
Conesa, H.M., Jiménez-Cárceles, F.J., 2007. The Mar Menor lagoon (SE Spain): a singular natural ecosystem threatened by human activities. Mar. Pollut. Bull. 54, 839–849. https://doi.org/10.1016/j.marpolbul.2007.05.007.
Coppens, J., Trolle, D., Jeppesen, E., Beklioglu, M., 2020. The impact of climate change on a Mediterranean shallow lake: insights based on catchment and lake modelling. Reg. Environ. Change 20, 62. https://doi.org/10.1007/s10113-020-01641-6.
CHS. Confederación Hidrográfica del Segura. 2015. Hydrological Plan of the Segura Basin 2015–2021.
Dargahi, B., Setegn, S.G., 2011. Combined 3D hydrodynamic and watershed modelling of Lake Tana, Ethiopia. J. Hydrol. 398, 44–64. https://doi.org/10.1016/j.jhydrol.2010.12.009.
De Pascalis, F., Pérez-Ruzafa, A., Gilabert, J., Marcos, C., Umgiesser, G., 2012. Climate change response of the Mar Menor coastal lagoon (Spain) using a hydrodynamic finite element model. Estuar. Coast Shelf Sci. 114, 118–129. https://doi.org/10.1016/j.ecss.2011.12.002.
Dile, Y.T., Daggupati, P., George, C., Srinivasan, R., Arnold, J., 2016. Introducing a new open source GIS user interface for the SWAT model. Environ. Model. Softw. 85, 129–138. https://doi.org/10.1016/j.envsoft.2016.08.004.
Domingo-Pinillos, J.C., Senent-Aparicio, J., García-Aróstegui, J.L., Baudron, P., 2018. Long term hydrodynamic effects in a semi-arid mediterranean multilayer aquifer: Campo de Cartagena in south-eastern Spain. Water 10 (10), 1320. https://doi.org/10.3390/w10101320.
Erena, M., Domínguez, J.A., Atenza, J.F., García-Galiano, S., Soria, J., Pérez-Ruzafa, A., 2020. Bathymetry time series using high spatial resolution satellite images. Water 12, 531. https://doi.org/10.3390/w12020531.
Ferrarin, C., Bajo, M., Bellafiore, D., Cucco, A., De Pascalis, F., Ghezzo, M., Umgiesser, G., 2014. Toward homogeneization of Mediterranean lagoons and their loss of hydrodiversity. Geophys. Res. Lett. 41, 5935–5941. https://doi.org/10.1002/2014GL060843.
Francés, F. Informe Sobre el Análisis de Afecciones de Diferentes Actuaciones en la Zona Sur Del Mar Menor Sobre Aportaciones a la Laguna de Agua, Sedimentos y Nitrógeno; Comunidad Autónoma de la Región de Murcia: Murcia, Spain, 2018. (In Spanish) https://www.canalmarmenor.es/documents/575990/659542/1_Informacion_base.pdf/10d2ae69-fe18-48a8-872d-9552aac173ea (accessed 17 February 2020).
García-Ayllón, S., 2017. Integrated management in coastal lagoons of highly complexity environments: resilience comparative analysis for three case-studies. Ocean Coast. Manag. 143, 16–25. https://doi.org/10.1016/j.ocecoaman.2016.10.007.
García-Ayllón, S., 2018. The Integrated Territorial Investment (ITI) of the Mar Menor as a model for the future in the comprehensive management of enclosed coastal seas. Ocean Coast. Manag. 166, 82–97. https://doi.org/10.1016/j.ocecoaman.2018.05.004.
García-Oliva, M., Pérez-Ruzafa, A., Umgiesser, G., McKiver, W., Ghezzo, M., De Pascalis, F., Marcos, C., 2018. Assessing the hydrodynamic response of the mar menor lagoon to dredging inlets interventions through numerical modelling. Water 10 (7), 959. https://doi.org/10.3390/w10070959.
García-Oliva, M., Marcos, C., Umgiesser, G., McKiver, W., Ghezzo, M., De Pascalis, F., Pérez-Ruzafa, A., 2019. Modelling the impact of dredging inlets on the salinity and temperature regimes in coastal lagoons. Ocean Coast. Manag. 180, 104913. https://doi.org/10.1016/j.ocecoaman.2019.104913.
García-Pintado, J., Martínez-Mena, M., Barberá, G.G., Albaladejo, J., Castillo, V.M., 2007. Anthropogenic nutrient sources and loads from a Mediterranean catchment into a coastal lagoon: Mar Menor. Spain. Sci. Total Environ. 373, 220–239. https://doi.org/10.1016/j.scitotenv.2006.10.046.
Gomis, D., Ruiz, S., Sotillo, M.G., Álvarez-Fanjul, E., Terradas, J., 2008. Low frequency Mediterranean sea level variability: the contribution of atmospheric pressure and wind. Glob. Planet. Chang. 63 (2–3), 215–229. https://doi.org/10.1016/j.gloplacha.2008.06.005.
Ha, L., Bastiaanssen, W.G.M., van Griensven, A., van Dijk, A.I.J.M., Senay, G.B., 2018. Calibration of spatially distributed hydrological processes and model parameters in SWAT using remote sensing data and an auto-calibration procedure: a case study in a Vietnamese River Basin. Water 10 (2), 212. https://doi.org/10.3390/w10020212.
Harbaugh, A.W., 2005. Modflow-2005, the US Geological Survey Modular Ground-Water Model: The Ground-Water Flow Process; US Department of the Interior, US Geological Survey: Reston, VA, USA.
Herbasch, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.-N., 2020. The ERA5 global reanalysis. Q. J. Roy. Meteor. Soc. 146, 1999–2049. https://doi.org/10.1002/qj.v146.73010.1002/qj.3803.
Herman, M.R., Hernandez-Suarez, J.S., Nejadhashemi, A.P., Kropp, I., Sadeghi, A.M., 2020. Evaluation of multi- and many-objective optimization techniques to improve the performance of a hydrologic model using evapotranspiration remote-sensing data. J. Hydrol. Eng. 25 (4), 04020006. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001896.
Inoue, M., Park, D., Justic, D., Wiseman, W.J., 2008. A high-resolution integrated hydrology-hydrodynamic model of the Barataria Basin system. Environ. Model. Softw. 23 (9), 1122–1132. https://doi.org/10.1016/j.envsoft.2008.02.011.
Jiménez-Martínez, J., Aravena, R., Candela, L., 2011. The role of leaky boreholes in the contamination of a regional confined aquifer. A case study: the Campo de Cartagena Region, Spain. Water Air Soil Poll. 215, 311–327. https://doi.org/10.1007/s11270-010-0480-3.
Jiménez-Martínez, J., García-Aróstegui, J.L., Hunink, J.E., Contreras, S., Baudron, P., Candela, L., 2016. The role of groundwater in highly human-modified hydrosystems: a review of impacts and mitigation options in the Campo de Cartagena- Mar Menor coastal plain. Environ. Rev. 24 (4), 377–392. https://doi.org/10.1139/er-2015-0089.
Jimeno-Sáez, P., Senent-Aparicio, J., Pérez-Sánchez, J., Pulido-Velázquez, D., 2018. A Comparison of SWAT and ANN Models for Daily Runoff Simulation in Different Climatic Zones of Peninsular Spain. Water 10 (2), 192. https://doi.org/10.3390/w10020192.
Jimeno-Sáez, P., Senent-Aparicio, J., Cecilia, J.M., Pérez-Sánchez, J., 2020. Using Machine-Learning algorithms for eutrophication modeling: case study of Mar Menor lagoon (Spain). Int. J. Environ. Res. Public Health 17 (4), 1189. https://doi.org/10.3390/ijerph17041189.
Kjerfve, B., 1994. Coastal Lagoons. In Coastal Lagoons Processes; Kjerfve, B., Ed.; Elsevier Science Publishers: Amsterdam, The Netherlands; Elsevier Oceanography Series 60, pp. 1–7.
Ladwig, R., Hanson, P.C., Dugan, H.A., Carey, C.C., Zhang, Y., Shu, L., Duffy, C.J., Cobourn, K.M., 2020. Lake thermal structure drives inter-annual variability in summer anoxia dynamics in a eutrophic lake over 37 years. Hydrol. Earth Syst. Sci. Discuss. 1–45. https://doi.org/10.5194/hess-2020-349.
Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A., Moatar, F., Pannard, A., Souchu, P., Lefebvre, A., Pinay, G., 2019. Eutrophication: a new wine in an old bottle? Sci. Total Environ. 651, 1–11. https://doi.org/10.1016/j.scitotenv.2018.09.139.
Lopes, V.A.R., Fan, F.M., Pontes, P.R.M., Siqueira, V.A., Collischonn, W., da Motta Marques, D., 2018. A first integrated modelling of a river-lagoon large-scale hydrological system for forecasting purposes. J. Hydrol. 565, 177–196. https://doi.org/10.1016/j.jhydrol.2018.08.011.
López-Ballesteros, A., Senent-Aparicio, J., Srinivasan, R., Pérez-Sánchez, J., 2019. Assessing the impact of best management practices in a highly anthropogenic and ungauged watershed using the SWAT model: a case study in the El Beal watershed (Southeast Spain). Agronomy 9 (10), 576. https://doi.org/10.3390/agronomy9100576.
López-Castejón, F., 2017. Caracterización de la hidrodinámica del Mar Menor y los flujos de intercambio con el Mediterráneo mediante datos in situ y modelado numérico. Ph.D. Thesis. Technical University of Cartagena, Cartagena, Spain.
MAPA. Ministerio de Agricultura, Pesca y Alimentación. 2010. Mapa de Cultivos y Aprovechamientos (2000–2010). https://www.mapa.gob.es/es/cartografia-y-sig/publicaciones/agricultura/mac_2000_2009.aspx (accessed 11 January 2020).
Martens, B., et al., 2017. GLEAM v3: satellite-based land evaporation and root-zone soil moisture. Geosci. Model Dev. 10 (5), 1903–1925. https://doi.org/10.5194/gmd-10-1903-2017.
Martínez-Alvarez, V., Gallego-Elvira, B., Maestre-Valero, J.F., Tanguy, M., 2011. Simultaneous solution for water, heat and salt balances in a Mediterranean coastal lagoon (Mar Menor, Spain). Estuar. Coast Shelf Sci. 91, 250–261. https://doi.org/10.1016/j.ecss.2010.10.030.
Miralles, D.G., Holmes, T.H.R., de Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J., 2011. Global land-surface evaporation estimated from satellite-based observations. Hydrol. Earth Syst. Sci. 15, 453–469. https://doi.org/10.5194/hess-15-453-2011.
MITECO. Ministerio para la Transición Ecológica y el Reto Demográfico. Cuantificación, control de la calidad y seguimiento piezométrico de la descarga de agua subterránea del acuífero Cuaternario del Campo de Cartagena al Mar Menor. https://www.miteco.gob.es/en/agua/temas/modelo-flujo-del-acuifero-mar-menor_tcm38-509676.pdf (accessed 22 July 2020).

Molina-Navarro, E., Martínez-Pérez, S., Sastre-Merlín, A., Bienes-Allas, R., 2014. Hydrologic modeling in a small Mediterranean basin as a tool to assess the feasibility of a limno-reservoir. J. Environ. Qual. 43 (1), 121–131. https://doi.org/10.2134/jeq2011.0360.

Molina-Navarro, E., Nielsen, A., Trolle, D., 2018. A QGIS plugin to tailor SWAT watershed delineations to lake and reservoir waterbodies. Environ. Modell. Softw. 108, 67–71. https://doi.org/10.1016/j.envsoft.2018.07.003.

Munar, A.M., Cavalcanti, J.R., Bravo, J.M., Fan, F.M., da Motta-Marques, D., Fragoso Jr, C.R., 2018. Coupling large-scale hydrological and hydrodynamic modeling: Toward a better comprehension of watershed-shallow lake processes. J. Hydrol. 564, 424–441. https://doi.org/10.1016/j.jhydrol.2018.07.045.

Nachtergaele, F.O., Van Velthuizen, H., Verelst, L., Wiberg, D., 2012. Harmonized World Soil Database, version 1.2; IIASA: Laxenburg, Austria.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I – a discussion of principles. J. Hydrol. 10, 282–290. https://doi.org/10.1016/0022-1694(70)90255-6.

Navarro, M.C., Pérez-Sirvent, C., Martínez-Sánchez, M.J., Vidal, J., Tovar, P.J., Bech, J., 2008. Abandoned mine sites as a source of contamination by heavy metals: a case study in a semi-arid zone. J. Geochem. Explor. 96, 183–193.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool: Theoretical Documentation, version 2009. Texas Water Resources Institute: College Station, TX, USA. https://swat.tamu.edu/media/99192/swat2009-theory.pdf (accessed 2 February 2020).

Nielsen, A., Bolding, K., Hu, F., Trolle, D., 2017. An open source QGIS-based workflow for model application and experimentation with aquatic ecosystems. Environ. Modell. Softw. 95, 358–364. https://doi.org/10.1016/j.envsoft.2017.06.032.

Nielsen, A., Hu, F., Schnelder-Meyer, N.A., Bolding, K., Andersen, T.K. Trolle, D., 2020. Introducing QWET – a QGIS-plugin for application, evaluation and experimentation with the WET model. Environ. Modell. Softw. Online. 10.1016/j.envsoft.2020.104886.

Nixon, S.W., 1982. Nutrient dynamics, primary production and fisheries yields of lagoons. Oceanol. Acta 5, 357–371.

Njue, N., Stenfert Kroese, J., Gräf, J., Jacobs, S.R., Weeser, B., Breuer, L., Rufino, M.C., 2019. Citizen science in hydrological monitoring and ecosystem services management: state of the art and future prospects. Sci. Total Environ. 693, 133531. https://doi.org/10.1016/j.scitotenv.2019.07.337.

Odusanya, A., Mehdi, B., Schürz, C., Oke, A.O., Awokola, O.S., Awomeso, J.A., Adejuwon, J.O., Schulz, K., 2019. Multi-site calibration and validation of SWAT with satellite-based evapotranspiration in a data sparse catchment in southwestern Nigeria. Hydrol. Earth Syst. Sci. 23, 1113–1144. https://doi.org/10.5194/hess-23-1113-201910.5194/hess-23-1113-2019-supplement.

Peng, J., Dadson, S., Leng, G., Duan, Z., Jagdhuber, T., Guo, W., Ludwig, R., 2019. The impact of Madden-Julian Oscillation on hydrological extremes. J. Hydrol. 571, 142–149. https://doi.org/10.1016/j.jhydrol.2019.01.055.

Pérez-Ruzafa, A., Marcos, C., Pérez-Ruzafa, I.M., 2011. Mediterranean coastal lagoons in an ecosystem and aquatic resources management context. Phys. Chem. Earth 36, 160–166. https://doi.org/10.1016/j.pce.2010.04.013.

Pérez-Ruzafa, A., Campillo, S., Fernández-Palacios, J.M., García-Lacunza, A., García-Oliva, M., Ibañez, H., Navarro-Martinez, P.C., Pérez-Marcos, M., Pérez-Ruzafa, I.M., Quispe-Becerra, J.I., Sala-Mirete, A., Sánchez, O., Marcos, C., 2019. Long term dynamic in nutrients, chlorophyll a, and water quality parameters in a coastal lagoon during a process of eutrophication for decades, a sudden break and a relatively rapid recovery. Front. Mar. Sci. 6, 26. https://doi.org/10.3389/fmars.2019.00026.

Puertes, C., Bautista, I., Lidón, A., Francés, F., 2021. Best management practices scenario analysis to reduce agricultural nitrogen loads and sediment yield to the semiarid Mar Menor coastal lagoon (Spain). Agric. Syst. 188, 103029 https://doi.org/10.1016/j.agsy.2020.103029.

Ramon, J., Lledó, L., Torralba, V., Soret, A., Doblas-Reyes, F.J., 2019. What global reanalysis best represents near-surface winds? Q. J. R. Meteorol. Soc. 145, 3236–3251. https://doi.org/10.1002/qj.3616.

Rupérez-Moreno, C., Senent-Aparicio, J., Martínez-Vicente, D., García-Aróstegui, J.L., Cabezas Calvo-Rubio, F., Pérez-Sánchez, J., 2017. Sustainability of irrigated agriculture with overexploited aquifers: the case of Segura basin (SE, Spain). Agric. Water Manag. 182, 67–76. https://doi.org/10.1016/j.agwat.2016.12.008.

Senent-Aparicio, J., Pérez-Sánchez, J., García-Aróstegui, J.L., Bielsa-Artero, A., Domingo-Pinillos, J.C., 2015. Evaluating groundwater management sustainability under limited data availability in semiarid zones. Water 7 (8), 4305–4322. https://doi.org/10.3390/w7084305.

Senent-Aparicio, J., Pérez-Sánchez, J., Bielsa-Artero, A.M., 2016. Asessment of sustainability in semiarid mediterranean basins: case study of the Segura Basin, Spain. Water Technol. Sci. 7, 67–84.

Senent-Aparicio, J., Pérez-Sánchez, J., Carrillo-García, J., Soto, J., 2017. Using SWAT and Fuzzy TOPSIS to assess the impact of climate change in the headwaters of the Segura River Basin (SE Spain). Water 9, 149. https://doi.org/10.3390/w9020149.

Terink, W., Lutz, A.F., Simons, G.W.H., Immerzeel, W.W., Droogers, P., 2015. SPHY v2.0: spatial processes in HYdrology. Geosci. Model Dev. 8 (7), 2009–2034. https://doi.org/10.5194/gmd-8-2009-2015.

Tobin, K., Marvin, E.B., 2017. Constraining SWAT calibration with remotely sensed evapotranspiration data. J. Am. Water Resour. Assoc. 53 (3), 593–604. https://doi.org/10.1111/jawr.2017.53.issue-310.1111/1752-1688.12516.

Umgiesser, G., Ferrarin, C., Cucco, A., De Pascalis, F., Bellafiore, D., Ghezzo, M., Bajo, M., 2014. Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling. J. Geophys. Res. Oceans 119, 2212–2226. https://doi.org/10.1002/2013JC009512.

Velasco, J., Lloret, J., Millán, A., Barahona, J., Abellán, P., Sánchez-Fernández, D., 2006. Nutrients and particulate inputs into the Mar Menor lagoon (SE Spain) from an intensive agricultural watershed. Water Air Soil Pollut. 176 (1–4), 37–56.

Velasco, A.M., Pérez-Ruzafa, A., Martínez-Paz, J.M., Marcos, C., 2018. Ecosystem services and main environmental risks in a coastal lagoon (Mar Menor, Murcia, SE Spain): the public perception. J. Nat. Conserv. 43, 180–189. https://doi.org/10.1016/j.jnc.2017.11.002.

Viaroli, P., Mistri, M., Troussellier, M., Guerzoni, S., Cardoso, A.C., 2005. Structure, functions and ecosystems alterations in Southern European coastal lagoons: preface. Hydrobiologia 550, 7–9.

Wu, B., Wang, G., Wang, Z., Liu, C., Ma, J., 2017. Integrated hydrologic and hydrodynamic modeling to assess water exchange in a data-scarce reservoir. J. Hydrol. 555, 15–30. https://doi.org/10.1016/j.jhydrol.2017.09.057.

Zhang, L., Lu, J., Chen, X., Liang, D., Fu, X., Sauvage, S., Sánchez-Pérez, J.M., 2017. Stream flow simulation and verification in ungauged zones by coupling hydrological and hydrodynamic models: a case study of the Poyang Lake ungauged zone. Hydrol. Earth Syst. Sci. 21, 5847–5861. https://doi.org/10.5194/hess-21-5847-2017.

4.3 RESEARCH PAPER 3: ASSESSING THE EFFECTIVENESS OF POTENTIAL BEST MANAGEMENT PRACTICES FOR SCIENCE-INFORMED DECISION SUPPORT AT THE WATERSHED SCALE: THE CASE OF THE MAR MENOR COASTAL LAGOON, SPAIN

López-Ballesteros, A.; Trolle, D.; Srinivasan, R.; Senent-Aparicio, J. (2023). Assessing the effectiveness of potential best management practices for science-informed decision support at the watershed scale: The case of the Mar Menor coastal lagoon, Spain. Science of the Total Environment, 859 (1), 160144. https://doi.org/10.1016/j.scitotenv.2022.160144

Science of the Total Environment 859 (2023) 160144

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Assessing the effectiveness of potential best management practices for science-informed decision support at the watershed scale: The case of the Mar Menor coastal lagoon, Spain

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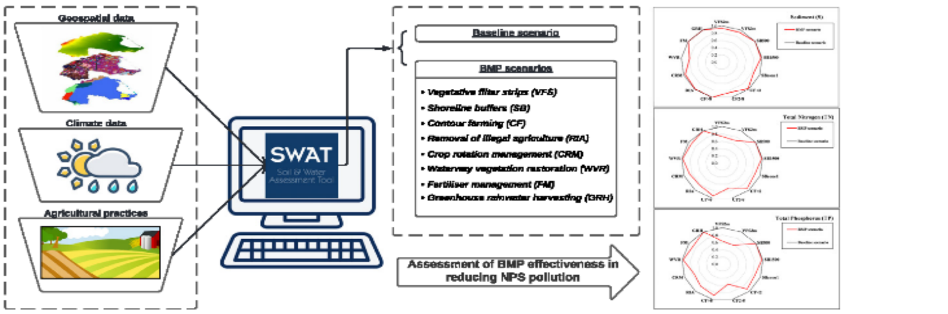
HIGHLIGHTS

- Mar Menor has experienced a significant environmental degradation in the last years.
- Several BMP scenarios proposed by legislations are assessed with the SWAT model.
- VFS and CF were found the most effective BMPs at the watershed scale.
- An effective combination of BMPs could reduce the nutrient exports by 70 %.
- The research findings can guide decision-makers to improve coastal lagoon situation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jurgen Mahlknecht

Keywords:
Soil and Water Assessment Tool (SWAT) model
Best management practices (BMP)
Mar Menor
Non-point source (NPS) pollution
Campo de Cartagena

ABSTRACT

Coastal lagoons are ecosystems of high environmental importance but are quite vulnerable to human activities. The continuous inflow of pollutant loads can trigger negative impacts on the ecological status of these water bodies, which is contrary to the European Green Deal. One example is the Mar Menor coastal lagoon in Spain, which has experienced significant environmental degradation in recent years due to excessive external nutrient input, especially from non-point source (NPS) pollution. Mar Menor is one of the largest coastal lagoons of the Mediterranean region and a site of great ecological and socio-economic value. In this study, the highly anthropogenic and complex watershed of Mar Menor, known as Campo de Cartagena (1244 km^2), was modelled with the Soil and Water Assessment Tool (SWAT) to analyse potential options for recovery of this unique system. The model was used to simulate several best management practices (BMP) proposed by recent Mar Menor regulations, such as vegetative filter strips, shoreline buffers, contour farming, removal of illegal agriculture, crop rotation management, waterway vegetation restoration, fertiliser management and greenhouse rainwater harvesting. Sixteen scenarios of individual and combined BMPs were analysed in this study. We found that, as individual measures, vegetative filter strips and contour farming were most effective in nutrient reduction: approximately 30 % for total nitrogen (TN) and 40 % for total phosphorus (TP). Moreover, waterway vegetation restoration showed the highest sediment (S) reduction at approximately 20 %. However, the combination of BMPs demonstrated clear synergistic effects, reducing S export by 38 %, TN by 67 %, and TP by 75 %. Selecting the most appropriate BMPs to be implemented at a watershed scale requires a holistic approach

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http://dx.doi.org/10.1016/j.scitotenv.2022.160144
Received 8 July 2022; Received in revised form 24 October 2022; Accepted 8 November 2022
Available online 12 November 2022

considering effectiveness in reducing NPS pollution loads and BMP implementation costs. Thus, we have demonstrated a way forward for enabling science-informed decision-making when choosing strategies to control NPS contamination at the watershed scale.

1. Introduction

Coastal lagoons are shallow water bodies generally separated from the open sea by a sandy bar, characterised by low water renewal ratios due to their limited water exchange with the sea and reduced freshwater inputs (Soria et al., 2022). According to the Habitats Directive of the European Union (EU, 1992), coastal lagoons are threatened sites declared as a priority for environmental protection, as they support ecosystems that are very vulnerable to hydrological alterations, water pollution and habitat loss (Pérez-Ruzafa et al., 2005). Coastal lagoons and their surroundings are often under high anthropogenic pressures and undergo significant socio-economic and environmental changes over the years (Upadhyay et al., 2022). The coastal lagoon areas exemplify the conflict of interest between the development of human activities and the ecological requirements of aquatic ecosystems (Flower and Thompson, 2009). Soria et al. (2022) identified thirty-seven coastal lagoons with a surface area larger than 10 km^2 in the Mediterranean region, and concluded that most of them showed eutrophication problems due to the pollution of their inflows. To cope with this issue, the European Green Deal developed a list of goals and actions to preserve biodiversity, reverse the environmental degradation and protect ecosystems (EC, 2019). Since eutrophication has been one the main environmental issues reported for coastal lagoons (Viaroli et al., 2010; Rodríguez-Gallego et al., 2017), this study focuses on the case of the highly anthropised Mar Menor coastal lagoon as a representative case to assess potential solutions for controlling contamination in coastal lagoons at the watershed scale.

Mar Menor is one of the largest coastal lagoons of the Mediterranean region (135 km^2), with significant cultural, socio-economic and ecological value. The lagoon and its adjacent areas are protected at the national and international levels. Mar Menor is included in the Ramsar wetland sites of international importance and the Specially Protected Areas of Mediterranean Importance (SPAMI; Boletín Ofical del Estado [BOE], 2020). Moreover, Perni et al. (2011) estimated the total economic value of the Mar Menor coastal lagoon under good ecological conditions to approximately 45M € per year. During the last few decades, the surroundings of Mar Menor have undergone significant changes because of tourism intensification and intensive agricultural expansion (Álvarez-Rogel et al., 2020). These changes have led to an increase in non-point source (NPS) pollution loads into the lagoon, negatively impacting its ecological status, exemplified by increasing algal levels, more frequent hypoxia events, and subsequent fish kills. Among major NPS sources, agriculture has been recognised as a main source of nutrients (Liu et al., 2013), such as nitrogen and phosphorus. Eutrophication is the main cause of water quality degradation in coastal lagoons (Le Moal et al., 2019), and its consequences adversely impact the local economy, mainly in the fishery and tourism sectors (Jimeno-Sáez et al., 2020). In the Mar Menor watershed, surface runoff can be very high due to common torrential rainfall events (Senent-Aparicio et al., 2021a), generating massive inflows of water and pollution loads into the coastal lagoon (García-Pintado et al., 2007) and further aggravating its vulnerability. Therefore, reducing NPS pollution from anthropogenic activities is required to avoid and reduce the severe environmental degradation of the Mar Menor coastal lagoon.

Throughout recent years, Spanish and regional governments have developed several legislations (BOE, 2020; Boletín Oficial de la Región de Murcia [BORM], 2019, 2018, 2017) to counteract the degradation of Mar Menor. Thus, the most recent Mar Menor laws have suggested implementing specific measures to achieve environmental goals, including a range of best management practices (BMP) in the complex and highly anthropogenic Mar Menor watershed known as Campo de Cartagena (CC). The CC is characterised by a semi-arid climate and ephemeral streams combined with intensive agriculture, mainly supported by groundwater pumping and the Tagus-Segura water transfer scheme (Alcolea et al., 2019). Vegetative filter strips, shoreline buffers, contour farming, removal of illegal agriculture, crop rotation management, waterway vegetation restoration, fertiliser management and greenhouse rainwater harvesting are some of the BMPs proposed by the regional government to limit NPS loading into the coastal lagoon. However, no efficiency assessment of the above-mentioned actions has yet been conducted at the whole watershed scale due to the complexity of the study area and the scarcity of reliable gauging data (Senent-Aparicio et al., 2021a). Therefore, there is a great need to analyse the potential effectiveness of the different BMPs in reducing NPS pollution at the watershed scale to support science-informed decision-making. Thus, a comprehensive understanding of cost-effectiveness and environmental benefits is essential for decision-makers and farmers to select the most appropriate BMPs (Wu et al., 2022).

Watershed modelling is a useful and practical approach for evaluating BMPs since it can assess their efficiency with few spatial and temporal limitations (Lee et al., 2020). Hydrological models, such as the Soil Water Assessment Tool (SWAT; Arnold et al., 1998), have been widely adopted as powerful science-based tools to analyse the role of BMPs in reducing sediment and nutrient losses (Martin et al., 2021; Shi and Huang, 2021; Liu et al., 2019; Uniyal et al., 2020). Moreover, a few studies on surrounding areas of the Mar Menor coastal lagoon have assessed the effectiveness of certain BMPs in reducing NPS pollution with the above-mentioned approach (Puertes et al., 2021; López-Ballesteros et al., 2019). However, these studies have only addressed specific sub-basins of the CC, not considering the entire watershed.

This study is the first to analyse BMPs at the entire watershed scale of the highly important Mar Menor lagoon. The study builds further on the model developed in the study by Senent-Aparicio et al. (2021a), who analysed the different components of the hydrological cycle of the Mar Menor using a combination of the SWAT and the QGIS Water Ecosystems Tool (QWET; Nielsen et al., 2017; Nielsen et al., 2020). Following the recommendations of Senent-Aparicio et al. (2021a), a new line of research based on evaluating the efficiency and cost-effectiveness of BMPs at the watershed scale was conducted using an enhanced and more accurate SWAT model of the CC for agricultural practices.

The main objectives of this research are to (1) improve hydrological modelling of the CC, including more accurate agricultural information, (2) evaluate the effect of individual and combined BMPs on NPS pollution loads that flow into the Mar Menor coastal lagoon at the watershed scale and (3) assess the cost-effectiveness of BMP implementation for controlling NPS pollutants. Additionally, this work intends to help stakeholders and policymakers achieve a better science-based understanding of the Mar Menor environmental issue and identify an effective management strategy at the watershed scale.

2. Materials and methods

2.1. Study area

The Mar Menor coastal lagoon watershed, CC, is located in the Segura River Watershed, a semi-arid region of the southeast portion of the Iberian Peninsula (Fig. 1).

This region has one of the highest structural water deficits in Europe (Senent-Aparicio et al., 2016), further aggravated by economic activities. The CC covers 1244 km^2, most of which is agricultural land (approximately 75 %). This area is considered one of the main national and international producers of agricultural products in Europe (Castejón-Porcel et al.,

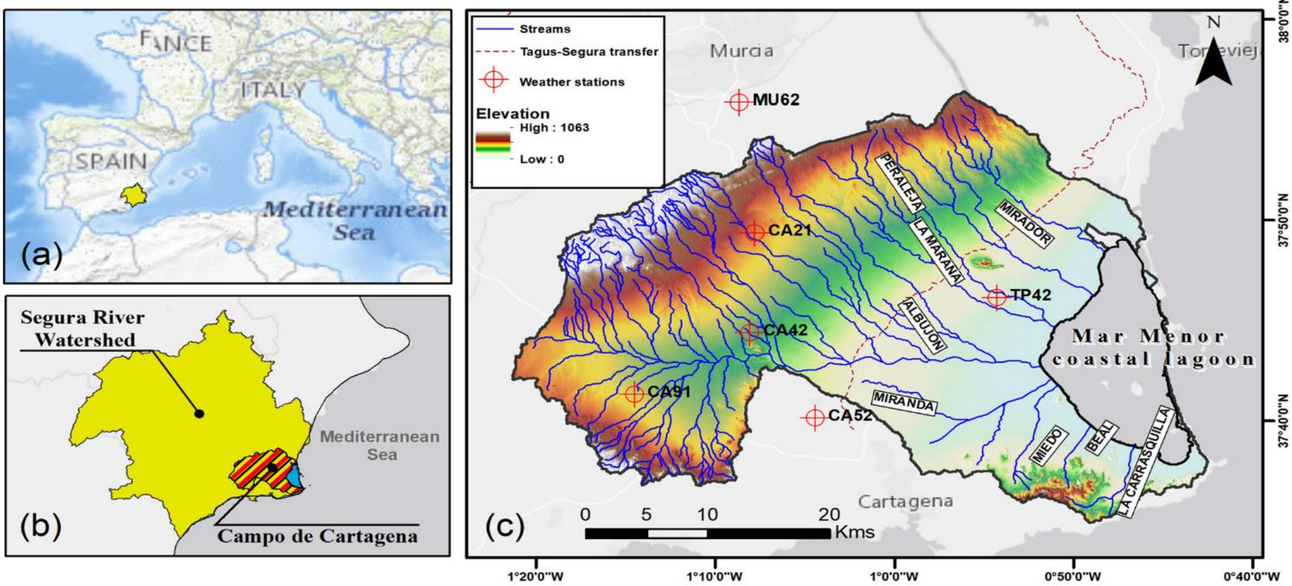

Fig. 1. a) Location of the Segura River Watershed; b) Location of the Campo de Cartagena (CC) within the Segura River Watershed; c) the CC.

2018). In addition, tourism has great relevance in the closest surrounding areas to the lagoon. Intensive irrigated agriculture in this region is mainly maintained by a combination of groundwater resources, reused wastewater, seawater desalination and the Tagus-Segura water transfer scheme (Álvarez-Rogel et al., 2020). The Tagus-Segura water transfer scheme, established in 1979, is one of the major water providers of the CC, with an average of 122 10^6 m^3 $year^{-1}$. However, recent studies (Senent-Aparicio et al., 2021b) have demonstrated that water availability from this source could decrease in upcoming years due to the impact of climate change on water resources at the headwaters of the Tagus River. Additionally, the water scarcity issues in this region have led to a high level of agricultural technification, with drip irrigation applied to approximately 90 % of crops (Alcon et al., 2011).

The semi-arid climate of the study area, corresponding to cold semi-arid climate (BSk) according to Köppen-Geiger climate classification, is characterised by an average annual temperature of approximately 17 °C (range 13°–24 °C) and average annual precipitation of 300 mm with high inter-annual variability. Ephemeral streams are the main drainage system of the CC, flowing only during intense rainfall events (Alcolea et al., 2019; Senent-Aparicio et al., 2015). Among all ephemeral streams, the eight most relevant in the CC are shown in Fig. 1: Mirador, Peraleja, La Maraña, Albujon, Miranda, Miedo, Beal and La Carrasquilla. Extreme rainfall events are common in Mediterranean watersheds and can produce severe floods (Garcia-Ayllon and Radke, 2021). During these extreme rainfall episodes, large amounts of water and NPS pollution loads are moved through ephemeral streams into the Mar Menor coastal lagoon (Velasco et al., 2006).

The CC's topography is characterised by gentle slope gradients (approximately 40 % of the slopes are <2 %) and altitude ranges from 0 to 1063 m above sea level. The dominant soil type is Calcaric Cambisols (FAO–ISRIC, 1990), a loam textural class mainly composed of silt and sand. Regarding land use, intensive irrigated agriculture is the dominant land use (45 %), followed by rain-fed agriculture (30 %) and forest and shrub lands (15 %). Intensive agriculture mainly consists of horticultural crops, citrus trees and greenhouses. In the horticulture of the CC, common agricultural practices are an annual three-crop rotation (broccoli, cantaloupe and lettuce) and the application of fertilisers (nitrogen and phosphorus) by fertigation.

2.2. Soil and water assessment tool

The SWAT model is one of the world's most extensively applied hydrological models (Gassman and Wang, 2015), and the one selected for this study. SWAT is a physically-based, semi-distributed, continuous-time hydrologic model developed by the United States Department of Agriculture (USDA) and Texas A&M University (Arnold et al., 1998). The SWAT model allows users to simulate water quality and quantity, nutrient and sediment loss and management practices at the watershed scale (Neitsch et al., 2011). Furthermore, SWAT can predict the effects of anthropogenic changes in complex watersheds (Lee et al., 2020) and is considered an effective tool for evaluating the impacts of NPS pollution on water quality variables such as sediment and nutrients (Liu et al., 2013). SWAT has also been widely used to evaluate water policies (Ricci et al., 2022; Čerkasova et al., 2021; Gassman et al., 2014). The SWAT model delineates streams and sub-basins based on a digital elevation model (DEM); each sub-basin is further divided into hydrologic response units (HRU) based on unique intersections of land uses, soil types and slopes. A water balance is derived for each HRU (Eq. (1)), and their outputs are aggregated through the channel network to obtain the hydrologic cycle of the watershed:

$$SW_{t\,i} = SW_{o\,i} + \Sigma\left(R_{day\,i} - Q_{surf\,i} - ET_i - W_{seep\,i} - Q_{gw\,i}\right) \quad (1)$$

where SW_t is the final soil water content (mm); SW_o is the initial soil water content on day i (mm); R_{day} is the precipitation on day i (mm); Q_{surf} is the surface runoff on day i (mm); ET is the evapotranspiration on day i (mm); W_{seep} is the percolation on day i (mm) and Q_{gw} is the groundwater return flow on day i (mm).

In SWAT, surface runoff is simulated by the Soil Conservation Service (SCS) Curve Number (CN) method (USDA-SCS, 1972), soil erosion is estimated by the Modified Universal Soil Loss Equation (MUSLE; Williams, 1975) and water quality variables are calculated by equations from the QUAL2E model (Brown and Barnwell, 1987). In this study, the Penman-Monteith method was selected to estimate potential evapotranspiration (PET). Detailed documentation of the SWAT model is found in Neitsch et al. (2011).

Table 1
SWAT input maps of the CC.

Map	Spatial resolution	Source
DEM	25 m × 25 m	National Geographic Institute of Spain
Land uses	200 m × 200 m	Spanish Ministry of Agriculture, Fisheries and Food (2000 – 2010)
Soil properties	1 km × 1 km	Harmonized World Soil Database

2.3. Model inputs and setup

SWAT is a hydrological model requiring a large amount of input data, such as meteorological variables, topography, land uses, soil maps and management practices (Neitsch et al., 2011). Meteorological variables in SWAT include daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. In this study, the climatic information was collected from six weather stations of the Murcian Institute of Agrarian and Food Research and Development located in and around the study area (Fig. 1). These weather stations provided observations of all meteorological variables from 2000 to 2021. Detailed information about the input maps used to set up the SWAT model of the CC is listed in Table 1.

This study used the open-source geographic information system (GIS) interface for SWAT (QSWAT; Dile et al., 2016) to prepare and execute the SWAT model. Based on the SWAT input maps, after applying the SWAT2lake tool (Molina-Navarro et al., 2018), which is a plugin to assist in the delineation of the entire watershed that flows into a reservoir or lagoon, the CC was discretised by 152 sub-basins. Subsequently, slope classes of <2 %, 2 %–8 % and >8 % combined with a minimum area threshold of 100 ha (any HRU below this threshold was disregarded) were selected, resulting in a total of 520 HRUs (Senent-Aparicio et al., 2021a).

In irrigated agricultural areas, a realistic representation of agricultural management practices is an important requirement to achieve good performance when simulating water quantity and quality (Samimi et al., 2020). Therefore, the main agricultural management practices of the dominant CC land use (irrigated agriculture) were included in the SWAT model. The intensive irrigated land use in the study area was mainly composed of horticultural crops, citrus trees and greenhouses. For horticultural crops, an annual three-crop rotation (broccoli, cantaloupe and lettuce) was the standard crop schedule implemented (Table 2). Fertilisation rates for each crop were obtained from official government documentation (BORM, 2012a, 2012b, 2012c; BOE, 2004). Additionally, irrigation volumes of the intensive agricultural area were extracted from the Hydrological Plan of the Segura River Watershed.

2.4. Model calibration and validation

Simulating the hydrologic response of semi-arid agricultural areas is challenging due to complexities related to anthropogenic alterations and, hence, model calibration in these regions (Samimi et al., 2020). Furthermore, the calibration process is hampered by the lack of reliable gauging data, as in the CC study case. Therefore, a calibration and validation approach based on satellite-based actual evapotranspiration (AET) data obtained from Global Land Evaporation Amsterdam Model version 3b (GLEAM v3b; Miralles et al., 2011) was carried out in this study, and for nutrient exports, we compared our baseline estimates with those estimated in other studies.

In agricultural areas, evapotranspiration is a key variable in the hydrologic cycle of the watershed (Odusanya et al., 2019). GLEAM v3b is an AET dataset generated by a combination of remote sensing observations from several satellites, highly validated with eddy-covariance towers and in-situ sensors (Martens et al., 2017), covering a data period from 2003 to 2015 at a spatial resolution of 0.25° regular grid. In recent years, several studies have satisfactorily applied and validated the satellite-based AET

Table 2
Standard crop schedule of the CC.

Year	Date		Operation	Application Rate	Crop
	Month	Day			
1	January	1	Sowing		Broccoli
1	January	1	Irrigation	~28 mm month^{-1}	Broccoli
1	January	1	Fertilisation[a]	245 KgN ha^{-1} year^{-1} 100 KgP ha^{-1} year^{-1}	Broccoli
1	April	30	Harvest and kill		Broccoli
1	May	1	Sowing		Cantaloupe
1	May	1	Irrigation	~48 mm month^{-1}	Cantaloupe
1	May	1	Fertilisation[a]	225 KgN ha^{-1} year^{-1} 105 KgP ha^{-1} year^{-1}	Cantaloupe
1	August	31	Harvest and kill		Cantaloupe
1	September	1	Sowing		Lettuce
1	September	1	Irrigation	~25 mm month^{-1}	Lettuce
1	September	1	Fertilisation[a]	100 KgN ha^{-1} year^{-1} 58 KgP ha^{-1} year^{-1}	Lettuce
1	December	31	Harvest and kill		Lettuce

[a] Total amount applied throughout the crop schedule.

calibration and validation process with GLEAM (Bennour et al., 2022; Odusanya et al., 2021; Puertes et al., 2021; López-Ballesteros et al., 2019).

The SWAT simulation period for the CC included a warm-up period of 3 years (2000 – 2002), a calibration period of 7 years (2003–2009) and a validation period of 6 years (2010–2015). Manual calibration was first conducted by selecting a SWAT parameter set relevant to AET (CN2, ESCO, EPCO, SOL_AWC and RCHRG_DP), comparing AET values from the SWAT with satellite-based AET values. Furthermore, the values of the calibrated AET parameters were preserved for consistency with the previous study (Senent-Aparicio et al., 2021a). Finally, the SWAT model performance of the CC was evaluated graphically and statistically. Originally, three well-established statistical evaluation indices were used: the coefficient of determination (R^2), the percent bias (PBIAS) and the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970). Moreover, the Kling-Gupta efficiency (KGE; Gupta et al., 2009) was included to comprehensively assess the SWAT model performance. R^2 ranges from 0 to 1, with a value closer to 1 producing the most accurate model. The PBIAS indicates model overestimation or underestimation, with an optimum value of 0. NSE and KGE ranges from $-\infty$ to 1, where 1 is the optimal value. For classifying the model performance, the rating proposed by Moriasi et al. (2015) and Kouchi et al. (2017) for a monthly time step were applied, where satisfactory thresholds were $R^2 > 0.6$, PBIAS $\leq \pm 25$ % and NSE and KGE ≥ 0.5. The calibrated and validated SWAT model of the CC was considered the baseline scenario for the next sections of this study.

2.5. Modelling individual BMP scenarios

The selection of BMPs was mainly based on the official legislation developed by the Spanish and regional governments (BOE, 2020; BORM, 2019, 2018) to counteract the degradation of Mar Menor. BMPs are expected to play a key role in the recovery process of Mar Menor (Álvarez-Rogel et al., 2020). In this study, vegetative filter strips, shoreline buffers, contour farming, removal of illegal agriculture, crop rotation management, waterway vegetation restoration, fertiliser management and greenhouse rainwater harvesting were the BMPs selected and implemented based on the baseline scenario. Although eight BMP types were assessed in this study, 13 individual BMP scenarios were simulated with SWAT as some BMPs were evaluated under several settings such as filter strips, shoreline buffers and contour farming. Therefore, 13 different individual BMP scenarios were designed and simulated in SWAT to estimate the reduction of NPS pollution loads flowing from the CC into the Mar Menor coastal lagoon.

2.5.1. Vegetative filter strips (VFS)

Vegetative filter strips (VFS) consist of installing a vegetated area along the edge of agricultural land to slow surface runoff, trap sediments and absorb nutrients. The SWAT model simulated the filter efficiency ($trap_{ef}$) of the VFS using Eq. (2) (Neitsch et al., 2011),

$$trap_{ef} = 0.367 \cdot FILTERW^{0.2967} \quad (2)$$

where *FILTERW* is the width of the VFS in metres.

According to BOE (2020), all agricultural land uses in the CC (approximately 75 % of the watershed) are forced to implement VFS. A filter strip width of 2–3 m is required for intensive irrigated agriculture, whereas for rain-fed agriculture, a filter strip width of 1 m is required in fields with average slopes <2 % and a filter strip width of 2 m in remaining slope classes. Therefore, two VFS scenarios were simulated in the SWAT. The first scenario applied the least restrictive filter strip width (2 m) in intensive irrigated land, while the second applied the 3 m filter strip width. In both scenarios, the VFS width of rain-fed land was applied as described above.

2.5.2. Shoreline buffers (SB)

Shoreline buffers (SB) can reduce NPS contamination by changing land-use patterns (Wang et al., 2013). SB consists of a band around the shore of the lagoon where land uses are modified according to the limitations imposed by law. Three SB scenarios were simulated with the SWAT model of the CC based on SB areas proposed by government regulations: (1) a buffer of 500 m from the Mar Menor shoreline (SB500; BORM, 2019); (2) a buffer of 1500 m (SB1500; BOE, 2020); and (3) a buffer including the special protection SB area established by BOE (2020) known as Zone 1 (SBzone1). These scenarios were implemented in SWAT by changing the intensive irrigated agriculture land uses inside the SB area to forest and shrub land use. The percentages of land-use change at the watershed scale are listed in Table 3.

2.5.3. Contour farming (CF)

Contour farming (CF) is an agricultural practice entailing planting, tilling and harvesting following the terrain contour lines. CF increases soil infiltration and decreases surface runoff, reducing soil erosion and NPS pollution loads that flow into streams, especially during intense rainfalls (Liu et al., 2013). CF was represented by changing the parameters CONT_CN and CONT_P to 65 and 0.8, respectively, in the SWAT operations module (.ops; Arnold et al., 2012). In this study, three CF scenarios were simulated to evaluate their effect on NPS pollution loads reduction for three different slope ranges (<2 %, 2 %–8 % and >8 %). Following the BOE (2020) requirements, CF was only applied for agricultural non-woody land uses of the CC.

2.5.4. Removal of illegal agriculture (RIA)

According to official data from SIGPAC (2016), farmers have officially declared approximately 474 km^2 of the CC as irrigated land with irrigation rights. However, according to the land-use map, the irrigated area in the CC is approximately 90 km^2 larger than the official data. Other reports have also identified these irregularities (Mar Menor Scientific Advisory Group, 2017), which are being prosecuted by law (BOE, 2020). Therefore, a scenario called the removal of illegal agriculture (RIA) has been simulated with SWAT to evaluate the impact of removing these illegal land uses on NPS pollution loads to the Mar Menor watershed. Thus, a new land-use map was created to simulate this RIA scenario, where approximately 90 km^2 of intensive irrigated land use was randomly removed and changed to forest and shrub lands. After introducing the modified land-use map, the calibrated SWAT model was re-established, and the RIA scenario was simulated.

Table 3
Land-use changes of shoreline buffers (SB) scenarios at the watershed scale.

Scenario	Intensive irrigated land use		Forest and shrub land use	
	Area (km^2)	Percentage[a] (%)	Area (km^2)	Percentage[a] (%)
Baseline	562.26	45.19	193.43	15.54
SB500	558.40	44.88	197.29	15.85
SB1500	538.07	43.25	217.62	17.49
SBzone1	484.08	38.91	271.61	21.83

[a] Percentage of total study area.

2.5.5. Crop rotation management (CRM)

Crop rotation management (CRM) consists of modifying the annual crop schedule from three-crop to two-crop rotation, as the BOE (2020) established. This CRM limitation mainly affects horticultural crops, where the standard crop schedule is as follows: broccoli, cantaloupe and lettuce. In this study, the CRM scenario was implemented in the SWAT model of the CC by removing the cantaloupe crop due to its market price instability (Puertes et al., 2021). Additionally, a vegetation cover (representing a catch crop) was established during the non-crop period to prevent soil erosion.

2.5.6. Waterway vegetation restoration (WVR)

Waterway vegetation restoration (WVR) consists of recovering the autochthonous vegetation of streams to reduce flow velocity and channel erosion, enhancing NPS pollution loads retention. This WVR measure has been contemplated in the government regulations (BOE, 2020) and is expected to be carried out in the main ephemeral streams of the study area in the next years (BOE, 2021). In this study, the WVR scenario was simulated by re-vegetating the last kilometre of the main ephemeral streams of the CC (Fig. 1). This BMP was implemented in SWAT by using its operations module (.ops), where grassed waterway parameters were established, such as Manning's n value for vegetated surfaces (GWATN = 0.1) and length of waterways with vegetation (GWATL = 1 km).

2.5.7. Fertiliser management (FM)

Water quality can be improved by reducing applied fertiliser from agricultural watersheds (Risal and Parajuli, 2022). This study represented the fertiliser management (FM) scenario by reducing fertiliser application rates in intensive agriculture areas of the CC. Hence, the applied nitrogen and phosphorus amounts were reduced by 20 %, as suggested in the guidelines provided by the Code of Good Agricultural Practices of Murcia (BORM, 2018) and the European Commission (EC, 2020).

2.5.8. Greenhouse rainwater harvesting (GRH)

The BOE (2020) established that all greenhouses inside the CC must implement rainwater harvesting systems with a capacity of at least 100 l m^{-2}. Rainwater harvesting consists of the interception and storage of rainwater for irrigation and stormwater reduction (Waidler et al., 2009). Thus, a greenhouse rainwater harvesting (GRH) scenario was simulated in this study to evaluate the effect of GRH in reducing NPS pollution loads at the watershed scale. The GRH scenario was simulated using the pond module (.pnd; Arnold et al., 2012) in the SWAT model of the CC. First, a supervised classification of the CC orthophotos obtained from digital aerial orthophotographs of the Spanish National Orthophoto Program (PNOA) was carried out in QGIS with the maximum likelihood algorithm (Basukala et al., 2017) to identify the location and estimate the area of each greenhouse per sub-basin (Fig. 2). A total greenhouse area of 23.74 km^2 was quantified in the CC. Finally, pond parameters were adjusted using the previous GIS information, such as the fraction of sub-basin covered by greenhouses (PND_FR), the volume of water to fill the deposit (PND_PVOL) and the water surface area of the filled deposit (PND_PSA).

2.6. Modelling combined BMP scenarios

Considering synergistic effects, combining BMPs may provide better results than individual BMPs at the watershed scale (Liu et al., 2019; López-Ballesteros et al., 2019; Mtibaa et al., 2018). In practice, several BMPs are often implemented simultaneously in agricultural areas to control NPS contamination (Uniyal et al., 2020). BMPs are usually classified as agricultural or structural. Agricultural BMPs (AgriBMPs) are practices carried out at the field scale by farmers, while structural BMPs (StruBMPs) are artificial or natural practices implemented outside the field borders. As can be observed in Table 4, this study simulated three different combined BMP scenarios,

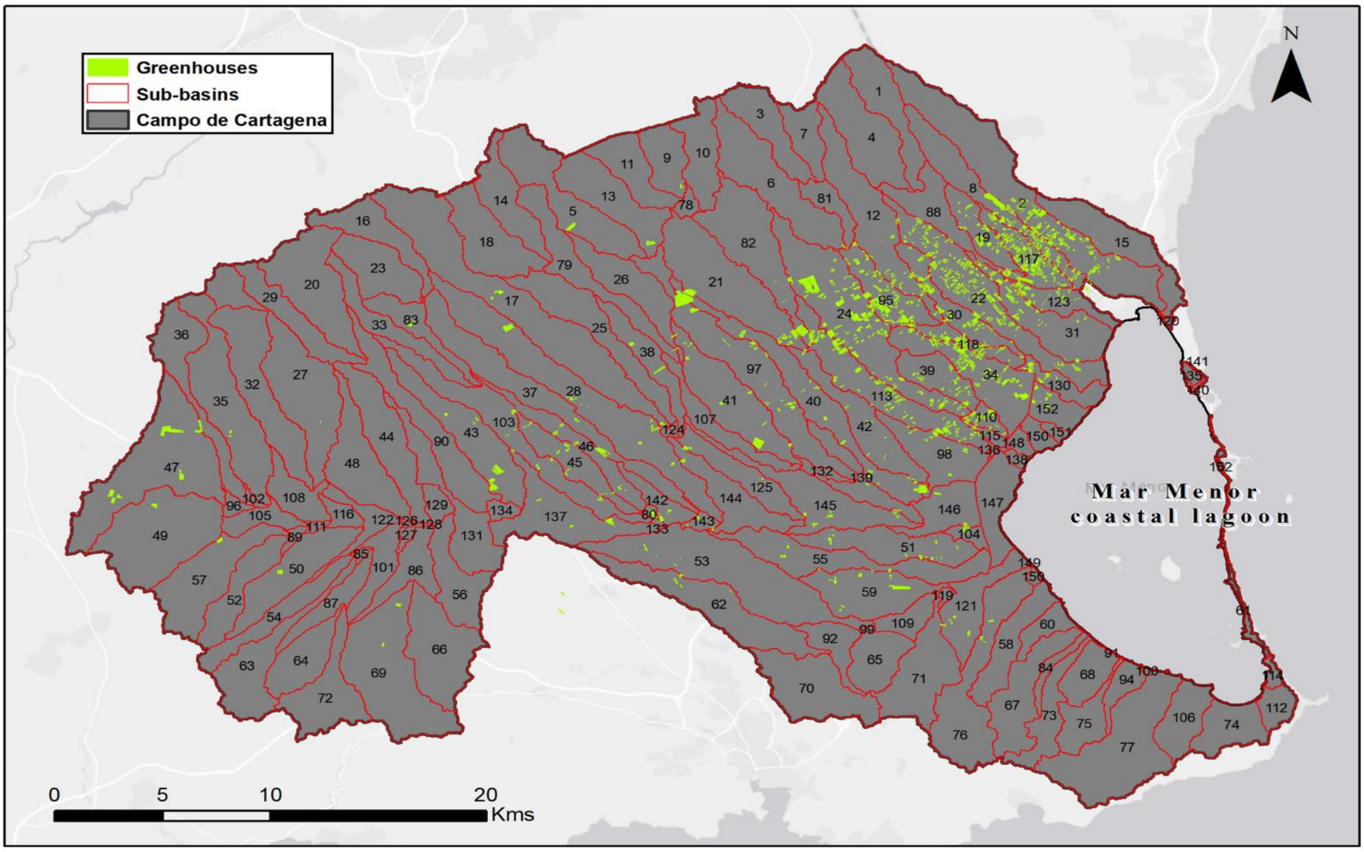

Fig. 2. Location of greenhouses and sub-basins in the CC.

two of them based on the previous BMP classification (AgriBMPs and StruBMPs) and the last one combining both scenarios (AllBMPs).

For the AgriBMPs scenario, the selected BMPs were: VFS of 2-metre width (VFS2m), CF for the slopes between 2 % and 8 % (CF2–8), CRM and FM. For the StruBMPs scenario, the selected BMPs were: RIA and WVR. This selection was carried out considering the BMP implementation responsibility, which for the AgriBMPs lied with the farmers, while the responsibility for the StruBMPs lied with the government. Finally, for the last scenario, AllBMPs, a combination of all the above-mentioned BMPs was simulated.

2.7. Assessing BMP scenarios and cost-effectiveness

Annual NPS pollution loads, such as sediment (S), total nitrogen (TN) and total phosphorus (TP), discharged into the Mar Menor were compared with those of the baseline scenario to evaluate the impact of implemented BMP scenarios at the watershed scale. The total amount of NPS pollution loads flowing into the Mar Menor through the ephemeral streams network was obtained by aggregating the outputs of all surrounding Mar Menor sub-basins. Following the approach proposed by López-Ballesteros et al. (2019), the effectiveness (%) of the BMPs scenarios was computed using Eq. (3) for 2003–2021.

$$Effectiveness = \frac{(Y_{baseline} - Y_{BMP})}{Y_{baseline}} \cdot 100 \tag{3}$$

where Y_{BMP} and $Y_{baseline}$ are the annual NPS pollution loads (t year^{-1}) produced by the selected BMP scenario and the baseline scenario, respectively. All final average effectiveness values were discussed with experts in the field.

Table 4
Combined BMP scenarios simulated.

Combined BMP scenario	Classification	Applied BMPs
AgriBMPs	Agricultural	VFS2m CF2–8 CRM FM
StruBMPs	Structural	RIA WVR
AllBMPs	Agricultural + structural	VFS2m CF2–8 CRM FM RIA WVR

Implementing BMPs also impacts farmers and society economically (Ricci et al., 2020). Therefore, a cost-effectiveness assessment was conducted to select the most effective BMPs at a reasonable economic cost. The cost-effectiveness (CE) ratio was calculated using the following expression (Eq. (4)):

$$CE\ ratio = \frac{Total\ Cost}{Effectiveness} \tag{4}$$

where *Total Cost* is the implementation cost in euros (€) of the simulated BMP scenario (Table 7) and *Effectiveness* is the percentage of change (%). The CE ratio represents the cost per percentage unit of change in NPS pollution loads. Therefore, a lower CE ratio means a more cost-effective

Table 5
Cost per hectare of each assessed BMP.

BMP	Cost per hectare (€/ha)	Source
Vegetative filter strips	10[a]	(López-Ballesteros et al., 2019)
Shoreline buffers	4000	(MITECO, 2019)
Contour farming	10	(López-Ballesteros et al., 2019)
Illegal agriculture removal	390	(MITERD, 2021)
Crop rotation management	10–100	(Amin et al., 2020)
Waterway vegetation restoration	5000	(MITECO, 2019)
Fertiliser management	100	(López-Ballesteros et al., 2019)
Greenhouse rainwater harvesting	6500[b]	(Sanches-Fernandes et al., 2015)

[a] Cost per installed metre width.
[b] Cost per rainwater harvesting system of 100 m^3.

scenario. Table 5 shows the cost per hectare estimated from the literature of each assessed BMP.

3. Results

3.1. SWAT model performance

The SWAT model of the CC achieved a good performance (Fig. 3) both in the calibration (R^2 = 0.73, PBIAS = −9.11 %, NS = 0.67 and KGE = 0.81) and the validation period (R^2 = 0.74, PBIAS = −5.22 %, NS = 0.71 and KGE = 0.82) for monthly AET according to the statistics criteria proposed by Moriasi et al. (2015) and Kouchi et al. (2017). A slight improvement in PBIAS was achieved compared to the previous SWAT model due to the more accurate information about agricultural management practices. More details about the AET manual calibration and selected SWAT parameters appear in Senent-Aparicio et al. (2021a).

In the SWAT model of the CC, the annual average values of the hydrologic cycle components for 2003–2021 were precipitation = 301 mm, PET = 1296 mm, AET = 408.5 mm, surface runoff = 38.1 mm, lateral flow = 7.25 mm and groundwater discharge = 4.7 mm. Similar water balance values were validated in a previous study by Senent-Aparicio et al. (2021a). AET was greater than precipitation, aligned with the distinctive agricultural nature of the CC.

Due to the lack of reliable gauging data to assess the SWAT model performance in simulating NPS pollutants, a soft validation (Arnold et al., 2015) was conducted for sediment and nutrient loads by comparing our annual estimates with those in other studies. Regarding sediment loads, the SWAT model of the CC estimated an average sediment yield of 2.52 t ha^{-1} $year^{-1}$, which is within the range of 0–5 t ha^{-1} $year^{-1}$ quantified by the National Soil Erosion Inventory 2002–2012 (MIMAM, 2012) for the study area and in line with the average estimation of approximately 2 t ha^{-1} $year^{-1}$ of Romero-Díaz et al. (2011) for this region. Regarding nutrient loads, SWAT estimated an average TN inflow to the Mar Menor coastal lagoon of 482.4 t $year^{-1}$ for 2003–2021, which is in agreement with the range (515 ± 176 t $year^{-1}$) of nitrogen inputs to Mar Menor obtained by García-Pintado et al. (2007). The average TP inflow simulated by SWAT was 242.2 t $year^{-1}$, similar to the TP value of approximately 240 t $year^{-1}$ estimated in other studies of the Mar Menor coastal lagoon (Mar Menor Scientific Advisory Group, 2017).

3.2. Efficiencies of individual BMP scenarios in reducing NPS pollution loads

The impact of each BMP on NPS pollution loads that flow into the Mar Menor is listed in Table 6 based on its effectiveness.

In the CC, VFS3m was the most effective individual BMP scenario in reducing TN and TP, with effectiveness values of 30.3 % and 41.3 %, respectively. For reducing S loads into the Mar Menor, WVR was found more effective than all other individual BMP scenarios, with a reduction of 20.4 %. In terms of land-use management practices, restoration of illegal agriculture to forest and shrub lands was the most effective scenario in abating TN and TP, with a reduction of 17.6 % and 19 %, respectively. Regarding CF scenarios, the results of this study showed that CF was most effective in the slope range of 2 %–8 %. Similar results about CF were found in other studies (Wu et al., 2022; Liu et al., 2013). Two agricultural BMP scenarios farmers can easily implement, CRM and FM, showed a low effect on S loads but reduced TN and TP discharge into the Mar Menor by 14.3 % and 25.2 %, and 7.7 % and 12.4 %, respectively. These results were consistent with the BMP trends of other studies in small parts of the study area (Puertes et al., 2021; López-Ballesteros et al., 2019).

3.3. Efficiencies of combined BMP scenarios in reducing NPS pollution loads

Fig. 4 shows the effectiveness of the combined BMP scenarios for the assessed NPS pollution loads in this study.

As can be observed in Fig. 4, all combined BMP scenarios simulated a reduction in NPS pollution in the Mar Menor. For sediment loads, 17.8 %, 21.9 % and 38 % effectiveness were estimated for the AgriBMPs, StruBMPs and AllBMPs scenarios, respectively. TN effectiveness was 59.6 % for the AgriBMPs scenario, 22.6 % for the StruBMPs scenario and 67.2 % for the AllBMPs scenario. TP effectiveness showed the highest reduction values, with 69.5 %, 23.1 % and 75.3 % for the AgriBMPs, StruBMPs and AllBMPs scenarios, respectively.

3.4. BMP cost-effectiveness

Table 7 shows the cost-effective assessment carried out in this study for all simulated BMP scenarios. CE ratios were obtained from the effectiveness results in both individual and combined BMP scenarios and BMP implementation costs shown in Table 7. The total cost considers the investment to implement each BMP at the watershed scale.

Among the individual BMP scenarios, CF2–8 was the most cost-effective with CE ratios of 19,175 for S, 9259 for TN and 6258 for TP. Regarding land-use changes, the buffer area of Zone 1 (SBzone1) showed a higher cost-effectiveness than the buffer area of 1500 m (SB1500) with CE values of 1,979,190, 2,282,569 and 2,171,611 for S, TN and TP, respectively. However, RIA was still the best BMP scenario for land-use changes in reducing nutrient inputs with CE ratios of 198,864 for TN and 184,211 for TP.

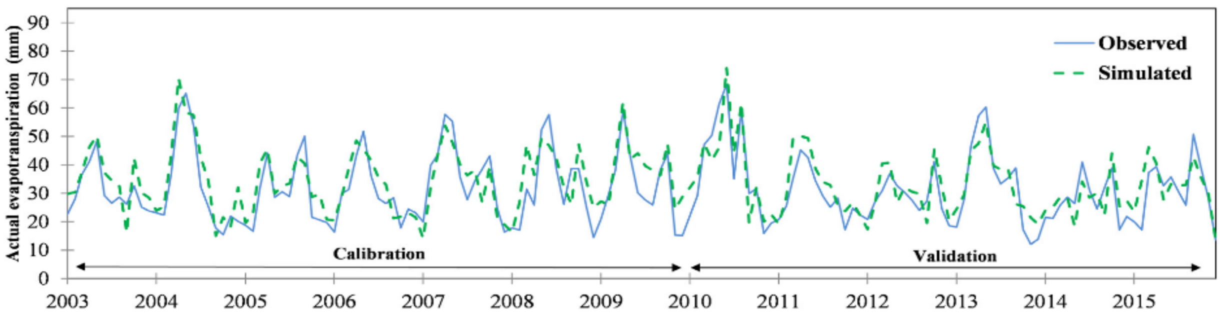

Fig. 3. Graphical comparison of AET for the calibration and validation periods.

Table 6
Summary of the effectiveness of individual BMP scenarios.

Individual BMP	Scenario details	Scenario ID	Effectiveness (%)		
			Sediment (S)	Total nitrogen (TN)	Total phosphorus (TP)
Vegetative filter strips	2 m width in irrigated agriculture	VFS2m	6.5	27.0	36.9
	3 m width in irrigated agriculture	VFS3m	7.2	30.3	41.3
Shoreline buffers	500 m buffer from the shoreline	SB500	–	–	–
	1500 m buffer from the shoreline	SB1500	2.5	2.1	2.4
	Zone 1 buffer from the shoreline	SBzone1	15.8	13.7	14.4
Contour farming	Slopes < 2 %	CF < 2	2.2	6.9	8.2
	Slopes between 2 % and 8 %	CF2–8	14.1	29.2	43.2
	Slopes > 8 %	CF > 8	0.1	6.6	11.3
Illegal agriculture removal		RIA	1.3	17.6	19.0
Crop rotation management		CRM	4.1	14.3	25.2
Waterway vegetation restoration		WVR	20.4	2.0	2.3
Fertiliser management		FM	–	7.7	12.4
Greenhouse rainwater harvesting		GRH	0.3	0.1	0.1

VFS was the second most cost-effective BMP, with CE ratios of 266,912 for S, 64,257 for TN and 47,017 for TP in the VFS2m scenario and approximately 15 % higher values in the VFS3m scenario. The WVR scenario, although being one the most expensive with a total cost of 10M €, had a remarkable performance in the CE ratio of S with a value of 490,196.

Regarding combined BMP scenarios, the initial investment to apply structural or agricultural BMP scenarios was similar with a total cost of >10M €. However, the CE ratio in reducing nutrients was better in the AgriBMPs scenario with values of 169,381 and 145,188 for TN and TP, respectively, than in the StruBMPs scenario with values of 597,708 for TN and 583,432 for TP. Despite the high implementation cost of the AllBMPs scenario (approximately 24M €), its CE ratio was satisfactory from a cost-effective point of view with values of 620,770, 351,143 and 313,401 for S, TN and TP, respectively.

4. Discussion

4.1. Efficiencies of individual and combined BMP scenarios in reducing NPS pollution loads

All the assessed BMP scenarios showed a reduction in S, TP and TN at a watershed scale except for FM, which only affected nutrients, and SB500, which had no effects on sediment and nutrients, likely since the coast of Mar Menor is mainly urban land use. VFS3m was one of the most effective individual BMP scenarios for reducing TN and TP. This could be attributed to its high level of implementation in the watershed (approximately 75 % of the CC). Similar efficiencies in reducing TN and TP were found for the CF2–8 scenario, because 2 %–8 % is the slope range where CF is usually most effective (Wu et al., 2022). Furthermore, WVR was found more effective than all other individual BMP scenarios for reducing S loads. This result is likely due to this kind of structural BMP usually works by promoting sedimentation and avoiding in-stream erosion (Nepal and Parajuli, 2022). The impact of GRH on NPS pollution loads was almost negligible at the watershed scale, possibly due to the greenhouse areas inside the CC only covering approximately 2 % of the watershed. It should be noted that the effectiveness of the BMPs could vary within the CC, as their effects are dependent on the slope, soil and land use types within CC. For example, most of the steeper slopes are located in the north-western part of CC, which means that this part could react somewhat differently to a specific BMPs compared to the flatter areas in the south-eastern part of CC near the coastal lagoon.

An optimal combination of BMPs can potentially result in a greater impact on the control of NPS contamination (López-Ballesteros et al., 2019) and an adequate number of BMPs must therefore be selected to achieve an efficient solution (Uniyal et al., 2020). As expected, combined BMPs also showed a higher effectivity in reducing NPS pollution loads than individual BMPs. However, the effectiveness of the combined BMP scenarios

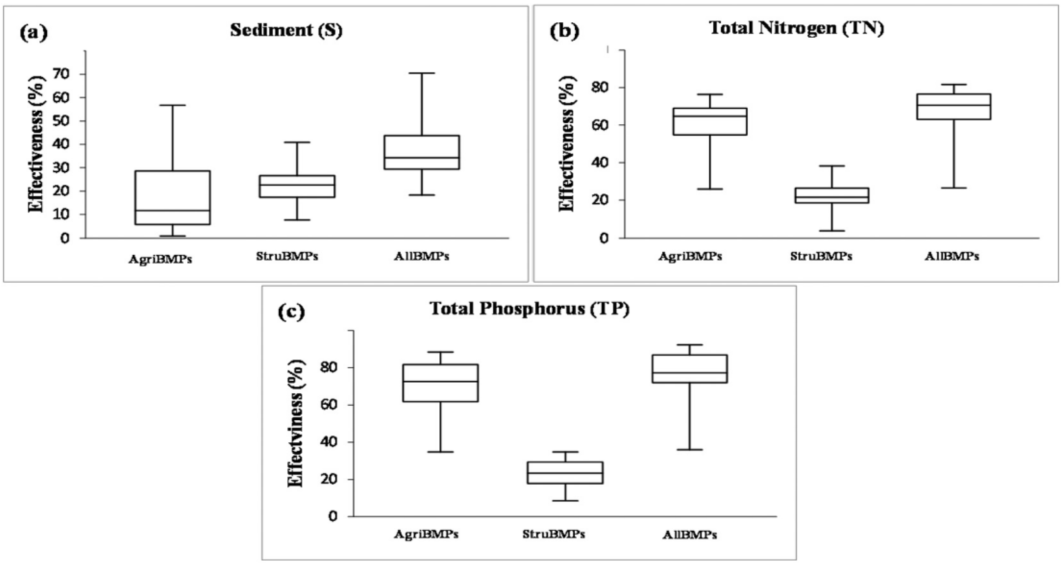

Fig. 4. Boxplot of the effectiveness of the combined BMP scenarios for the 19-year period (2003−2021).

Table 7
Assessment of BMP cost-effectiveness for controlling NPS contamination.

Scenario ID	Area (ha)	Total cost (€)	CE ratio		
			S	TN	TP
VFS2m	93,446	1,734,928	266,912	64,257	47,017
VFS3m	93,446	2,297,188	319,054	75,815	55,622
SB500	386	1,544,000	–	–	–
SB1500	2418.5	9,674,000	3,869,600	4,606,667	4,030,833
SBzone1	7817.8	31,271,200	1,979,190	2,282,569	2,171,611
CF < 2	21,800.7	218,007	99,094	31,595	26,586
CF2–8	27,036.6	270,366	19,175	9259	6258
CF > 8	11,973.6	119,736	1,197,360	18,142	10,596
RIA	8974.3	3,500,000	2,692,308	198,864	184,211
CRM	44,852	2,466,860	601,673	172,508	97,891
WVR	2000	10,000,000	490,196	5000,000	4,347,826
FM	56,226	5,622,600	–	730,208	453,435
GRH	2374	1,543,100	5,143,667	15,431,000	15,431,000
AgriBMPs	93,446	10,094,754	566,388	169,381	145,188
StruBMPs	10,974.3	13,500,000	617,480	597,708	583,432
AllBMPs	95,446	23,594,754	620,770	351,143	313,401

differed greatly. The AgriBMPs scenario was found to be more effective in reducing nutrient inputs than the StruBMPs scenario. This higher effectiveness of the AgriBMPs scenario in reducing TN and TP can be attributed to the fact that it operates at the source of the nutrient production. On the other hand, the StruBMPs scenario had the best performance in reducing sediment inputs into Mar Menor, which is in accordance with the results of the individual BMPs. Finally, the AllBMPs scenario showed the synergistic effects of implementing all the BMPs at the same time. As can be observed in Fig. 4, it had the highest effectiveness in controlling the NPS contamination. The results of this study suggest that implementing a combination of BMPs can be a better solution to reduce the NPS pollution loads inputs into the Mar Menor coastal lagoon at a watershed scale than individual BMPs. Overall, the results of this study can provide information for a better management of nutrients, which is relevant to 16 of the 17 Sustainable Development Goals (SDG) proposed by the United Nations (UN) (Kanter et al., 2016), especially the SDGs that focus on tackling environmental problems (SDG 3, 6, 11–15). An effective nutrient management could also help reach a balance in the trade-offs between environmental sustainability and economic development.

In this study, all the assessed BMPs have been extracted from the government regulation (BOE, 2020) and thereby their implementation is mandatory. However, most of them have not been applied yet due to the lack of consensus between the stakeholders and the absence of coordination in the public administration (Guaita-García et al., 2022). One reason for the lack of consensus could be the assessment of the effectiveness of these BMPs, which has not been evaluated until now. Therefore, the effectiveness of BMPs should be scientifically demonstrated to gain the trust of stakeholders and, in that way, to reach a consensus to prioritize the better measures to protect the Mar Menor coastal lagoon.

4.2. BMP cost-effectiveness

BMPs are critical for reducing NPS contamination, but a balance between their implementation cost and their effectiveness should be achieved. The CF2-8 scenario showed the best CE ratio because the implementation of CF is inexpensive, only involving changes in how the land is managed. With regards to the land use change BMPs, RIA was the best scenario in terms of CE, since its implementation cost was negligible compared to the other land-use management practices. The differences of CE values between the VFS2m and the VFS3m scenario showed that 2 m filter strip width was more profitable than 3 m width. Restoration of vegetation in the main ephemeral streams of the CC was an expensive measure. However, this scenario (WVR) showed an acceptable CE ratio in reducing sediments inputs to Mar Menor. A similar action was proposed by the Spanish government with an investment of 70M € (MITERD, 2021), although that proposal included a larger scope than the one simulated in this study. The assessment of cost-effectiveness carried out in this study is expected to help decision-makers when selecting the most appropriate BMPs, it is important to note that the priority order of these measures could change if subsidies were provided, which would likely lead to better acceptance of BMP implementation by farmers (Ricci et al., 2022).

The differences in the CE ratios between StruBMPs and AgriBMPs can be attributed to the fact that the AgriBMP scenario had a higher effectiveness in reducing TN and TP loads that flow into the coastal lagoon. The AllBMPs scenario was considered economically sustainable and its benefits can have a major impact on improving the environmental situation of the Mar Menor coastal lagoon. Although in general terms, the implementation cost of the assessed BMP scenarios may seem expensive, it is negligible in comparison with the economic value of the Mar Menor under good status, which amounts to 45M € per year according to Perni et al. (2011), is a negligible cost. Therefore, private and public investments are necessary to get the implementation of BMPs at the watershed scale.

4.3. Limitations and uncertainties

Model results are affected by several uncertainties, including errors in input data, simplification of complex processes and non-unique model parameter values (Evenson et al., 2021). In this study, input data uncertainty could be significant due to the lack of reliable gauging observations. Although weather records are very complete, gauging data of streamflow, sediment and nutrient loads are missing. This puts a major constraint on the calibration and validation of the model. This limitation was overcome to some extent by using satellite-based AET data, although the spatial resolution may result in an additional error. In areas characterised by a semi-arid climate and an agricultural nature such as CC, AET is the main driver of the water balance (Odusanya et al., 2019). Remote sensing data allow to deal with the limited availability of hydrological data (Bennour et al., 2022). In this study, it was assumed that water balance components and nutrient and sediment loads were well estimated and a soft-validation was carried out to validate these estimates. However, some uncertainties remain and the results should be cautiously interpreted. All BMP scenarios were designed based on literature, thus their effectiveness were not validated with field observations. However, a study by Arabi et al. (2007) demonstrated that a relative intercomparison between different BMP scenarios is affected by lower uncertainty, providing consistent results when ranking their effectiveness.

5. Conclusions

Despite the scarcity of reliable data and the high complexity of the study area, an improved SWAT model of the CC for agricultural practices was achieved in this study. This more accurate modelling of the Mar Menor watershed provided a useful tool to simulate BMP scenarios and estimate their impact at the watershed scale. Moreover, this model could assist with a better global understanding of the Mar Menor environmental issues. As its main objective, this study simulated several BMP scenarios at the watershed scale to evaluate their impact on controlling NPS pollution in the CC and test possible solutions to improve the Mar Menor ecological status.

Regarding individual BMPs, VFS and CF were the most effective in reducing nutrients exports at the watershed scale. In terms of land-use management practices, RIA showed the highest reduction of nutrients and also the best CE ratio for this type of BMPs. Therefore, prosecuting illegal agriculture can be a relevant action to improve the Mar Menor ecological status. The combination of several BMPs showed a synergistic effect and was the best solution for reducing NPS pollution loads inputs into the Mar Menor. The scenario with the most implemented BMPs of this study (AllBMPs) gave the highest reduction percentages. Thus, the results obtained in this study can have important implications in selecting the most appropriate BMPs to effectively reduce the NPS pollution loads that flow into the Mar Menor coastal lagoon. Mar Menor's law enforcement may positively impact the ecological status of Mar Menor, although the most effective and cost-effective measures should be prioritised over others. Future research could consider identifying critical areas of intervention for a more effective implementation of BMPs and simulating other potential scenarios. The modelling approach, simulated BMP scenarios and outcomes of this study can be applied to similar coastal lagoon areas also affected by highly anthropogenic watersheds, guiding decision-makers in controlling NPS contamination issues.

CRediT authorship contribution statement

Adrián López-Ballesteros: Conceptualization, Investigation, Methodology, Writing – original draft. **Dennis Trolle:** Supervision, Writing – review & editing. **Raghavan Srinivasan:** Supervision, Writing – review & editing. **Javier Senent-Aparicio:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

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.

Acknowledgments

This work has received funding from the European Union Horizon 2020 research and innovation programme within the framework of the project SMARTLAGOON under grant agreement No. 101017861. This research is a result of Adrián López-Ballesteros internship (EST21/00096) funded by Ministry of Universities of Spain. Adrián López-Ballesteros acknowledges funding support by the Spanish FPU scholarship for the training programme for academic staff (FPU17/00923). Authors acknowledge Scribbr editing services for proofreading the text. Authors also acknowledge the valuable comments and suggestions provided by four anonymous reviewers which greatly contributed to improve this manuscript.

References

Alcolea, A., Contreras, S., Hunink, J.E., García-Aróstegui, J.L., Jiménez-Martínez, J., 2019. Hydrogeological modelling for the watershed management of the mar menor coastal lagoon (Spain). Sci. Total Environ. 663, 901–914. https://doi.org/10.1016/j.scitotenv.2019.01.375.

Alcon, F., de Miguel, M.D., Burton, M., 2011. Duration analysis of adoption of drip irrigation technology in southeastern Spain. Technol. Forecast. Soc. 78 (6), 991–1001. https://doi.org/10.1016/j.techfore.2011.02.001.

Álvarez-Rogel, J., Barberá, G.G., Maxwell, B., Guerrero-Brotons, M., Díaz-García, C., Martínez-Sánchez, J.J., Sallent, A., Martínez-Ródenas, J., González-Alcaraz, M.N., Jiménez-Cárceles, F.J., Tercero, C., Gómez, R., 2020. The case of mar menor eutrophication: state of the art and description of tested nature-based solutions. Ecol. Eng. 158, 106086. https://doi.org/10.1016/j.ecoleng.2020.106086.

Amin, M.G.M., Veith, T.L., Shortle, J.S., Karsten, H.D., Kleinman, P.J.A., 2020. Addressing the spatial disconnect between national-scale total maximum daily loads and localized land management decisions. J. Environ. Qual. 49, 613–627. https://doi.org/10.1002/jeq2.20051.

Arabi, M., Govindaraju, R.S., Hantush, M.M., 2007. A probabilistic approach for analysis of uncertainty in the evaluation of watershed management practices. J. Hydrol. 333 (2–4), 459–471. https://doi.org/10.1016/j.jhydrol.2006.09.012.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. J. Am. Water Resour. Assoc. 34, 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x.

Arnold, J.G., Youssef, M.A., Yen, H., White, M.J., Sheshukov, A.Y., Sadeghi, A.M., Moriasi, D.N., Steiner, J.L., Amatya, D.M., Skaggs, R.W., Haney, E.B., Jeong, J., Arabi, M., Gowda, P.H., 2015. Hydrological processes and model representation: impact of soft data on calibration. T. ASABE 58 (6), 1637–1660. https://doi.org/10.13031/trans.58.10726.

Arnold, J.G., Moriasi, D., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Griensven, A.V., Liew, M., Kannan, M., Jha, M.K., 2012. SWAT: model use, calibration, and validation. T. ASABE 55 (4), 1491–1508. https://doi.org/10.13031/2013.42256.

Bennour, A., Jia, L., Menenti, M., Zheng, C., Zeng, Y., Asenso Barnieh, B., Jiang, M., 2022. Calibration and validation of SWAT model by using hydrological remote sensing observables in the Lake Chad Basin. Remote Sens. 14 (6), 1511. https://doi.org/10.3390/rs14061511.

BOE. Boletín ofical del Estado, 2004. ORDEN APA/1657/2004, de 31 de mayo, por la que se establece la norma técnica específica de la identificación de garantía nacional de producción integrada de cítricos. Boletín Oficial del Estado, Spain (In Spanish).

BOE. Boletín ofical del Estado, 2020. Ley 3/2020, de 27 de julio, de recuperación y protección del Mar Menor. Boletín Oficial del Estado, Spain (In Spanish).

BOE. Boletín ofical del Estado, 2021. Resolución de 14 de mayo de 2021, de la Dirección General de Calidad y Evaluación Ambiental, por la que se formula informe de impacto ambiental del proyecto "Restauración hidrológico-forestal para reducir el riesgo de inundación y mejora ambiental de las Ramblas las Matildes, el Beal, la Carrasquilla y el Barranco de Ponce. T.M. Cartagena (Murcia)". Boletín Oficial del Estado, Spain (In Spanish).

BORM. Boletín Oficial de la Región de Murcia, 2012. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de lechuga. Boletín Oficial de la Región de Murcia: Murcia, Spain (In Spanish).

BORM. Boletín Oficial de la Región de Murcia, 2012. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de melón y sandía. Boletín Oficial de la Región de Murcia: Murcia, Spain (In Spanish).

BORM. Boletín Oficial de la Región de Murcia, 2012. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de bróculi. Boletín Oficial de la Región de Murcia: Murcia, Spain (In Spanish).

BORM. Boletín Oficial de la Región de Murcia, 2017. Decreto-Ley n° 1/2017, de 4 de abril, de medidas urgentes para garantizar la sostenibilidad ambiental en el entorno del Mar Menor. Boletín Oficial de la Región de Murcia: Murcia, Spain (In Spanish).

BORM. Boletín Oficial de la Región de Murcia, 2018. Ley 1/2018, de 7 de Febrero, de medidas urgentes para garantizar la sostenibilidad ambiental en el entorno del Mar Menor. Boletín Oficial de la Región de Murcia: Murcia, Spain (In Spanish).

BORM. Boletín Oficial de la Región de Murcia, 2019. Decreto–Ley n° 2/2019, de 26 de diciembre, de protección integral del Mar Menor. Boletín Oficial de la Región de Murcia: Murcia, Spain, 2019 (In Spanish).

Basukala, A.K., Oldenburg, C., Schellberg, J., Sultanov, M., Dubovyk, O., 2017. Towards improved land use mapping of irrigated croplands: performance assessment of different image classification algorithms and approaches. Eur. J. Remote Sens. 50 (1), 187–201. https://doi.org/10.1080/22797254.2017.1308235.

Brown, L.C., Barnwell, T.O., 1987. The enhanced stream and water quality models QUAL2 and QUAL2-UNCAS. Documentation and User Manual. US Environmental Protection Agency, Environmental Research Laboratory, Athens, GE, USA.

Castejón-Porcel, G., Espín-Sánchez, D., Ruiz- Alvarez, V., García-Marín, R., Moreno-Muñoz, D., 2018. Runoff water as a resource in the Campo de Cartagena (Region of Murcia): current possibilities for use and benefits. Water 10 (4), 1–25. https://doi.org/10.3390/w10040456.

Čerkasova, N., Umgiesser, G., Erturk, A., 2021. Modelling framework for flow, sediments and nutrient loads in a large transboundary river watershed: a climate change impact assessment of the Nemunas River watershed. J. Hydrol. 598, 126422. https://doi.org/10.1016/j.jhydrol.2021.126422.

Dile, Y.T., Daggupati, P., George, C., Srinivasan, R., Arnold, J., 2016. Introducing a new open source GIS user interface for the SWAT model. Environ. Model. Softw. 85, 129–138. https://doi.org/10.1016/j.envsoft.2016.08.004.

EC. European Commission, 2020. Farm to Fork strategy for a fair, healthy and environmentally-friendly food system. European Commission. https://ec.europa.eu/food/farm2fork_en (accessed 07 July 2022).

EC. European Commission, 2019. The European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed 05 September 2022).

European Union, E.U., 1992. Council directive 92/43/EEC of 21 may 1992 on the conservation of natural habitats and of wild fauna and flora. Off. J. Eur. Union 206, 7–50 (accessed 07 July 2022) http://data.europa.eu/eli/dir/1992/43/oj.

Evenson, G.R., Kalcic, M., Wang, Y.C., Robertson, D., Scavia, D., Martin, J., Aloysius, N., Apostel, A., Boles, C., Brooker, M., Confesor, R., Dagnew, A.T., Guo, T., Kast, J., Kujawa, H., Muenich, R.L., Murumkar, A., Redder, T., 2021. Uncertainty in critical source area predictions from watershed-scale hydrologic models. J. Environ. Manag. 279, 111506. https://doi.org/10.1016/j.jenvman.2020.111506.

FAO–ISRIC. Food and Agriculture Organization of the United Nations–International Soil Reference and Information Centre, 1990. Guidelines for Profile Description. 3rd ed. FAO–ISRIC, Roma, Italy.

Flower, R.J., Thompson, J.R., 2009. An overview of integrated hydro-ecological studies in the MELMARINA project: monitoring and modelling coastal lagoons—making management tools for aquatic resources in North Africa. Hydrobiologia 622, 3–14. https://doi.org/10.1007/s10750-008-9674-8.

Garcia-Ayllon, S., Radke, J., 2021. Geostatistical analysis of the spatial correlation between territorial anthropization and flooding vulnerability: application to the DANA phenomenon in a Mediterranean watershed. Appl. Sci. 11 (2), 809. https://doi.org/10.3390/app11020809.

García-Pintado, J., Martínez-Mena, M., Barberá, G.G., Albaladejo, J., Castillo, V.M., 2007. Anthropogenic nutrient sources and loads from a Mediterranean catchment into a coastal lagoon: Mar Menor, Spain. Sci. Total Environ. 373 (1), 220–239. https://doi.org/10.1016/j.scitotenv.2006.10.046.

Gassman, P.W., Sadeghi, A.M., Srinivasan, R., 2014. Applications of the SWAT model special section: overview and insights. J. Environ. Qual. 43 (1), 1–8. https://doi.org/10.2134/jeq2013.11.0466.

Gassman, P.W., Wang, Y., 2015. IJABE SWAT special issue: innovative modeling solutions for water resource problems. Int. J. Agric. Biol. Eng. 8, 1–8. https://doi.org/10.3965/j.ijabe.20150803.1763.

Guaita-García, N., Martínez-Fernández, J., Barrera-Causil, C.J., Fitz, H.C., 2022. Stakeholder analysis and prioritization of management measures for a sustainable development in the social-ecological system of the mar menor (SE, Spain). Environ. Dev. 42, 100701. https://doi.org/10.1016/j.envdev.2022.100701.

Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: implications for improving hydrological modelling. J. Hydrol. 377 (1–2), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003.

MIMAM. Ministerio de Medio Ambiente, 2012. Inventario Nacional de Erosión de Suelos 2002–2012. Dirección General de Conservación de la Naturaleza. Ministerio de Medio Ambiente: Murcia, Spain. (In Spanish). https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/libro30_ines_murcia_tcm30-153794.pdf (accessed 07 July 2022).

Jimeno-Sáez, P., Senent-Aparicio, J., Cecilia, J.M., Pérez-Sánchez, J., 2020. Using machine-learning algorithms for eutrophication modeling: case study of mar menor lagoon (Spain). Int. J. Environ. Res. Public Health 17 (4), 1189. https://doi.org/10.3390/ijerph17041189.

Kanter, D.R., Zhang, X., Howard, C.M., 2016. Nitrogen and the sustainable development goals. International Nitrogen Initiative Conference. Melbourne, Australia. http://agronomyaustraliaproceedings.org/images/sampledata/ini2016/pdf-papers/INI2016_Howard_Clare.pdf (accessed 05 September 2022).

Kouchi, D.H., Esmaili, K., Faridhosseini, A., Sanaeinejad, S.H., Khalili, D., Abbaspour, K.C., 2017. Sensitivity of calibrated parameters and water resource estimates on different objective functions and optimization algorithms. Water 9 (6), 384. https://doi.org/10.3390/w9060384.

Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A., Moatar, F., Pannard, A., Souchu, P., Lefebvre, A., Pinay, G., 2019. Eutrophication: a new wine in an old bottle? Sci. Total Environ. 651 (1), 1–11. https://doi.org/10.1016/j.scitotenv.2018.09.139.

Lee, S., McCarty, G.W., Moglen, G.E., Li, X., Wallace, C.W., 2020. Assessing the effectiveness of riparian buffers for reducing organic nitrogen loads in the coastal plain of the Chesapeake Bay watershed using a watershed model. J. Hydrol. 585, 124779. https://doi.org/10.1016/j.jhydrol.2020.124779.

Liu, R., Zhang, P., Wang, X., Chen, Y., Shen, Z., 2013. Assessment of effects of best management practices on agricultural non-point source pollution in Xiangxi River watershed. Agric. Water Manag. 117, 9–18. https://doi.org/10.1016/j.agwat.2012.10.018.

Liu, Y., Wang, R., Guo, T., Engel, B.A., Flanagan, D.C., Lee, J.G., Li, S., Pijanowski, B.C., Collingsworth, P.D., Wallace, C.W., 2019. Evaluating efficiencies and cost-effectiveness of best management practices in improving agricultural water quality using integrated SWAT and cost evaluation tool. J. Hydrol. 577, 123965. https://doi.org/10.1016/j.jhydrol.2019.123965.

López-Ballesteros, A., Senent-Aparicio, J., Srinivasan, R., Pérez-Sánchez, J., 2019. Assessing the impact of best management practices in a highly anthropogenic and ungauged watershed using the SWAT model: a case study in the El beal watershed (Southeast Spain). Agronomy 9 (10), 576. https://doi.org/10.3390/agronomy9100576.

MITECO. Ministerio para la Transición Ecológica, 2019. Análisis de soluciones para el objetivo del vertido cero al Mar Menor proveniente del Campo de Cartagena: Estudio de Impacto Ambiental. (In Spanish). https://www.miteco.gob.es/es/agua/temas/concesiones-y-autorizaciones/eia_tomoi_tcm30-489386.pdf (accessed 07 July 2022).

MITERD. Ministerio para la Transición Ecológica y el Reto Demográfico, 2021. Marco de actuaciones prioritarias para recuperar el Mar Menor. Ministerio para la Transición Ecológica y el Reto Demográfico: Madrid, Spain. (In Spanish). https://www.miteco.gob.es/es/ministerio/servicios/participacion-publica/marcoactuacionesmarmenor_tcm30-532519.pdf (accessed 07 July 2022).

Mar Menor Scientific Advisory Group, 2017. Informe integral sobre el estado ecológico del Mar Menor. Comité de Asesoramiento Científico del Mar Menor: Murcia, Spain. (In Spanish). https://canalmarmenor.carm.es/wp-content/uploads/2020/07/Informe-Integral-sobre-el-estado-ecol%C3%B3gico-del-Mar-Menor.pdf (accessed 07 July 2022).

Martens, B., Miralles, D.G., Lievens, H., Van Der Schalie, R., De Jeu, R.A.M., Fernández-Prieto, D., Beck, H.E., Dorigo, W.A., Verhoest, N.E.C., 2017. GLEAM v3: satellite-based land evaporation and root-zone soil moisture. Geosci. Model Dev. 10, 1903–1925. https://doi.org/10.5194/gmd-10-1903-2017.

Martin, J.F., Kalcic, M.M., Aloysius, N., Apostel, A.M., Brooker, M.R., Evenson, G., Kast, J.B., Kujawa, H., Murumkar, A., Becker, R., Boles, C., Confesor, R., et al., 2021. Evaluating management options to reduce Lake Erie algal blooms using an ensemble of watershed models. J. Environ. Manag. 280, 111710. https://doi.org/10.1016/j.jenvman.2020.111710.

Miralles, D.G., Holmes, T.R.H., De Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J., 2011. Global land-surface evaporation estimated from satellite-based observations. Hydrol. Earth Syst. Sci. 15, 453–469. https://doi.org/10.5194/hess-15-453-2011.

Molina-Navarro, E., Nielsen, A., Trolle, D., 2018. A QGIS plugin to tailor SWAT watershed delineations to lake and reservoir waterbodies. Environ. Model. Softw. 108, 67–71. https://doi.org/10.1016/j.envsoft.2018.07.003.

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. T. ASABE 58 (6), 1763–1785. https://doi.org/10.13031/trans.58.10715.

Mtibaa, S., Hotta, N., Irie, M., 2018. Analysis of the efficacy and cost-effectiveness of best management practices for controlling sediment yield: A case study of the Joumine watershed, Tunisia. Sci. Total Environ. 616-617, 1–16. https://doi.org/10.1016/j.scitotenv.2017.10.290.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I – a discussion of principles. J. Hydrol. 10 (3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool: Theoretical Documentation, Version 2009. Texas Water Resources Institute, College Station, TX, USA.

Nepal, D., Parajuli, P.B., 2022. Assessment of best management practices on hydrology and sediment yield at watershed scale in Mississippi using SWAT. Agriculture 12 (4), 518. https://doi.org/10.3390/agriculture12040518.

Nielsen, A., Bolding, K., Hu, F.R.S., Trolle, D., 2017. An open source QGIS-based workflow for model application and experimentation with aquatic ecosystems. Environ. Model. Softw. 95, 358–364. https://doi.org/10.1016/j.envsoft.2017.06.032.

Nielsen, A., Hu, F.R.S., Schnelder-Meyer, N.A., Bolding, K., Andersen, T.K., Trolle, D., 2020. Introducing QWET – a QGIS-plugin for application, evaluation and experimentation with the WET model: environmental modelling and software. Environ. Model. Softw. 135, 104886. https://doi.org/10.1016/j.envsoft.2020.104886.

Odusanya, A.E., Mehdi, B., Schürz, C., Oke, A.O., Awokola, O.S., Awomeso, J.A., Adejuwon, J.O., Schulz, K., 2019. Multi-site calibration and validation of SWAT with satellite-based evapotranspiration in a data-sparse catchment in southwestern Nigeria. Hydrol. Earth Syst. Sci. 23, 1113–1144. https://doi.org/10.5194/hess-23-1113-2019.

Odusanya, A.E., Schulz, K., Biao, I., Degan, B.A.S., Mehdi-Schulz, B., 2021. Evaluating the performance of streamflow simulated by an eco-hydrological model calibrated and validated with global land surface actual evapotranspiration from remote sensing at a catchment scale in West Africa. Reg. Stud. 37, 100893. https://doi.org/10.1016/j.ejrh.2021.100893.

Perni, A., Martínez-Carrasco, F., Martínez-Paz, J.M., 2011. Economic valuation of coastal lagoon environmental restoration: mar menor (SE Spain). Cienc. Mar. 37, 175–190. https://doi.org/10.7773/cm.v37i2.1889.

Puertes, C., Bautista, I., Lidón, A., Francés, F., 2021. Best management practices scenario analysis to reduce agricultural nitrogen loads and sediment yield to the semiarid mar menor coastal lagoon (Spain). Agric. Syst. 188, 103029. https://doi.org/10.1016/j.agsy.2020.103029.

Pérez-Ruzafa, A., Marcos, C., Gilabert, J., 2005. The ecology of the Mar Menor coastal lagoon: a fast changing ecosystem under human pressure. Coastal Lagoons. Ecosystem Processes and Modeling for Sustainable Use and Development. CRC Press, Boca Raton, FL, USA, pp. 392–422.

Ricci, G.F., D'Ambrosio, E., De Girolamo, A.M., Gentile, F., 2022. Efficiency and feasibility of best management practices to reduce nutrient loads in an agricultural river basin. Agric. Water Manag. 259, 107241. https://doi.org/10.1016/j.agwat.2021.107241.

Ricci, G.F., Jeong, J., De Girolamo, A.M., Gentile, F., 2020. Effectiveness and feasibility of different management practices to reduce soil erosion in an agricultural watershed. Land Use Policy 90, 104306. https://doi.org/10.1016/j.landusepol.2019.104306.

Risal, A., Parajuli, P.B., 2022. Evaluation of the impact of best management practices on streamflow, sediment and nutrient yield at field and watershed scales. Water Resour. Manag. 36, 1093–1105. https://doi.org/10.1007/s11269-022-03075-7.

Rodríguez-Gallego, L., Achkar, M., Defeo, O., Vidal, L., Meerhoff, E., Conde, D., 2017. Effects of land use changes on eutrophication indicators in five coastal lagoons of the southwestern Atlantic Ocean. Estuar. Coast. Shelf Sci. 188, 116–126. https://doi.org/10.1016/j.ecss.2017.02.010.

Romero-Díaz, A., Ruiz-Sinoga, J.D., Belmonte-Serrato, F., 2011. Tasas de erosión hídrica en la Región de Murcia. Bol. Asoc. Geógrafos Españoles 56, 129–153.

Samimi, M., Mirchi, A., Moriasi, D., Ahn, S., Alian, S., Taghvaeian, S., Sheng, Z., 2020. Modeling arid/semi-arid irrigated agricultural watersheds with SWAT: applications, challenges, and solution strategies. J. Hydrol. 590, 125418. https://doi.org/10.1016/j.jhydrol.2020.125418.

Sanches-Fernandes, L.F., Terêncio, D.P.S., Pacheco, F.A.L., 2015. Rainwater harvesting systems for low demanding applications. Sci. Total Environ. 529, 91–100. https://doi.org/10.1016/j.scitotenv.2015.05.061.

Senent-Aparicio, J., Pérez-Sánchez, J., Bielsa-Artero, A.M., 2016. Assessment of sustainability in semiarid mediterranean basins: case study of the Segura Basin, Spain. Water Technol. Sci. 7, 67–84.

Senent-Aparicio, J., Pérez-Sánchez, J., García-Aróstegui, J.L., Bielsa-Artero, A., Domingo-Pinillos, J.C., 2015. Evaluating groundwater management sustainability under limited data availability in semiarid zones. Water 7 (8), 4305–4322. https://doi.org/10.3390/w7084305.

Senent-Aparicio, J., López-Ballesteros, A., Cabezas, F., Pérez-Sánchez, J., Molina-Navarro, E., 2021b. A modelling approach to forecast the effect of climate change on the tagus-Segura interbasin water transfer. Water Resour. Manag. 35, 3791–3808. https://doi.org/10.1007/s11269-021-02919-y.

Senent-Aparicio, J., López-Ballesteros, A., Nielsen, A., Trolle, D., 2021a. A holistic approach for determining the hydrology of the mar menor coastal lagoon by combining hydrological & hydrodynamic models. J. Hydrol. 603, 127150. https://doi.org/10.1016/j.jhydrol.2021.127150.

Shi, W., Huang, M., 2021. Predictions of soil and nutrient losses using a modified SWAT model in a large hilly-gully watershed of the Chinese Loess Plateau. Int. Soil Water Conserv. Res. 9 (2), 291–304. https://doi.org/10.1016/j.iswcr.2020.12.002.

SIGPAC. Sistema de Información Geográfica de Parcelas Agrícolas, 2016. Ministerio de Agricultura, Pesca y Alimentación. (In Spanish) https://www.mapa.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/. (Accessed 7 July 2022).

Soria, J., Pérez, R., Sòria-Pepinyà, X., 2022. Mediterranean coastal lagoons review: sites to visit before disappearance. J. Mar. Sci. Eng. 10 (3), 347. https://doi.org/10.3390/jmse10030347.

USDA-SCS. United States Department of Agriculture–Soil Conservation Service, 1972. National Engineering Handbook, Section 4, Hydrology. USDA Soil Conservation Service, Washington, DC. http://irrigationtoolbox.com/NEH/Part%20630%20Hydrology/neh630-ch15.pdf (accessed 07 July 2022).

Uniyal, B., Jha, M.K., Verma, A.K., Anebagilu, P.K., 2020. Identification of critical areas and evaluation of best management practices using SWAT for sustainable watershed management. Sci. Total Environ. 744, 140737. https://doi.org/10.1016/j.scitotenv.2020.140737.

Upadhyay, P., Linhoss, A., Kelble, C., Ashby, S., Murphy, N., Parajuli, P.B., 2022. Applications of the SWAT model for coastal watersheds: review and recommendations. T. ASABE 65 (2), 453–469. https://doi.org/10.13031/ja.14848.

Velasco, J., Lloret, L., Millán, A., Barahona, J., Abellán, P., Sánchez-Fernández, D., 2006. Nutrient and particulate inputs into the mar menor lagoon (SE Spain) from an intensive agricultural watershed. Water Air Soil Poll. 176, 37–56. https://doi.org/10.1007/s11270-006-2859-8.

Viaroli, P., Azzoni, R., Bartoli, M., Giordani, G., Naldi, M., Nizzoli, D., 2010. Primary productivity, biogeochemical buffers and factors controlling trophic status and ecosystem processes in Mediterranean coastal lagoons: a synthesis. Adv. Oceanogr. Limnol. 1 (2), 271–293. https://doi.org/10.1080/19475721.2010.528937.

Waidler, D., White, M., Steglich, E., Wang, S., Williams, J., Jones, C.A., Srinivasan, R., 2009. Conservation Practice Modeling Guide for SWAT and APEX. Texas Water Resources Institute, College Station, TX, USA (accessed 07 July 2022) https://hdl.handle.net/1969.1/94928.

Wang, X., Hao, F.H., Zhang, X., 2013. Optimization of best management practices for non-point source pollution in Danjiangkou reservoir basin. China Environ. Sci. 33 (7), 1335–1343.

Williams, J.R., 1975. Sediment routing for agricultural watersheds. J. Am. Water Resour. Assoc. 11 (5), 965–974. https://doi.org/10.1111/j.1752-1688.1975.tb01817.x.

Wu, L., Liu, X., Chen, J., Li, J., Yu, Y., Ma, X., 2022. Efficiency assessment of best management practices in sediment reduction by investigating cost-effective tradeoffs. Agr. Water Manage. 265, 107546. https://doi.org/10.1016/j.agwat.2022.107546.

4.4 SÍNTESIS DE RESULTADOS Y DISCUSIÓN

4.4.1 Bondad del ajuste de la modelización

La bondad del ajuste de la modelización fue satisfactoria tanto grafica como estadísticamente para todos los modelos desarrollados en los artículos de la tesis de acuerdo a los criterios propuesto por Moriasi et al. (2015). La Tabla 6 muestra el valor final de los parámetros del modelo SWAT obtenidos durante la calibración automática con SWATCUP (López-Ballesteros et al., 2019) y la calibración manual (Senent-Aparicio et al. 2021; López-Ballesteros et al., 2023).

Tabla 6. Valor final de los parámetros calibrados del modelo SWAT.

Publicación	Parámetro	Valor
López-Ballesteros et al. (2019)	CN2.mgt	-7.24%
	ESCO.hru	0.86
	EPCO.hru	0.14
	SOL_AWC.sol	+14.84
	SOL_BD.sol	-8.2%
	SOL_K.sol	-5.32%
	CANMX.hru	12.1
	ALPHA_BF.rte	0.16
Senent-Aparicio et al. (2021)		
López-Ballesteros et al. (2023)	CN2.mgt	-5%
	ESCO.hru	0.75
	EPCO.hru	0.3
	SOL_AWC.sol	-10%
	RCHRG_DP.gw	0.4

Durante la calibración automática se realizó un análisis de sensibilidad con SWATCUP que identificó a los parámetros ESCO, CN2 y EPCO como los de mayor influencia en la calibración con datos de evapotranspiración real. Estos parámetros del modelo SWAT se encuentran estrechamente relacionados con la evaporación del suelo y la cantidad de agua en el mismo. Con respecto a la bondad del ajuste gráfica, las Figuras 7, 8 y 9 muestran los resultados del proceso de calibración y validación llevado a cabo en cada uno de los modelos desarrollados en esta tesis tanto los hidrológicos como la parte hidrodinámica.

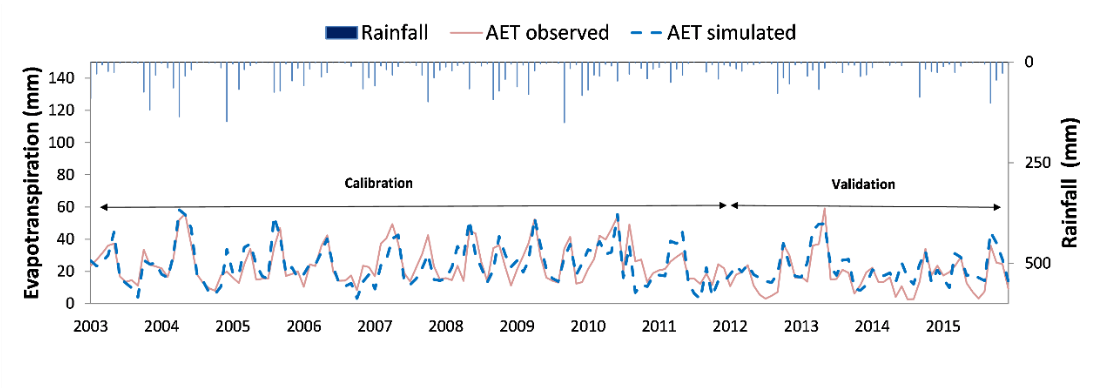

Figura 7. Gráfico de comparación de la evapotranspiración observada y simulada con SWAT para la cuenca de la rambla del Beal. Fuente: López-Ballesteros et al. (2019).

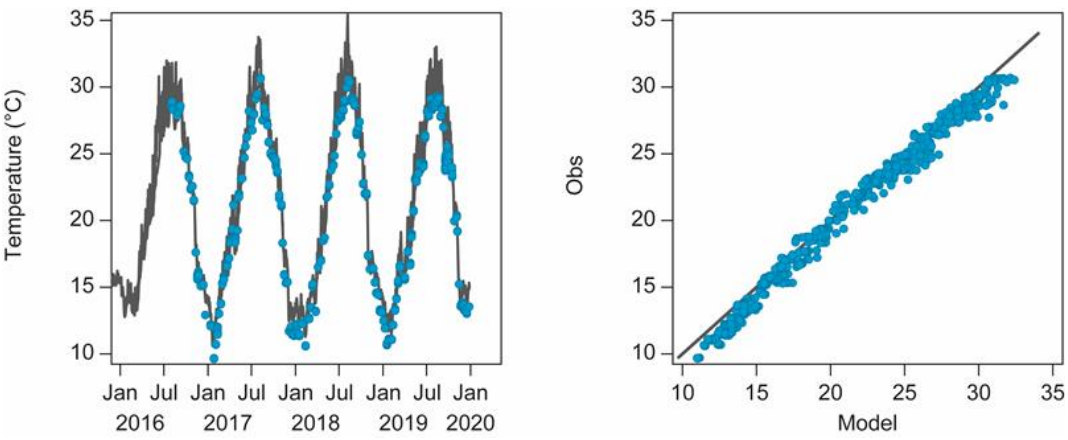

Figura 8. Gráfico de comparación de la termodinámica observada y simulada con WET para la laguna costera del Mar Menor. Fuente: Senent-Aparicio et al. (2021).

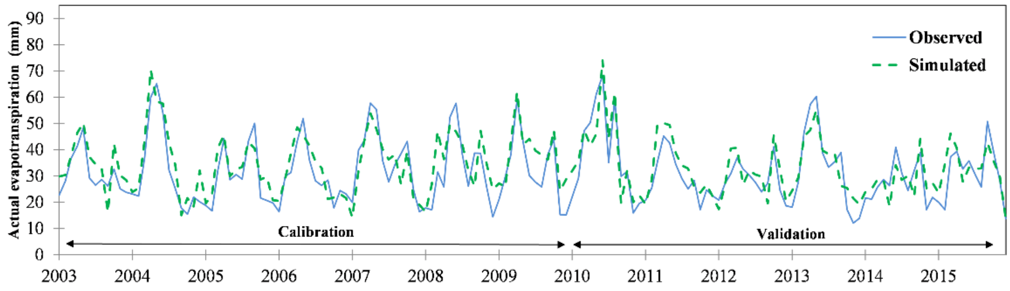

Figura 9. Gráfico de comparación de la evapotranspiración observada y simulada con SWAT para la cuenca hidrográfica del Mar Menor. Fuente: López-Ballesteros et al. (2023).

Con respecto a la bondad del ajuste estadística, la Tablas 7 y 8 muestran información sobre los valores de los estadísticos evaluados en cada una de las publicaciones de la tesis. En todos los modelos con SWAT se utilizó un periodo inicial de calentamiento de tres años (2000 – 2003).

Tabla 7. Valor de los estadísticos durante la calibración y validación con SWAT.

Publicación	Proceso	Período	Estadísticos			
			KGE	NSE	R2	PBIAS
López-Ballesteros et al. (2019)	Calibración	2003 - 2011	0.78	0.58	0.81	3.9%
	Validación	2012 - 2015	0.67	0.53	0.83	-25.3%
Senent-Aparicio et al. (2021)	Calibración	2003 - 2009	-	0.68	0.77	-11.43%
	Validación	2010 - 2015	-	0.75	0.78	-7.35%
López-Ballesteros et al. (2023)	Calibración	2003 - 2009	0.81	0.67	0.73	-9.11%
	Validación	2010 - 2015	0.82	0.71	0.74	-5.22%

Tabla 8. Valor de los estadísticos durante la validación con WET.

Publicación	Proceso	Período	Estadísticos			
			KGE	NSE	R2	PBIAS
Senent-Aparicio et al. (2021)	Validación	2016 - 2019	-	0.98	-	2.7%

Como puede observarse en la Tabla 8, el modelo SWAT del Campo de Cartagena desarrollado en Senent-Aparicio et al. (2021) muestra unos estadísticos ligeramente diferentes con respecto al mismo modelo de López-Ballesteros et al. (2023). Este hecho se debe a que en López-Ballesteros et al. (2023) se añadió información más detallada sobre las prácticas agrícolas llevas a cabo en la zona de estudio. Esta información agrícola fue extraída de la documentación oficial (BORM, 2012a, 2012b, 2012c; BOE, 2004) y su efecto se vio reflejado en una mejora del PBIAS. Los mejores valores estadísticos de KGE con respecto a NSE se deben a que este último pone un mayor énfasis en la captura de los valores punta (Gupta et al., 2009).

4.4.2 Ciclo hidrológico y balance hídrico de las zonas de estudio

Conocer la magnitud de las componentes del ciclo hidrológico o del balance de agua es importante para poder conocer la influencia de cada una de ellas sobre la zona de estudio y poder llevar a cabo una mejor gestión de los recursos hídricos. La Figura 10 muestra el ciclo hidrológico extraído de la modelización con SWAT correspondiente a la rambla del Beal (López-Ballesteros et al., 2019) para el período 2003-2015.

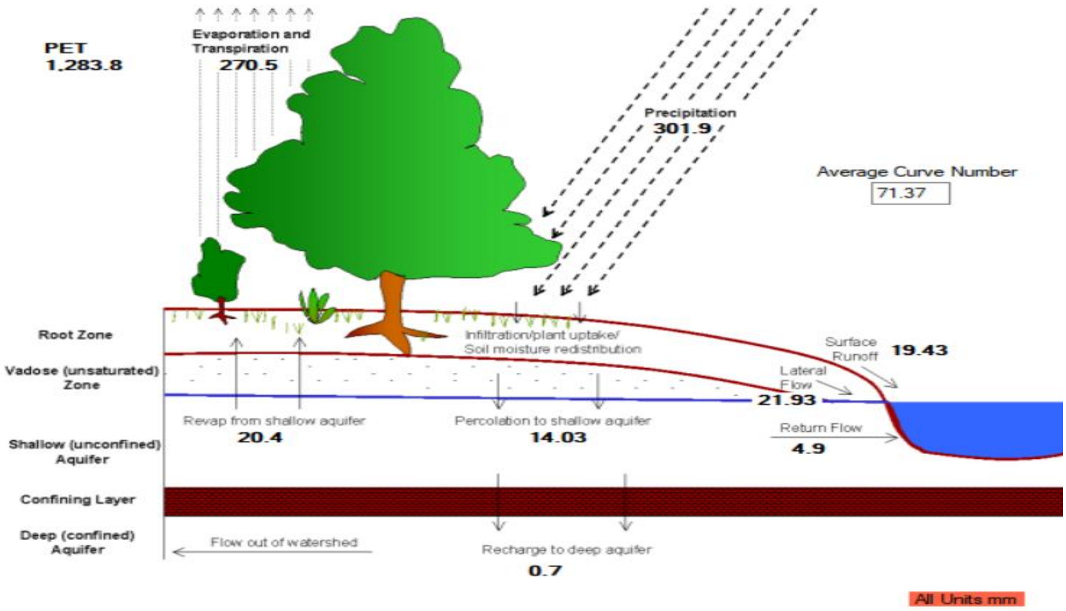

Figura 10. Ciclo hidrológico de la cuenca de la rambla del Beal (2003 – 2015).

El ciclo hidrológico de toda la cuenca vertiente al Mar Menor fue calculado tanto para el modelo de Senent-Aparicio et al. (2021) (Figura 11) como para su versión mejorada en López-Ballesteros et al. (2023) (Figura 12).

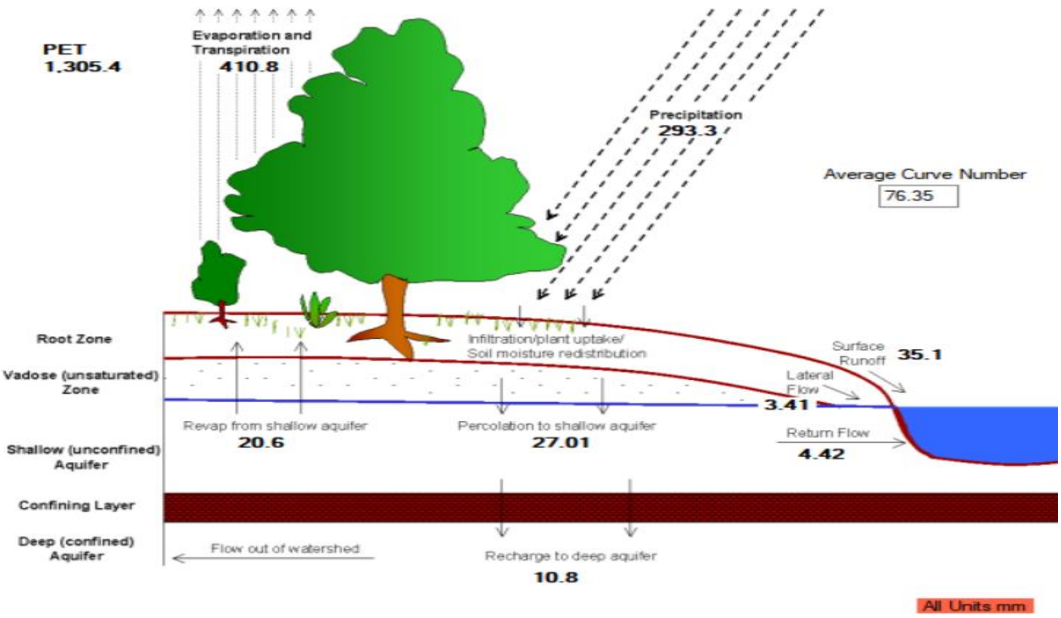

Figura 11. Ciclo hidrológico de la cuenca del Campo de Cartagena (2003 – 2019).

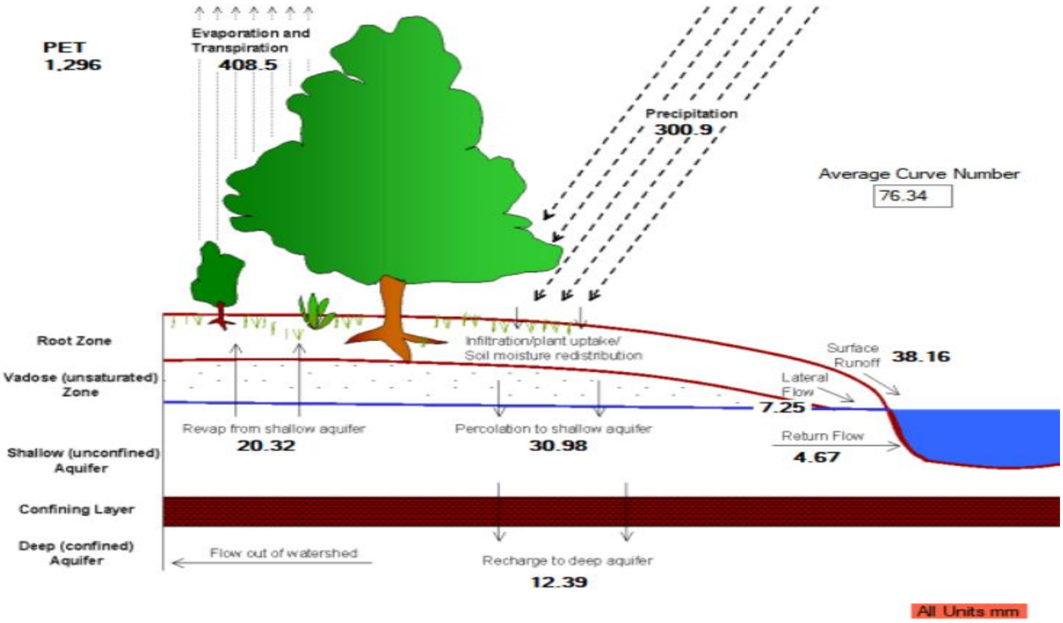

Figura 12. Ciclo hidrológico de la cuenca del Campo de Cartagena (2003 – 2021).

En las Figuras 10, 11 y 12 se puede observar uno de los aspectos más característicos del ciclo hidrológico en zona semiáridas, el cual consiste en la evaporación de casi la totalidad de la precipitación. Además, debido al marcado carácter agrícola del Campo de Cartagena, también se observa una evapotranspiración real mayor que la precipitación. Este hecho muestra claramente la gran influencia del regadío en la zona de estudio. Las ligeras diferencias observadas entre las Figuras 11 y 12 se deben principalmente a la ampliación del período de estudio y a la mejora de la parte agrícola del modelo del Campo de Cartagena en López-Ballesteros et al. (2023).

La estimación del balance hídrico de la laguna costera del Mar Menor fue uno de los objetivos principales en Senent-Aparicio et al. (2021). La Figura 13 muestra los valores obtenidos de la componentes del balance hídrico del Mar Menor para el período 2003 - 2019.

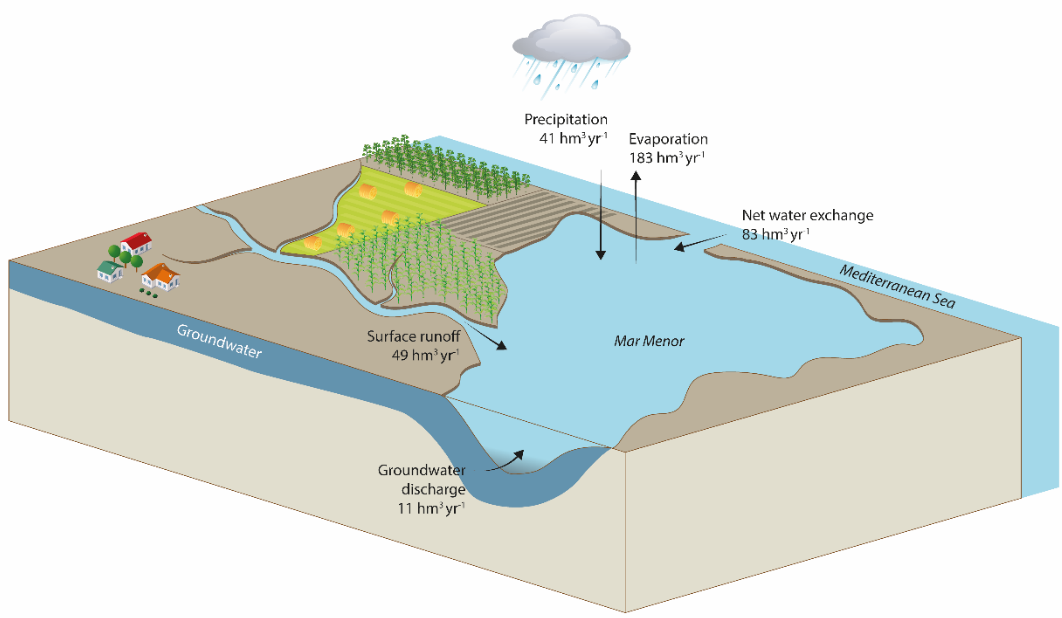

Figura 13. Balance hídrico de la laguna costera del Mar Menor (2003 – 2019). Fuente: Senent-Aparicio et al. (2021).

Durante el cálculo del balance hídrico (Figura 13) se observó una entrada generalizada de agua desde el Mar Mediterráneo al Mar Menor. Sin embargo, esta entrada positiva se vio modifica los años en los que se produjeron los grandes eventos de precipitación extrema o DANA (2016 y 2019). Conocer con mayor detalle la dinámica hídrica tanto de la cuenca hidrográfica como de las masas de agua permite una toma de decisiones más efectiva ante la búsqueda de posibles soluciones para los problemas ambientales que enfrenta las zonas de agricultura intensiva.

4.4.3 Efectividad de los escenarios de BMP

El objetivo principal de los estudios López-Ballesteros et al. (2019) y López-Ballesteros et al. (2023) consistió en la evaluación de la efectividad de distintas BMPs en la reducción de sedimentos y nutrientes entrantes a la laguna costera del

Mar Menor. Las Tablas 9 y 10 muestran la efectividad de los escenarios de BMPs simulados para S, TN y TP.

Tabla 9. Efectividad de los escenarios de BMPs simulados en López-Ballesteros et al. (2019).

BMP	**Escenario**	**Efectividad (%)**		
		Sedimentos (S)	**Nitrógeno total (TN)**	**Fósforo total (TP)**
Implantación de barreras vegetales	2 m de ancho	4	7	5
	3 m de ancho	4	8	7
	5 m de ancho	5	10	7
Cambios de usos del suelo	Reforestación	27	16	20
Plantación siguiendo las curvas de nivel		6	10	8
Reducción de la aplicación de fertilizantes		-	2	-
Construcción y restauración de diques		90	15	22
	BMPs agrícolas	7	14	10
	BMPs estructurales	93	18	23
	Todas las BMPs	93	32	33

Tabla 10. Efectividad de los escenarios de BMPs simulados en López-Ballesteros et al. (2023).

BMP	**Escenario**	**Efectividad (%)**		
		Sedimentos (S)	**Nitrógeno total (TN)**	**Fósforo total (TP)**
Implantación de barreras vegetales	2 m de ancho	6.5	27.0	36.9

	3 m de ancho	7.2	30.3	41.3
Cambios de usos del suelo	Buffer 500 m	-	-	-
	Buffer 1500 m	2.5	2.1	2.4
	Buffer Zona 1	15.8	13.7	14.4
	Agricultura ilegal	1.3	17.6	19.0
Plantación siguiendo las curvas de nivel	Pendientes < 2%	2.2	6.9	8.2
	Pendientes entre 2% y 8%	14.1	29.2	43.2
	Pendientes > 8%	0.1	6.6	11.3
Cambios en la rotación anual de cultivos		4.1	14.3	25.2
Restauración de la vegetación de los cauces		20.4	2.0	2.3
Reducción de la aplicación de fertilizantes		-	7.7	12.4
Recolección de aguas de lluvia en los invernaderos		0.3	0.1	0.1
	BMPs agrícolas	17.8	59.6	69.5
	BMPs estructurales	21.9	22.6	23.1
	Todas las BMPs	38	67.2	75.3

La mayoría de las BMPs simuladas de forma individual mostraron ser efectivas para la reducción de sedimentos y nutrientes en mayor o menor grado. Sin embargo, esta efectividad se vio aumentada en todos los escenarios de combinación de BMPs. Las diferencias entre los valores de BMPs de las Tablas 9 y 10, se deben principalmente al ámbito de aplicación de las mismas. Mientras que la cuenca del Campo de Cartagena es mayoritariamente agrícola (alrededor del 75%), la pequeña cuenca de la rambla del Beal presenta un uso principal del suelo de extracciones mineras abandonadas. Por tanto, de forma general se puede observar que mientras en cuencas de gran porcentaje de uso de suelo agrícola las BMPs aplicadas sobres los cultivos poseen una gran influencia, en cuencas con un menor porcentaje agrícola la aplicabilidad de las BMPs sobre otras zonas resulta más efectiva.

4.4.4 Análisis de coste-eficacia

Como se ha demostrado a lo largo de la presente tesis, la implantación de BMPs es necesaria para poder reducir la cantidad de sedimentos y nutrientes entrantes al Mar Menor. Sin embargo, también es necesario encontrar un equilibrio entre su coste de implementación y su efectividad. Para ello las Tablas 11 y 12 muestran la evaluación de coste-eficacia realizada tanto en López-Ballesteros et al. (2019) como en López-Ballesteros et al. (2023). En este análisis de coste-eficacia se estimó el coste total de implantación de los escenarios de BMPs utilizando para ello valores extraídos de la bibliografía consultada.

Tabla 11. Coste-eficacia de los escenarios de BMPs evaluados en López-Ballesteros et al. (2019).

BMP	**Escenario**	**Coste total (€)**	**CE ratio**		
			Sedimentos (S)	**Nitrógeno total (TN)**	**Fósforo total (TP)**
Implantación de barreras vegetales	3 m de ancho	3,240	48	21	91
Cambios de usos del suelo	Reforestación	10,212,000	24,898	33,594	85,331
Plantación siguiendo las curvas de nivel		1,080	11	6	24

Reducción de la aplicación de fertilizantes		10,800	-	267	-
Construcción y restauración de diques		800,000	575	2,790	5,885
	BMPs agrícolas	15,120	132	57	257
	BMPs estructurales	11,012,000	7,693	32,124	79,397
	Todas las BMPs	11,027,120	7,640	18,109	55,922

Tabla 12. Coste-eficacia de los escenarios de BMPs evaluados en López-Ballesteros et al. (2023).

BMP	**Escenario**	**Coste total (€)**	**CE ratio**		
			Sedimentos (S)	**Nitrógeno total (TN)**	**Fósforo total (TP)**
Implantación de barreras vegetales	2 m de ancho	1,734,928	266,912	64,257	47,017
	3 m de ancho	2,297,188	319,054	75,815	55,622
Cambios de usos del suelo	Buffer 500 m	1,544,000	-	-	-
	Buffer 1500 m	9,674,000	3,869,600	4,606,667	4,030,833
	Buffer Zona 1	31,271,200	1,979,190	2,282,569	2,171,611
	Agricultura ilegal	3,500,000	2,692,308	198,864	184,211

Plantación siguiendo las curvas de nivel	Pendientes < 2%	218,007	99,094	31,595	26,586
	Pendientes entre 2% y 8%	270,366	19,175	9,259	6,258
	Pendientes > 8%	119,736	1,197,360	18,142	10,596
Cambios en la rotación anual de cultivos		2,466,860	601,673	172,508	97,891
Restauración de la vegetación de los cauces		10,000,000	490,196	5,000,000	4,347,826
Reducción de la aplicación de fertilizantes		5,622,600	-	730,208	453,435
Recolección de aguas de lluvia en los invernaderos		1,543,100	5,143,667	15,431,000	15,431,000
	BMPs agrícolas	10,094,754	566,388	169,381	145,188
	BMPs estructurales	13,500,000	617,480	597,708	583,432
	Todas las BMPs	23,594,754	620,770	351,143	313,401

Tanto en López-Ballesteros et al. (2019) como en López-Ballesteros et al. (2023) se demostró que las BMPs agrícolas son las que presenta una mayor coste-eficacia en cuanto a la reducción de sedimentos y nutrientes. Esto se debe principalmente a su bajo coste de implementación en comparación con las BMPs estructurales. Sin embargo, su implementación no es tan rentable al ser los agricultores los encargados de su instalación, si se compara con el poder económico de los gobiernos encargados de la implementación de los otros tipos de BMPs. Perni et al. (2011) estimó el valor económico total de la laguna costera del Mar Menor bajo buenas condiciones ecológicas en aproximadamente 45 millones de euros por año.

Este dato refleja que la implementación de escenarios combinados de BMPs supone un coste asumible al compararse con el valor de la laguna costera bajo condiciones aceptables.

Todos los resultados obtenidos durante la evaluación de las BMPs permiten a los encargados de la toma de decisiones realizar su trabajo basándose en demostraciones científicas y así poder implementar soluciones efectivas para poder tener mayor control sobre la contaminación procedente de fuentes difusas a escala de cuenca. La presente tesis supone a su vez una mejora en el conocimiento científico de la zona de estudio, tanto en el funcionamiento hidrológico de la cuenca como en la hidrodinámica de la laguna costera del Mar Menor.

V – CONCLUSIONS AND FUTURE RESEARCH

V – CONCLUSIONS AND FUTURE RESEARCH

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

Despite several challenges, such as the scarcity of data and the high complexity of the study area, a holistic model for science-informed decision support in intensive agricultural areas was achieved in this study. In particular, an integrated SWAT model of the Campo de Cartagena watershed was provided in combination with the hydrodynamic part of the WET model. Therefore, the main objective of this PhD thesis was successfully fulfilled. All the developed models showed a good performance in calibration and validation processes. In the SWAT model, the novel approach of calibrating with satellite-derived evapotranspiration data, provided a useful tool to evaluate the performance of hydrological models in ungauged areas. Moreover, the successful simulation of the Mar Menor water balance enhanced the confidence in the holistic model results. However, these results should be interpreted as possible trends and not as exact values due to the model uncertainties and limitations.

The developed model, apart from assisting with a better global understanding of the Mar Menor environmental problem, provided the possibility of assessing the effectiveness of potential BMP scenarios. Therefore, an evaluation of the impact of BMPs on reducing non-point source pollution, such as sediments and nutrients, was carried out in this study. This assessment was first conducted in a small basin located within the Mar Menor watershed, known as "El Beal". In this first phase, ten BMPs scenarios were simulated and findings showed that the most effective BMPs were the check dam restoration and the reforestation. It was also observed a synergistic effect where all effectiveness values improved when BMPs were combined. The final phase consisted of extending the BMP assessment to the whole watershed of the Mar Menor coastal lagoon. In this part, a total of 16 BMP scenarios, extracted from official legislation, were simulated and evaluated. At the watershed scale, the most effective BMPs in reducing sediment and nutrient loads flowing into the coastal lagoon were vegetative filter strips, contour farming and prosecuting illegal agriculture. Moreover, the synergistic effects of the combination of BMPs was observed again. Regarding the cost-effective assessment, agricultural BMP scenarios proved to be the best solution from an economical point of view. This result is attributed to fact that implementation of agricultural BMPs is less expensive than other BMP implementation such as structural. Moreover, it is expected that the socio-economic benefits will be higher than total implementation cost in all assessed BMP scenarios.

In summary, results from this PhD thesis may guide decision-makers to select and prioritize the implementation of the most appropriated BMPs to effectively counteract the environmental degradation of the coastal lagoon. Other important outcome of this Phd thesis is the holistic approach applied to estimate the water balance of the Mar Menor coastal lagoon. The combination of hydrologic and hydrodynamic models provided an innovative tool to simulate the water balance components. Moreover, the results could help in a better understanding of the processes that govern the hydrology of the coastal lagoon and thereby advance the scientific knowledge of this study case. The developed model complex could provide a strong basis for further studies focus on identifying potential solutions to improve the Mar Menor environmental issues. Future research could be addressed to indicate and assess critical areas of intervention inside the "Campo de Cartagena" for a more effective BMPs implementation. A coordination and consensus between stakeholders is necessary to effectively apply measures to return the Mar Menor coastal lagoon to its good ecological status. Additionally, the modelling and methodological approaches, simulated BMP scenarios and outcomes of this PhD thesis can be extended to similar anthropogenic areas where observed data are scarce.

VI - REFERENCIAS BIBLIOGRÁFICAS

VI – REFERENCIAS BIBLIOGRÁFICAS

Abbaspour, K.C. SWAT-CUP-2012: SWAT Calibration and Uncertainty Program—A User Manual; Swiss Federal Institute of Aquatic Science and Technology: Dubendorf, Switzerland, 2012.

Álvarez-Rogel, J., Barberá, G.G., Maxwell, B., Guerrero-Brotons, M., Díaz-García, C., Martínez-Sánchez, J.J., Sallent, A., Martínez-Ródenas, J., González-Alcaraz, M.N., Jiménez-Cárceles, F.J., Tercero, C., Gómez, R., 2020. The case of Mar Menor eutrophication: State of the art and description of tested Nature-Based Solutions. Ecological Engineering, 158, 106086. https://doi.org/10.1016/j.ecoleng.2020.106086

Álvarez-Rogel, J., Jiménez-Cárceles, F. J., Nicolás, C. E., 2006. Phosphorus and nitrogen content in the water of a coastal wetland in the Mar Menor lagoon (SE Spain): relationships with effluents from urban and agricultural areas. Water, Air, and Soil Pollution, 173 (1), 21-38. https://doi.org/10.1007/s11270-005-9020-y

Alcolea, A., Contreras, S., Hunink, J.E., García-Aróstegui, J.L., Jiménez-Martínez, J., 2019. Hydrogeological modelling for the watershed management of the Mar Menor coastal lagoon (Spain). Science of the Total Environment, 663, 901–914. https://doi.org/10.1016/j.scitotenv.2019.01.375

Alcon, F., de Miguel, M.D., Burton, M., 2011. Duration analysis of adoption of drip irrigation technology in southeastern Spain. Technological Forecasting and Social Change, 78 (6), 991-1001. https://doi.org/10.1016/j.techfore.2011.02.001

Arnold, J.G., Moriasi, D., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Griensven, A.V., Liew, M., Kannan, M., Jha, M.K., 2012. SWAT: Model use, calibration, and validation. Transactions of the ASABE, 55 (4), 1491–1508. https://doi.org/10.13031/2013.42256

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment Part I: model development. Journal of the American Water Resources Association, 34, 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

BOE. Boletín ofical del Estado, 2004. ORDEN APA/1657/2004, de 31 de mayo, por la que se establece la norma técnica específica de la identificación de garantía nacional de producción integrada de cítricos. Boletín Oficial del Estado: Spain.

BOE. Boletín ofical del Estado, 2020. Ley 3/2020, de 27 de julio, de recuperación y protección del Mar Menor. Boletín Oficial del Estado: Spain.

BORM. Boletín Oficial de la Región de Murcia, 2012a. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de lechuga. Boletín Oficial de la Región de Murcia: Murcia, Spain.

BORM. Boletín Oficial de la Región de Murcia, 2012b. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de melón y sandía. Boletín Oficial de la Región de Murcia: Murcia, Spain.

BORM. Boletín Oficial de la Región de Murcia, 2012c. Orden de 10 de mayo de 2012, de la Consejería de Agricultura y Agua por la que se regulan las normas técnicas de producción integrada en el cultivo de bróculi. Boletín Oficial de la Región de Murcia: Murcia, Spain.

BORM. Boletín Oficial de la Región de Murcia, 2017. Decreto-Ley nº 1/2017, de 4 de abril, de medidas urgentes para garantizar la sostenibilidad ambiental en el entorno del Mar Menor. Boletín Oficial de la Región de Murcia: Murcia, Spain.

BORM. Boletín Oficial de la Región de Murcia, 2018. Ley 1/2018, de 7 de Febrero, de medidas urgentes para garantizar la sostenibilidad ambiental en el entorno del Mar Menor. Boletín Oficial de la Región de Murcia: Murcia, Spain.

BORM. Boletín Oficial de la Región de Murcia, 2019. Decreto–Ley n◦ 2/2019, de 26 de diciembre, de protección integral del Mar Menor. Boletín Oficial de la Región de Murcia: Murcia, Spain, 2019.

Carreño Fructuoso, M.F., 2015. Seguimiento de los cambios de usos y su influencia en las comunidades y hábitats naturales en la cuenca del Mar Menor, 1988-2009, con el uso de SIG y teledetección. Tesis Doctoral. Universidad de Murcia.

Comité de Asesoramiento Científico del Mar Menor, 2017. Informe integral sobre el estado ecológico del Mar Menor. Comité de Asesoramiento Científico del Mar Menor: Murcia, Spain. https://canalmarmenor.carm.es/wp-content/uploads/2020/07/Informe-Integral-sobre-el-estado-ecol%C3%B3gico-del-Mar-Menor.pdf

Dile, Y.T., Daggupati, P., George, C., Srinivasan, R., Arnold, J., 2016. Introducing a new open source GIS user interface for the SWAT model. Environmental Modelling & Software, 85, 129–138. https://doi.org/10.1016/j.envsoft.2016.08.004

EC. European Commission, 2020. Farm to Fork strategy for a fair, healthy and environmentally-friendly food system. European Commission. https://ec.europa.eu/food/farm2fork_en

EU Regulation 1306/2013. Regulation (EU) No 1306/2013 of the European Parliament and of the Council of 17 December 2013 on the financing, management and monitoring of the common agricultural policy. European Commission. http://data.europa.eu/eli/reg/2013/1306/2020-12-29

FAO–ISRIC, 1990. Food and Agriculture Organization of the United Nations–International Soil Reference and Information Centre. Guidelines for Profile Description, 3rd ed., FAO–ISRIC: Roma, Italy.

García-Pintado, J., Martínez-Mena, M., Barberá, G.G., Albaladejo, J., Castillo, V.M., 2007. Anthropogenic nutrient sources and loads from a Mediterranean catchment into a coastal lagoon: Mar Menor, Spain. Science of the Total Environment, 373, 220–239. https://doi.org/10.1016/j.scitotenv.2006.10.046

Gassman, P.W., Sadeghi, A.M., Srinivasan, R., 2014. Applications of the SWAT model special section: overview and insights. Journal Environmental Quality, 43 (1), 1–8. https://doi.org/10.2134/jeq2013.11.0466

Green, W.H., Ampt, G.A., 1911. Studies on soil Physics. The Journal of Agricultural Science, 4, 1–24.

Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. Journal of Hydrology, 377 (1-2), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003

Hargreaves, G. L., Hargreaves, G. H., Riley, J. P., 1985. Irrigation water requirement for Senegal River Basin. Journal of Irrigation and Drainage Engineering, 111 (3), 265–275. https://doi.org/10.1061/(ASCE)0733-9437(1985)111:3(265)

Liu, R., Zhang, P., Wang, X., Chen, Y., Shen, Z., 2013. Assessment of effects of best management practices on agricultural non-point source pollution in Xiangxi River watershed. Agricultural Water Management, 117, 9–18. https://doi.org/10.1016/j.agwat.2012.10.018

López-Ballesteros, A., Senent-Aparicio, J., Srinivasan, R., Pérez-Sánchez, J., 2019. Assessing the impact of best management practices in a highly anthropogenic and ungauged watershed using the SWAT model: a case study in the El Beal watershed (Southeast Spain). Agronomy, 9 (10), 576. https://doi.org/10.3390/agronomy9100576

López-Ballesteros, A., Trolle, D., Srinivasan, R., Senent-Aparicio, J., 2023. Assessing the effectiveness of potential best management practices for science-informed decision support at the watershed scale: The case of the Mar Menor coastal lagoon, Spain. Science of the Total Environment, 859 (1), 160144. https://doi.org/10.1016/j.scitotenv.2022.160144

Martínez-Fernández J., Esteve-Selma M.A., 2000. Estimación de la entrada de nutrientes de origen agrícola en el Mar Menor mediante un modelo dinámico. Mediterranea, 17, 19–26.

Miralles, D.G., Holmes, T.R.H., De Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J., 2011. Global land-surface evaporation estimated from satellite-based observations. Hydrology and Earth System Sciences, 15, 453–469. https://doi.org/10.5194/hess-15-453-2011

Molina-Navarro, E., Andersen, H. E., Nielsen, A., Thodsen, H., Trolle, D., 2017. The impact of the objective function in multi-site and multi-variable calibration of the SWAT model.

Environmental Modelling & Software, 93, 255-267. https://doi.org/10.1016/j.envsoft.2017.03.018

Molina-Navarro, E., Nielsen, A., Trolle, D., 2018. A QGIS plugin to tailor SWAT watershed delineations to lake and reservoir waterbodies. Environmental Modelling & Software, 108, 67–71. https://doi.org/10.1016/j.envsoft.2018.07.003

Monteith J.L., 1965. Evaporation and the environment. In The State and Movement of Water in Living Organisms. XIXth Symposium. Society for Experimental Biology, Swansea, Cambridge University Press, 205-234.

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Transactions of the ASABE, 58 (6), 1763–1785. https://doi.org/10.13031/trans.58.10715

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I – A discussion of principles. Journal of Hydrology, 10 (3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool: Theoretical Documentation, version 2009. Texas Water Resources Institute: College Station, TX, USA.

Nielsen, A., Bolding, K., Hu, F., Trolle, D., 2017. An open source QGIS-based workflow for model application and experimentation with aquatic ecosystems. Environmental Modelling & Software, 95, 358–364. https://doi.org/10.1016/j.envsoft.2017.06.032.

Perni A, Martínez-Carrasco F, Martínez-Paz J.M., 2011. Economic valuation of coastal lagoon environmental restoration: Mar Menor (SE Spain). Ciencias Marinas, 37, 175–190. https://doi.org/10.7773/cm.v37i2.1889

Priestley, C.H.B., Taylor. R.J., 1972. On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. Division of Atmospheric Physics, Common wealth Scientific and

Industrial Research Organization. https://doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2

Ricci, G.F., Jeong, J., De Girolamo, A.M., Gentile, F., 2020. Effectiveness and feasibility of different management practices to reduce soil erosion in an agricultural watershed. Land Use Policy, 90, 104306. https://doi.org/10.1016/j.landusepol.2019.104306

Risal, A., Parajuli, P.B., 2022. Evaluation of the impact of best management practices on streamflow, sediment and nutrient yield at field and watershed scales. Water Resources Management, 36, 1093–1105. https://doi.org/10.1007/s11269-022-03075-7

Rouholahnejad, E., Abbaspour, K.C., Srinivasan, R., Bacu, V., Lehmann, A., 2014. Water resources of the Black Sea Basin at high spatial and temporal resolution. Water Resource Research, 50, 5866-5885. https://doi.org/10.1002/2013WR014132

Senent-Aparicio, J., López-Ballesteros, A., Cabezas, F., Pérez-Sánchez, J., Molina-Navarro, E., 2021. A modelling approach to forecast the effect of climate change on the Tagus-Segura interbasin water transfer. Water Resources Management, 35, 3791-3808. https://doi.org/10.1007/s11269-021-02919-y

Senent-Aparicio, J., López-Ballesteros, A., Nielsen, A., Trolle, D., 2021. A holistic approach for determining the hydrology of the mar menor coastal lagoon by combining hydrological & hydrodynamic models. Journal of Hydrology, 603, 127150. https://doi.org/10.1016/j.jhydrol.2021.127150

Senent-Aparicio, J., Pérez-Sánchez, J., Bielsa-Artero, A.M., 2016. Asessment of sustainability in semiarid mediterranean basins: case study of the Segura Basin, Spain. Water Science and Technology, 7, 67–84.

USDA-SCS, 1972. National Engineering Handbook, Section 4, Hydrology. USDA Soil Conservation Service, Washington DC. http://irrigationtoolbox.com/NEH/Part%20630%20Hydrology/neh630-ch15.pdf

Umgiesser, G., Ferrarin, C., Cucco, A., De Pascalis, F., Bellafiore, D., Ghezzo, M., Bajo, M., 2014. Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling. Journal of Geophysical Research: Oceans, 119, 2212–2226. https://doi.org/10.1002/2013JC009512

Upadhyay, P., Linhoss, A., Kelble, C., Ashby, S., Murphy, N., Parajuli, P. B., 2022. Applications of the SWAT model for coastal watersheds: Review and recommendations. Journal of the ASABE, 65 (2), 453-469. https://doi.org/10.13031/ja.14848

Waidler, D., White, M., Steglich, E.,Wang, S.,Williams, J., Jones, C.A., Srinivasan, R., 2009. Conservation Practice Modeling Guide for SWAT and APEX. Texas Water Resources Institute: College Station, TX, USA. https://hdl.handle.net/1969.1/94928

VII - ANEXOS

ANEXO I: CALIDAD DE LAS PUBLICACIONES

1. <u>López-Ballesteros, A.</u>; Senent-Aparicio, J.; Srinivasan, R.; Pérez-Sánchez, J. (2019). Assessing the impact of best management practices in a highly anthropogenic and ungauged watershed using the SWAT model: A case study in the El Beal Watershed (Southeast Spain). Agronomy, 9 (10), 576.

    - Índice de impacto (2019): **2,603**
    - Puesto en el JCR: **18/91**
    - Categoría: **Agronomy**
    - Cuartil: **Q1**

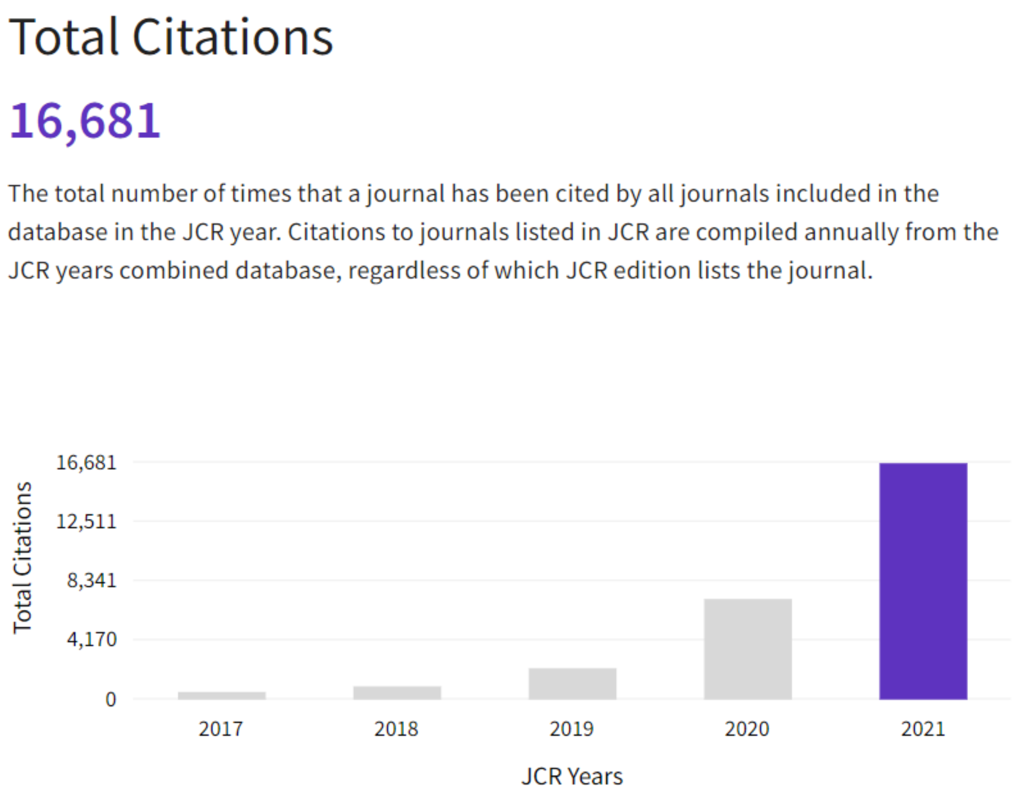

Figura 14. Citas totales de la revista Agronomy a lo largo de los últimos 5 años.

2. Senent-Aparicio, J.; López-Ballesteros, A.; Nielsen, A.; Trolle, D. (2021). A holistic approach for determining the hydrology of the mar menor coastal lagoon by combining hydrological & hydrodynamic models. Journal of Hydrology, 603, 127150.

    - Índice de impacto (2021): **6,708**
    - Puesto en el JCR: **9/100**
    - Categoría: **Water Resources**
    - Cuartil: **Q1**

Total Citations

85,140

The total number of times that a journal has been cited by all journals included in the database in the JCR year. Citations to journals listed in JCR are compiled annually from the JCR years combined database, regardless of which JCR edition lists the journal.

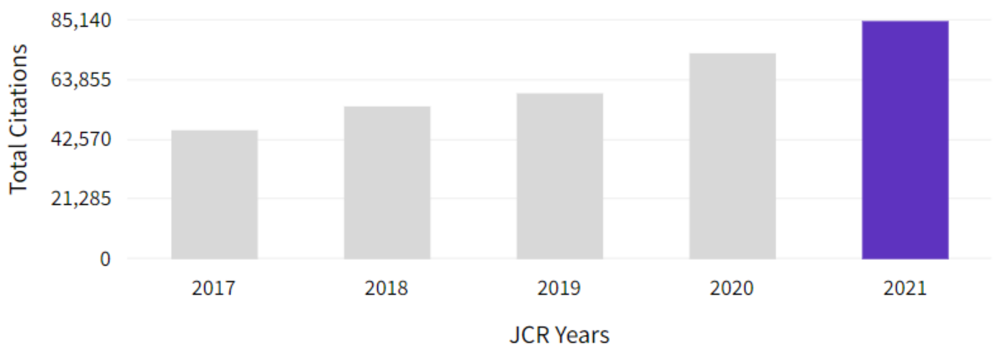

Figura 15. Citas totales de la revista Journal of Hydrology a lo largo de los últimos 5 años.

3. López-Ballesteros, A.; Trolle, D.; Srinivasan, R.; Senent-Aparicio, J. (2023). Assessing the effectiveness of potential best management practices for science-informed decision support at the watershed scale: The case of the Mar Menor coastal lagoon, Spain. Science of the Total Environment, 859 (1), 160144.

    - Índice de impacto (2021): **10,753**
    - Puesto en el JCR: **26/279**
    - Categoría: **Environmental Sciences**
    - Cuartil: **Q1**

Total Citations

328,228

The total number of times that a journal has been cited by all journals included in the database in the JCR year. Citations to journals listed in JCR are compiled annually from the JCR years combined database, regardless of which JCR edition lists the journal.

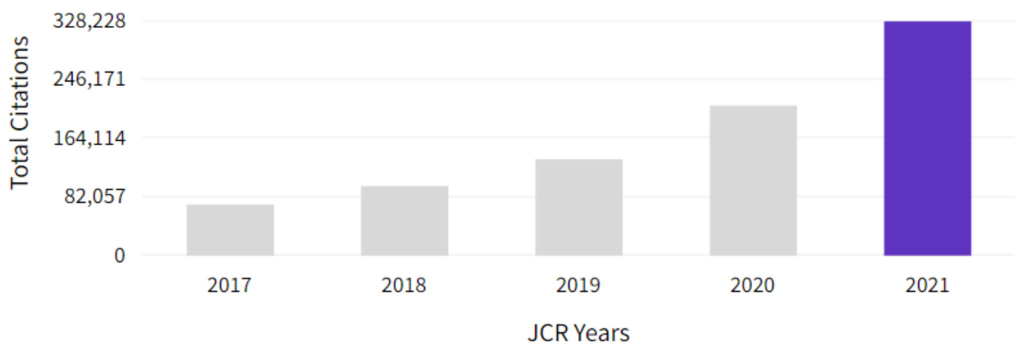

Figura 16. Citas totales de la revista Science of the Total Environment a lo largo de los últimos 5 años.

ANEXO II: OTRAS PUBLICACIONES Y MÉRITOS

A lo largo del tiempo de realización de la presente tesis, se han alcanzado una serie de logros entre los que se incluyen otras publicaciones en revistas científicas, participación en congresos nacionales e internacionales, registros de la propiedad intelectual y ayudas de estancias en el extranjero.

Otras publicaciones:
Jiménez-Navarro, I. C., Jimeno-Sáez, P., **López-Ballesteros, A.**, Pérez-Sánchez, J., Senent-Aparicio, J. (2021). Impact of Climate Change on the Hydrology of the Forested Watershed That Drains to Lake Erken in Sweden: An Analysis Using SWAT+ and CMIP6 Scenarios. Forests, 12(12), 1803. https://doi.org/10.3390/f12121803
Senent-Aparicio, J., Blanco-Gómez, P., **López-Ballesteros, A.**, Jimeno-Sáez, P., Pérez-Sánchez, J. (2021). Evaluating the potential of Glofas-era5 river discharge reanalysis data for calibrating the SWAT model in the Grande San Miguel River Basin (El Salvador). Remote Sensing, 13(16), 3299. https://doi.org/10.3390/rs13163299
Senent-Aparicio, J., **López-Ballesteros, A.**, Cabezas, F., Pérez-Sánchez, J., Molina-Navarro, E. (2021). A Modelling Approach to Forecast the Effect of Climate Change on the Tagus-Segura Interbasin Water Transfer. Water Resources Management, 35(11), 3791-3808. https://doi.org/10.1007/s11269-021-02919-y
Aznarez, C., Jimeno-Sáez, P., **López-Ballesteros, A.**, Pacheco, J. P., Senent-Aparicio, J. (2021). Analysing the impact of climate change on hydrological ecosystem services in Laguna del Sauce (Uruguay) using the SWAT model and remote sensing data. Remote Sensing, 13(10), 2014. https://doi.org/10.3390/rs13102014
Senent-Aparicio, J., Jimeno-Sáez, P., **López-Ballesteros, A.**, Giménez, J. G., Pérez-Sánchez, J., Cecilia, J. M., Srinivasan, R. (2021). Impacts of swat weather generator statistics from high-resolution datasets on monthly streamflow

simulation over Peninsular Spain. Journal of Hydrology: Regional Studies, 35, 100826. https://doi.org/10.1016/j.ejrh.2021.100826
Pérez-Sánchez, J., Senent-Aparicio, J., Martínez Santa-María, C., **López-Ballesteros, A.** (2020). Assessment of ecological and hydro-geomorphological alterations under climate change using SWAT and IAHRIS in the Eo river in Northern Spain. Water, 12(6), 1745. https://doi.org/10.3390/w12061745
López-Ballesteros, A., Senent-Aparicio, J., Martínez, C., Pérez-Sánchez, J. (2020). Assessment of future hydrologic alteration due to climate change in the Aracthos River basin (NW Greece). Science of The Total Environment, 733, 139299. https://doi.org/10.1016/j.scitotenv.2020.139299
Senent-Aparicio, J., Liu, S., Pérez-Sánchez, J., **López-Ballesteros, A.**, Jimeno-Sáez, P. (2018). Assessing impacts of climate variability and reforestation activities on water resources in the headwaters of the Segura River Basin (SE Spain). Sustainability, 10(9), 3277. https://doi.org/10.3390/su10093277
Senent-Aparicio, J., **López-Ballesteros, A.**, Pérez-Sánchez, J., Segura-Méndez, F. J., Pulido-Velazquez, D. (2018). Using multiple monthly water balance models to evaluate gridded precipitation products over peninsular Spain. Remote Sensing, 10(6), 922. https://doi.org/10.3390/rs10060922

Congresos nacionales e internacionales:
López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P., Pérez-Sánchez, J. (2022). MapSWAT: A QGIS extension for preparing SWAT input maps. International Soil And Water Assessment Tool Conference. Prague, Czech Republic.
López-Ballesteros, A., Senent-Aparicio, J. (2022). Evaluación del impacto de las prácticas de gestión agrícola sobre los sedimentos y nutrientes entrantes al Mar Menor. VIII Jornadas de Investigación y Doctorado. Murcia, Spain.
López-Ballesteros, A., Senent-Aparicio, J., Nielsen, A., Trolle, D. (2021). Coupling SWAT and WET Models for Modeling of Highly Anthropized Coastal Lagoons. Case Study: Mar Menor (SE Spain). AGU Fall Meeting 2021. New Orleans, United States of America.
Segura-Méndez, F.J., Senent-Aparicio, J., **López-Ballesteros, A.**, Jimeno-Sáez, P., Pérez-Sánchez, J. (2021). Evolución de la vulnerabilidad del acuífero cuaternario

en el Campo de Cartagena a partir del método DRASTIC. Caso de estudio: cuenca de Miranda. Congreso Ibérico de las Aguas Subterráneas CIAS2021. Valencia, Spain.
López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P., Pérez-Sánchez, J. (2021). Efectos del cambio climático sobre los caudales máximos de diseño en la España peninsular. Congreso Nacional del Agua Orihuela 2021. Alicante, Spain.
López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P. (2021). Modelización hidrológica mediante SWAT de la cuenca vertiente al Mar Menor. VII Jornadas de Investigación y Doctorado. Murcia, Spain.
López-Ballesteros, A., Senent-Aparicio, J., Pérez-Sánchez, J., Jimeno-Sáez, P. (2020). Efecto sobre las inundaciones de la implementación de prácticas agrícolas en la rambla del Albujón. Congreso Nacional de Inundaciones Orihuela 2020. Alicante, Spain.
López-Ballesteros, A., Senent-Aparicio, J., Pérez-Sánchez, J. (2020). Desarrollo de una herramienta para la delimitación de cuencas hidrográficas en QGIS mediante Python. VI Jornadas Investigación y Doctorado. Murcia, Spain.
Senent-Aparicio, J., Pérez-Sánchez, J., Jimeno-Sáez, P., **López-Ballesteros, A.** (2020). Aprendizaje basado en problemas aplicado a las asignaturas de la rama de Hidráulica e Hidrología en el Grado de Ingeniería Civil. 4th International Virtual Conference on Educational Research and Innovation (CIVINEDU 2020). Madrid, Spain.
López-Ballesteros, A., Senent-Aparicio, J., Stavridis, A., Pérez-Sánchez, J. (2019). Assessing the impact of climate change for Aracthos river basin (NW Greece) using SWAT model. International Soil And Water Assessment Tool Conference. Vienna, Austria.
López-Ballesteros, A., Senent-Aparicio, J., Pérez-Sánchez, J. (2019). Modeling the impacts of best management practices on water quality of El Beal wadi (SE Spain). International Soil And Water Assessment Tool Conference. Vienna, Austria.
López-Ballesteros, A., Senent-Aparicio, J., Cabezas, F., Pérez-Sánchez, J. (2019). Impacts of climate change on the Tagus Segura Interbasin Water Transfer. 11th World Congress on Water Resources and Environment (EWRA 2019). Madrid, Spain.

López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P. (2019). Calibración y validación del modelo SWAT mediante datos de evapotranspiración satelital. V Jornadas de Investigación y Doctorado. Murcia, Spain.
López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P. (2019). Modelización hidrológica de la Rambla de la Carrasquilla mediante datos de teledetección. Congreso Nacional del Agua 2019. Alicante, Spain.
Pérez-Sánchez, J., Senent-Aparicio, J., **López-Ballesteros, A.** (2018). Modeling the Impact of Climate Change on Water Resources in the Headwaters of the Tagus River Basin. International Soil And Water Assessment Tool Conference. Bruselas, Belgium.
López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P. (2018). Aplicación del Modelo Hidrológico SWAT en la cuenca del río Guadiela. IV Jornadas de Investigación y Doctorado. Murcia, Spain.

Registros de la propiedad intelectual:
López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P., Pérez-Sánchez, J. EasyBasin. CMU-000009-2021.
López-Ballesteros, A., Senent-Aparicio, J., Jimeno-Sáez, P., Pérez-Sánchez, J. MapSWAT. CMU-000010-2021.

Estancias en el extranjero:
Texas A&M University. Ayudas complementarias de movilidad destinadas a beneficiarios del programa de Formación del Profesorado Universitario (FPU). Ministerio de Educación y Formación Profesional. 01/03/2022 - 31/05/2022
Aarhus University. Staff mobility for teaching and training activities. EU's Erasmus+ programme. 24/01/2022 - 28/01/2022