International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

A review of Soil and Water Assessment Tool (SWAT) studies of Mediterranean catchments

Praveen Holisagar[1], Manu Kambar[1], Manjunath Pattepur[1], MD Faizan Ahmed[1].

Dayanand Sagar College of Engineering, Bengaluru - 560078

---***---

Abstract - *The Soil and Water Assessment Tool (SWAT) is a well-established eco-hydrological model that has been extensively applied to watersheds across the globe. This work reviews over two decades (2002–2022) of SWAT studies conducted on Mediterranean watersheds. A total of 260 articles have been identified since the earliest documented use of the model in a Mediterranean catchment back in 2002; of which 62% were carried out in Greece, Italy, or Spain. SWAT applications increased significantly in recent years since 86% of the reviewed papers were published in the past decade. A major objective for most of the reviewed works was to check the applicability of SWAT to specific watersheds. A great number of publications included procedures of calibration and validation and reported performance results. SWAT applications in the Mediterranean region mainly cover water resources quantity and quality assessment and hydrologic and environmental impacts evaluation of land use and climate changes. Nevertheless, a tendency towards a multi-purpose use of SWAT is revealed. The numerous examples of SWAT combined with other tools and techniques outline the model's flexibility. Several studies performed constructive comparisons between Mediterranean watersheds' responses or compared SWAT to other models or methods. The effects of inputs on SWAT outputs and innovative model modifications and improvements were also the focus of some of the surveyed articles. However, a significant number of studies reported difficulties regarding data availability, as these are either scarce, have poor resolution or are not freely available. Therefore, it is highly recommended to identify and develop accurate model inputs and testing data to optimize the SWAT performance.*

***Key Words*: Soil and water assessment tool , Watershed modeling, Mediterranean catchment , Model performance.**

1. INTRODUCTION

The Mediterranean region is basically defined by its climate, often described as a rainy winter, and dry summer climate (Ewald et al., 2010). Total precipitation values in this climatic transition area are significantly variable in time and space. The high spatial variability is reflected by the amounts of mean annual precipitation in the region which broadly range from less than 200 mm/year in North Africa up to 2000 mm/year over the mountains of the Dinaric Alps (Lelieveld et al., 2012; Xoplaki et al., 2004). In terms of temporal distribution, precipitation can also vary inter-annually and seasonally, often causing long-lasting droughts or extreme events such as flash floods (García-Ruiz et al., 2011).

The Mediterranean basin portrays more than climatic features. It is currently characterized by rich biodiversity (Cuttelod et al., 2008), suitable natural conditions for agriculture with increasing dependencies on irrigation (Harmanny and Malek, 2019), a dense and rapidly growing population of which one-third is condensed along the shared coastline (Riccaboni et al., 2021; Worldmeter, 2022), changes in agricultural patterns and accelerated urbanization (mostly at the expenses of agricultural land) leading to remarkable land use changes (Ferreira et al., 2022; García-Nieto et al., 2018), unevenly distributed water resources with high water stress in some sub-regions (Benoit and Comeau, 2006; Fader et al., 2020; Mekonnen and Hoekstra, 2016; United Nations, 2017) and expected future climate change impacts (Giannakopoulos et al., 2009; Lionello and Scarascia, 2018; Lionello et al., 2014; Ludwig et al., 2011; Mariotti et al., 2015; Tramblay et al., 2020).

According to most climate models, the Mediterranean Basin is expected to experience regional warming at rates exceeding global averages by about 20%, as well as drastic rainfall reductions scoring up to 12% decrease for global warming of 3 ◦ C (Ali et al., 2022). Although the region does not score the highest predicted warming rates, risks associated with these changes are particularly high for Mediterranean societies and ecosystems due to their high exposure and weak resilience.

These characteristics convey complex and dynamic interactions between natural and anthropogenic elements that are better reflected at the watershed scale. Mediterranean watersheds (MW) are very diverse in terms of covered area. As mentioned in Ducrocq et al. (2016), small to medium size local catchments, mostly corresponding to intermittent and ephemeral small rivers, represent 58% of the total Mediterranean hydrological system. The remaining part is made up of 21 watersheds that extend over more than 10 000 km^2 each (e.g., Ebro, Po, Rhone, and the ˆ Upper Nile).

International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

Watersheds within the Mediterranean basin display highly variable hydrological processes both at temporal and spatial levels driven by multiple factors: sub-climatic conditions, geographical position, topography, hydrogeological and aquifer systems, presence of lakes, dams, and reservoirs, human activities, etc. Consequently, watershed managers in the Mediterranean region are often faced with an array of challenges when trying to simultaneously meet human needs and maintain natural resources sustainability (F´e d'Ostiani, 2004). Effective watershed management requires a deeper comprehension of these hydrologic systems, which can be practically reached through accurate modeling. Therefore, watershed models have become essential tools to address hydrologic and environmental issues within Mediterranean catchments and to predict their evolution under global changes.

The Soil and Water Assessment Tool (SWAT) is one of the most extensively used eco-hydrological models internationally, as documented by previous review studies and a wide literature collection that now exceeds 5000 studies (CARD, 2022). SWAT is a continuous-time, semi-distributed, process-based small watershed to river basin-scale model (Arnold et al., 1998). The first officially released version of SWAT goes back to 1993 (Engel et al., 1993). Since it was developed, it has undergone continuous expansion of capabilities and improvement of many of its modules leading to its latest reconstructed version "SWAT+" (Bieger et al., 2017).

). The development of several versions of GIS-based interfaces since 1994 (Srinivasan and Arnold, 1994) greatly facilitated the use of SWAT by enabling straightforward translations of data into model inputs. The new SWAT model generation SWAT+ was developed in order to overcome the restricted potential flexibility that the current SWAT structure reached after thirty years of thriving development. SWAT + provides a more flexible spatial representation of interactions and processes within a watershed. Although lacking in calibration support, SWAT + has a number of advantages over SWAT in terms of database management, coding flexibility, connectivity, reservoir operation, and aquifer boundary (Yen et al., 2019).

The SWAT model allows the simulation of hydrologic, sediment, and pollutants processes as well as crop growth and management practices in a watershed by using the water balance approach. The SWAT operates by first dividing the drainage basin into sub-basins. Each sub-basin is further partitioned into a number of hydrologic response units (HRUs). These are distinctive topography-soil–land use combinations. The simulations for each HRU are subsequently aggregated for the sub-basin by a weighted mean. Neitsch et al. (2011) documentation provides a detailed model functioning literature.

While still keeping a comprehensive nature, SWAT has proved to be a robust and flexible interdisciplinary modeling tool that can be used to simulate a variety of watershed problems, as evidenced by several SWAT overview articles for special issues (e.g., Gassman et al., 2007; Gassman et al., 2014). SWAT applications include the simulation of surface and ground water quality and quantity (e.g., Aouissi et al., 2014; Nikolaidis et al., 2013; Othman and Gueddari, 2014; Pisinaras et al., 2009; Zettam et al., 2020), the prediction of the environmental impact of land use, land management practices, and climate change (e.g., Almeida et al., 2018; Choukri et al., 2020; Epelde et al., 2015; Glavan et al., 2015; Molina-Navarro et al., 2014; Pulighe et al., 2021; Serpa et al., 2017), soil erosion prevention and control (e.g., Ben Khelifa et al., 2021; Mosbahi and Benabdallah, 2020; Mtibaa et al., 2018; Ricci et al., 2020), point and non-point source pollution control (e.g., Candela et al., 2012; De Girolamo and Lo Porto, 2020; Salvetti et al., 2008), and regional watershed management (e.g., Nkwasa et al., 2022), among others.

To date, there are a few reviews of SWAT applications for global sub- regions such as the Upper Nile basin countries (van Griensven et al., 2012), Brazil (Bressiani et al., 2015), Southeastern Asia (Tan et al., 2019), and Africa (Akoko et al., 2021). However, no existing SWAT review paper has focused on modeling Mediterranean watersheds yet. Therefore, this review aims to bridge this gap by synthesizing the existing SWAT-based peer-reviewed journal literature reporting SWAT research in Mediterranean catchments mainly from literature compiled by the Center for Agriculture and Rural Development (CARD). The objectives of this review are to summarize the key findings of the reported SWAT applications in Mediterranean watersheds, to analyze the overall implications of these studies for the Mediterranean region, to identify current SWAT modeling challenges that limit its effectiveness, and to suggest recommendations for future research.

2. ARTICLES SELECTION PROCESS

The methodology consists of selecting studies from the official SWAT database that have been published over the last two decades and that report SWAT applications within the Mediterranean region. The process starts by defining the study area, then overviewing the collected database.

Study Area Definition

There is no generally accepted delineation of the Mediterranean region. In biogeography, the Mediterranean region consists of the lands surrounding the Mediterranean Sea that have mostly a Mediterranean climate, which is favorable to the flourishing of characteristic Mediterranean ecosystems (EC, 2010). The study area definition is not strictly based on the occurrence of the Mediterranean climate. It also considers other shared features (e.g.,

International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

homogenous geological and physiographic settings, important historical and present socio-economic exchanges, and intense anthropogenic pressure) and subjective criteria (including Portugal and the Northern Nile region as part of the overall geographical unit). Therefore, for the purpose of this study, the area encompasses regions from 23 countries, thereby counting portions of three continents (Fig. 1): Southern Europe northwards (Albania, Bosnia and Herzegovina, Croatia, Cyprus, France, Greece, Italy, Malta, Monaco, Montenegro, Portugal, Slovenia, and Spain), Southwestern Asia eastwards (Egypt, Israel, Lebanon, Palestine, Syria, and Turkey), and Northern Africa to the southwards (Algeria, Libya, Morocco, and Tunisia).

Overview of selected papers

The SWAT Literature Database for Peer-Reviewed Journal Articles (CARD, 2022) was the primary source of the SWAT-related publications that served as the basis for this review. The search for the term "SWAT" for the maximal available period 1984–2022 in this public domain database (accessed on March 18, 2022) led to over 5000 SWAT-related articles at the time. In total, there were 273 articles available studying watersheds within the previously defined study area per the first selection, including a few non-English articles, articles related to non-Mediterranean watersheds characterized by a Mediterranean climate, and articles only using SWAT outputs from previous studies. Once the first ever published article on modeling a Mediterranean catchment using SWAT was identified (Varanou et al., 2002), the selected period was refined to 2002–2022. In addition, the ScienceDirect and Google Scholar databases were also used to identify recently published articles and to further check the initial set of articles. Preprints, editorials, conference proceedings, theses, and technical reports were excluded. A total of 260 articles were ultimately selected for this review. These were then overviewed based on chronological and spatial distribution, modeled basin size, performance assessment, and publishing journals.

The number of publications increased significantly in recent years both worldwide and regionally. In the Mediterranean region, 86% of the studies were published during the decade 2012–2022 and the highest number of articles (37) was scored in 2020 (Fig. 1). There were only 8 articles published in 2021. SWAT's expansion of use is motivated by the fact that it is now ingrained in literature, well documented, freely accessible, innovatively promoted (international conferences, workshops and free online tutorials), and has already been successfully applied globally and specifically in the cases of numerous Mediterranean drainage basins.

The Mediterranean regions with the highest numbers of papers in this review were Greece, Italy, Spain, Portugal, and equally Tunisia and Turkey with 58, 56, 48, 26, and 17 papers, respectively. Thereby, about 62% of these studies were carried out in Greece, Italy or Spain. Only studies included within the defined study area limits were considered. Studies on transboundary watersheds or including catchments from more than one country were counted as a study for each of the involved countries, making a total of 281 studies.

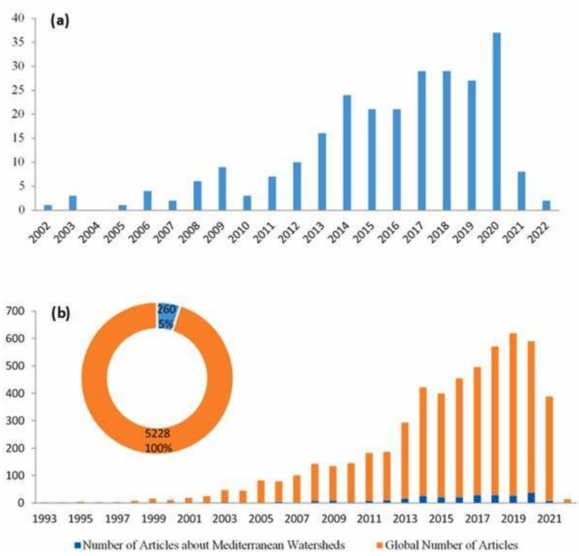

Fig. 1. Number of papers by year (a) for MW and (b) compared to global evolution.

Total of 158 articles for the Northwestern Mediterranean (NWM), 84 papers for the Eastern Mediterranean (EM), and 39 studies for the Southern Mediterranean (SM). This discrepancy can be potentially due to data availability/public data access of watershed-related information since in European Union (EU) countries data are typically collected and shared since longer (thanks to the EU harmonization), differently from other areas.

The watersheds simulated using the SWAT model in the selected articles vary in terms of area (Fig. 2a). Watersheds 'sizes range from a minimum of 0.19 ha (a Tuscanian vineyard site; Napoli et al., 2013) to a maximum of 4 489 000 km^2 (entire Nile River basin; Nkwasa et al., 2022). The 298 modeled watersheds in the reviewed studies include sub-basins, transboundary basins, parts of transboundary basins, experimental watersheds, small fields, etc. Many SWAT applications were conducted on the same or similar case studies but for different objectives, by different research teams and/or model versions. This allows comparisons of SWAT results. 28% and 23% of the modeled watersheds are of 100–500 km^2 or less than 100 km^2 areas, respectively.

This can be mainly explained by two reasons: (i) the number of small watersheds is pronounced due to the high variability in hydrologic processes in the region and (ii) Mediterranean zones mostly cover coastal regions, thus only allowing counting sub-watersheds. This highlights a need for more regional, most-likely cross-border, large-scale river

International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

watershed systems SWAT modeling in the Mediterranean region.

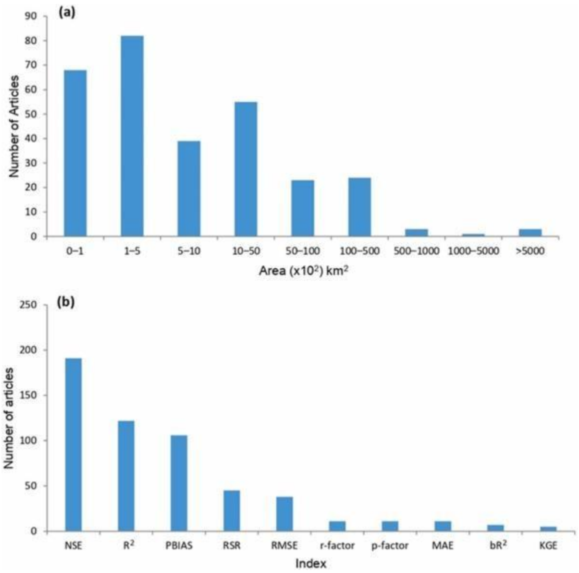

Fig. 2. (a) Number of watersheds distribution by area and **(b)** top ten SWAT evaluation statistics used in the reviewed publications.

The performance of SWAT was assessed using several model evaluation methods among which the ten most widely used are shown in Fig. 5b. NSE (Nash–Sutcliffe efficiency), R^2 (the coefficient of determination) and PBIAS (percent bias) were the most commonly adapted evaluation indices, with 191, 122, and 106 papers, respectively. 64 studies used NSE, R^2 and PBIAS simultaneously. The total index values is greater than the referred 260 publications because some SWAT capability assessment studies reported more than one evaluation method and sometimes more than one value for the same indice, but for different parameters.

The papers surveyed in this work were published across 104 different journals. The ten journals with the highest number of studies are presented in Fig. 6, with Science of the Total Environment publishing 32 papers. The remaining 143 reviewed articles (56% of the total) were published as follows: 23% in a single journal; 13% as two articles per journal; 12% as three articles per journal; and 8% as four articles per journal.

3. SWAT APPLICATIONS IN MEDITERRANEAN CATCHMENT

Given the diverse applications of SWAT modeling, the reviewed SWAT studies can be categorized in various ways. We grouped the selected articles into the following summary sections: foundational model performance assessment, evaluation of water resources quantity and quality, soil erosion and sedimentation studies, prediction of land use and/or climate changes' impacts on hydrology and pollutant losses, Best Management Practices (BMPs) evaluation and risk assessment. Some of these categories overlap each other. Table 1 lists an overview of the primary SWAT applications that have been reported for Mediterranean watersheds. Although several studies only tested the feasibility of the model, the simulation of the hydrologic balance and the model performance are not listed in Table 1 since these procedures are included in all the applications, regardless of the focus of the study.

Table -1: The main application categories of SWAT studies of Mediterranean watersheds.

Study Category		Number of studies
Water resources		91
Soil erosion and sedimentation		28
Land use and/or climate changes' impacts	Land use change	21
	Climate change	42
	Combined changes	15
Best Management Practices		34
Risk Assessment	Droughts	3
	Floods	4
	Wildfires	3
Water resources		91

SWAT model performance assessment

Prior to any application, a verification of the SWAT model's accuracy is necessary. Foundational hydrological analyses and model testing ensure SWAT's capability to reproduce the dynamics of the simulated system and consequently adequately support scenario analysis.

Overall, SWAT succeeded at reproducing the hydrological cycle in different Mediterranean catchments as explicitly evidenced by Gikas et al. (2006), Mendas et al. (2010), Briak et al. (2016), Carvalho-Santos et al. (2017), Efthimiou (2018), Hallouz et al. (2018), and Khalid (2018) among many others. For example, the model succeeded to reflect the different hydrological processes in the R'dom watershed, Morocco (Brouziyne et al., 2018), and provided reasonable water budget and streamflow results for three Greek watersheds in the Menoikio Mountain Range and for the Thasos Island (Koutalakis et al., 2017). Most of the SWAT modelers report in the reviewed publications some type of hydrologic calibration, be it graphical and/or statistical, for streamflow in a first rank. Validation results were also commonly reported. NSE, R^2, and PBIAS are the most widely used statistics. In the reviewed works, authors performed either manual or auto-calibration or both and SWAT-CUP (Abbaspour et al., 2007) was often employed for sensitivity analysis, calibration, and validation of the SWAT model. When judging the level of success of SWAT performance results, Moriasi et al. (2007) was often cited.

For instance, SWAT was used by Aouissi et al. (2014) to model water quality in the Tunisian Joumine catchment and compared monthly simulated flows to observed flows. The model performed well with very good NSE and R^2 values during both the calibration and validation periods. To evaluate SWAT hydrologic predictions, a wide range of other statistical analysis approaches have been considered in the studied publications. For example, in addition to NSE and R^2, Boskidis et al. (2012) used the following methods: scattergrams, the simple and the normalized root mean square error (RMSE and NRMSE), the normalized objective function (NOF), the mean error and the mean absolute error (ME and MAE), and the standard error of the estimate (SEE).

Choukri et al. (2020) obtained a good model performance based on visual and statistical (according to R^2, NSE, and PBIAS) evaluations between simulated and observed streamflow and sediment yield at the monthly time step. In another example, Martínez-Salvador and Conesa-García (2020) estimated NSE, RSR, and PBIAS indices to check whether SWAT can be applied to a semi-arid karst basin to predict water discharge and sediment loads. The monthly flow rate and sediment load showed good and acceptable results, respectively, and there was a notable improvement in the employed indices the annual time step, particularly during calibration. In the study of Napoli et al. (2017), SWAT also effectively simulated daily base, peak, and total runoff, scoring a very good performance.

Nevertheless, some discrepancies between simulated and observed results in SWAT calibration have been disclosed. In the study of De Girolamo et al. (2017b) for example, SWAT was able to reproduce streamflow in temporary rivers, but its performance under extremely low flow conditions was considered as a weak point. Kateb et al. (2020) indicated that SWAT succeeded in reproducing the hydrological cycle in the Beni Haroun dam drainage area (Algeria), but the calibration of the model using the observations on the liquid flow rates only was not sufficient, the model required a second calibration with observations on the solid flow rates.

Ouessar et al. (2009) confirmed that uncertainties in observed daily precipitation and streamflow rates are the main cause of deviation in the reproduction of the observed events by SWAT. Aouissi et al. (2018) indicated that the SWAT model performance was greatly affected by spatial rainfall variability and that the use of more input rainfall gauges does not necessarily imply more realistic SWAT predictions.

There were also some difficulties related to SWAT calibration for watersheds under Mediterranean conditions and characterized by high climate variability and extremely intense rainfall events. In Ramos et al. (2015a) study, the average soil water content, runoff, and sediment yield during moderately intense events were satisfactorily predicted by SWAT, but it was not the case for high-intensity events. Martinez-Casanovas et al. (2016) also stated that during high-intensity rainfall events, SWAT tends to overestimate runoff and peak discharge.

A SWAT simulation of monthly streamflow and monthly sediment yield performed by El-Sadek and Irevem (2014) resulted in respectively good and satisfactory NSE values for three land cover datasets during the calibration period. Several variables were used by Pulido-Velazquez et al. (2015) in order to calibrate SWAT, namely streamflow, groundwater recharge, crop yield, and nitrate leaching. These parameters were calibrated sequentially because of the inter-dependencies between constituents. This forms a good example of SWAT model calibration as the evaluated constituents were all considered during calibration and all available data were used in the calibration procedure. Simulated values of river discharge, crop yields, groundwater levels and nitrate concentrations fit well to the observed ones. SWAT performances in the study conducted by D'Ambrosio et al. (2020) varied from acceptable to very good, depending on the gauge and the calibrated variables (streamflow, total suspended solids, total nitrogen, and total phosphorus). They described obtaining a "relatively poor" SWAT performance as a commonly faced issue. This problem is particularly accurate for temporary streams, due to the intermittent natural flow and wastewater treatment plants discharge.

As a preliminary step for the calibration and validation of the SWAT model, the most sensitive parameters were often identified based on expert judgment or a sensitivity analysis. To evaluate how different parameters influence the predicted model outputs and further enhance calibration, many authors conducted SWAT sensitivity analysis procedures and reported their results. For instance, a sensitivity analysis performed by Licciardello et al. (2011) in an experimental Sicilian catchment revealed that SWAT was more sensitive to the potential evapotranspiration (PET) parameter than other parameters impacting surface runoff. The watershed's water balance was more realistically simulated by the Penman–Monteith method than by the other existing PET methods scoring NSE values superior to 0.75 in surface runoff simulation at the monthly time step during both calibration and validation. Mosbahi et al. (2014) also performed a sensitivity analysis for streamflow in the Sarrath River basin, a semi-arid Mediterranean catchment, and identified the most sensitive among eight selected parameters. This facilitated the calibration of hydrology which showed that SWAT accurately predicted runoff and performed well.

By conducting SWAT parameter calibration and uncertainty analysis using the GLUE approach, Sellami et al. (2016) showed that in dry periods hydrological parametric uncertainty became more important than climate model uncertainty. The comparison of different uncertainty analysis techniques such as SUFI-2, GLUE, and ParaSol revealed that SWAT forecasts are always affected by uncertainty and that uncertainty quantification is a challenging task. Sellami et al. (2013) strongly suggested the separation of each uncertainty source to improve hydrological modeling. Their study findings outlined that the prediction of uncertainty in SWAT is specific to the study watershed and depends on the uncertainty analysis method used.

Through analyzing the reviewed articles, it can be concluded that the SWAT model predictions accuracy are dependent on the quality of input data, the parameterization of the model, as well as the availability of monitoring data during the simulation periods for performing calibration procedures. A large number of the reviewed works relied only on streamflow for model calibration, mainly due to lack of other observed data. Many works highlight the importance of performing sensitivity analysis and how it facilitates the calibration task. Checking the water balance components during the calibration process to make sure that the predictions are reasonable for the study watershed was also recommended in several works. It is also noticeable that many studies report no explicit uncertainty analysis results emphasizing that future SWAT applications should focus more on this aspect.

SWAT studies on water resources

Water resources are vulnerable to a variety of problems. The reviewed studies exposed and discussed many of them such as water overuse, deterioration of water quality because of high pollutant loads and nonpoint source nutrient and pesticide transport, contamination of lakes, salinization of groundwater, reservoir siltation, etc. Some of the reviewed studies focused on groundwater only or surface water only and some considered both surface and ground water. Many papers also discussed the implications of certain land management practices and the effects of climate change on water availability.

SWAT was applied to Gallego-Cinca River system (Spain) within a ´ multi-model and multi-scenario framework to assess the long-term sustainability of water resources (Haro-Monteagudo et al., 2020). Milewski et al. (2020) used SWAT to assess the effect of climatic and human-induced changes on surface and subsurface water resources. In a study conducted by Carvalho-Santos et al. (2017), SWAT simulations revealed that under current climate conditions, the existence of a single reservoir is insufficient to solve the existing water supply shortages. Essenfelder and Giupponi, 2020 presented a novel approach coupling SWAT with machine learning to model watersheds under Interbasin Water Transfers. This made it possible to simulate both the hydrological processes and water flow that occur within the watersheds limits as well as the external hydraulic contributions.

Using an integrated SWAT-MODFLOW-MT3DMS model, Eshtawi et al. (2016) succeeded to quantify interactions between surface and ground water in quantity and quality under expanding urbanization. The integrated model also helped to investigate aquifer sustainability scenarios within the Gaza Strip boundary. By integrating SWAT with GROWA and FEFLOW in an experimental methodology for nitrate contaminant vulnerability analysis, Uhan et al. (2011) demonstrated that 31% of the most nitrate-vulnerable zones in Lower Savinja Valley case study (Slovenia) require groundwater nitrate mitigation. Ertürk et al. (2017) effectively integrated SWAT with the DRASTIC vulnerability assessment method to assess groundwater vulnerability to pollution risk for the Dalyan region located in southwestern Turkey. According to the results, there is a high risk of groundwater pollution in 46% of the study area, 62% of which consists of agricultural land.

SWAT's ability to simulate water quality was confirmed in many published studies from the Mediterranean region. For instance, a recent study conducted by Zettam et al. (2020) showed through SWAT simulations large amounts of nitrates embedded in the Algerian Tafna watershed.

Reservoirs and groundwater are both affected to a health threatening level of water pollution. Moreover, the Mediterranean Sea received large discharge of nitrates from the Tafna headwaters. Through SWAT simulations of nitrate pollution in an intensively irrigated watershed located in Spain, Sorando et al. (2019) suggested that irrigation water and nitrogen fertilizers dosing should meet crop requirements. Similarly, SWAT studies in Galvan et al. (2009) ´ and Galvan ´ et al. (2016) showed how huge loads of contaminants can be generated from acid mine drainage pollution by quantifying the huge metal loadings transported by the Odiel River (Spain) and identifying the source of half of total pollution.

Othman and Gueddari (2014) used SWAT to examine agricultural and human pollution in one of the tributaries of the Sidi Salem Dam Reserve (Tunisia) and revealed that the misuse of agricultural fertilizers resulted in concerning nitrate and phosphorus levels. Darwiche-Criado et al. (2017) also applied SWAT to model water flows and nitrate discharges in a Spanish irrigated agricultural area and demonstrated that both off-stream and in-stream wetlands can be suitable sinks for runoff contaminants.

The apportionment of nutrient loads carried to the Venice Lagoon was assessed by Azzellino et al. (2013) using SWAT demonstrating a significant contribution of external pollutant sources which are not affected by management measures. SWAT modeling also enabled the evaluation of the recovery time needed for groundwater recharge and results assumed that no measures are taken in the bordering watersheds to reduce the groundwater springs' nitrate concentrations. Brito et al. (2018) succeeded at implementing a reservoir model using input data obtained from SWAT, which further served to test the efficiency of management measures in reducing pollution in the actual reservoir.

SWAT studies on soil erosion and sedimentation

Soil erosion is a major concern in the Mediterranean region. Numerous examined research articles concentrated on estimating erosion, simulating sediment transport, and evaluating sediment deposition.

SWAT was used to identify and prioritize vulnerable lands to erosion in order to implement appropriate management interventions. Martinez-Casasnovas et al. (2012) for example estimated runoff and soil loss in a small Catalonian drainage area using SWAT and gave a detailed diagnostic of the different sediment sources.

Hallouz et al. (2018) applied GIS-integrated SWAT to a small agricultural Mediterranean watershed to simulate discharge and quantify erosion and estimated that the basin's average yearly total sediment was at 54.24 t ha^{-1}. In order to suggest measures to mitigate soil depletion, Ricci et al. (2018) also used SWAT to simulate runoff and soil loss in a typical Mediterranean drainage basin. They found that the largest sources of sediment were winter wheat and olive groves, and that deposition in channel flow is highest when there is an alluvial plain. Panagopoulos et al. (2019) implemented SWAT in a highly erodible Greek island with a typical Mediterranean climate and steep topography to estimate the soil loss vulnerability. The authors concluded that the island's high erosion vulnerability could be considerably reduced only in the case of integrating grazing management within a vegetation regeneration plan including reforestation.

Some weak erosion rates were also recorded in the Mediterranean region. Using SWAT soil erosion predictions, Mosbahi et al. (2013) demonstrated that a greater portion of the Tunisian Sarrath River basin was subject to low and moderate soil erosion risk, with only 10% of the watershed being susceptible to erosion. This finding suggests that variations in the type of land cover and gradient slope are the primary factors influencing erosion rates in different areas of the catchment. Bouslihim et al. (2020) also demonstrated by modeling the Mazer and El Himer watersheds (Morocco) using SWAT that all examined sub-basins displayed weak rates of soil loss.

Since dam siltation is a common problem in the Mediterranean region and particularly in the Maghreb area, several SWAT sedimentation studies exclusively treated this issue. SWAT was used for modeling the Moroccan N'fis basin with an aim to minimize the rate of siltation in Lalla Takerkoust dam (Markhi et al., 2019). The results showed that soil erosion brought on by deforestation is the primary factor contributing to the high sediment production.

SWAT was used by Boufala et al. (2019) to locate zones with very significant soil loss in the Upper Sebou watershed (Morocco), and it was revealed that the corresponding reservoir's estimated siltation rate was 2.12 Mm^3/year and the water erosion rates were judged to be low. The results of this study were validated by bathymetric surveys and the authors confirmed the model reliability in modeling Moroccan watersheds. Furthermore, Pacetti et al. (2020) applied SWAT to evaluate different scenarios of mine decommissioning, aiming at supporting the identification of the best strategies to avoid reservoir sedimentation and suggested that afforestation and river restoration lead to a strong reduction of sediment yield while a downward trend occurred for water yield.

SWAT accurately simulated the erosion regimes of the Arachtos catchment (Greece) and adequately quantified the reservoir impact on the river sediment yields (Panagopoulos et al., 2008). With the aid of SWAT, different scenarios for land use change were implemented in the study catchment to test out potential decreases in soil losses and sediment transport to the reservoir.

SWAT studies on the effects of land use change and/or climate change on hydrology and pollutant losses

Individually or in combination, land use/cover change and climate projection scenarios and their hydrologic and environmental effects are a very common category of applications in the reviewed articles. The SWAT was used for the simulation of past scenarios (so the weight of changes is better evaluated) and projected conditions (for future prediction) to effectively plan land use and develop appropriate mitigation measures.

Land use change scenarios

The impact of land use change on watershed processes is determined by the settings of the area, the type of change, its spatial distribution, and its extent. SWAT simulations conducted by Glavan et al. (2013) demonstrated that although the impact of land use changes over a period of about 220 years back in history on the total and green water in two Slovenian Mediterranean watersheds was statistically negligible, it had a significant impact on the seasonal flows. Through simulating water components for three urbanization scenarios using SWAT, Hamad et al. (2012) concluded that the response of the Gaza zone in terms of hydrology will be considerably impacted by land cover changes. SWAT was also employed by Aouissi et al. (2015) to quantify the great effects agricultural land use and practice changes had on the nitrate fluxes in the Joumine catchment (Tunisia). Sertel et al. (2019)'s SWAT application in a rapidly urbanizing Turkish watershed emphasized the considerable role that urbanization of agricultural area changes plays in hydrological dynamics.

Climate change scenarios

In the Mediterranean area, which is considered a "hotspot" for climate research, SWAT was used to model the hydrologic and environmental effects of historical climate patterns in comparison to climate change estimates. Many reviewed SWAT applications incorporated different climate change scenarios such as variations in temperature, evapotranspiration, and rainfall.

The first SWAT study in the Mediterranean region published in a peer-reviewed journal (Varanou et al., 2002) included simulations of six future climate scenarios that led to a drop in streamflow, an increase in flooding intensity for specific return periods, and an annual decrease of the nitrate loads to the waterbody. The application of SWAT to eighteen large Portuguese drainage basins helped simulate the gradual changes in climate variables and assess how these changes impact water resources, and plant and sediment yields (Nunes et al., 2008).

SWAT simulation results for the Upper Tiber watershed (Italy) predicted that future temperature and precipitation changes would cause significant reductions in water yield both annually and seasonally (Fiseha et al., 2014). Results from SWAT simulations in Pascual et al. (2015) suggested that the expected changes in climate at the end of the current century will significantly alter water supplies in Mediterranean watersheds. Glavan et al. (2015) applied SWAT to the Reka catchment (Slovenia) to simulate the impacts of six different climate change scenarios on hydrology and water quality. With few exceptions, results for the baseline and future climatic scenarios indicated an average rise in precipitation and an increase in average annual sediment loads by the end of the twenty-first century.

Paparrizos and Matzarakis (2017) concluded through simulating future climate change scenarios using SWAT that zones with Mediterranean conditions would be extremely vulnerable and that winter runoff is expected to face the most crucial reductions. Rodríguez-Blanco et al. (2016) used SWAT to evaluate the potential medium and long-term effects of projected changes in climate in a small rural Mediterranean catchment and found that suspended sediment would be noticeably affected. In comparison to a simulated historical period, the Greek Aracthos River basin's coupled SWAT-IAHRIS model was able to predict a future decrease in precipitation and flow as well as an increase in temperature (Lopez-Ballesteros et al., 2020´).

In the Mediterranean island of Crete, Nerantzaki et al. (2019) used a combination of Karst-SWAT and several climate change scenarios to predict declines in surface and karstic spring flows as well as a continuous rise in irrigation water demand and water scarcity throughout the projected period. Based on various configurations of global circulation and regional climate models, De Girolamo et al. (2017a) defined several scenarios of climate change. Under these settings, SWAT estimated a decline in blue water and total water yields as well as a change in the flow regime into drier conditions. According to SWAT results for an ungauged insular Mediterranean catchment (Afrouses basin, Greece), due to global changes in climate, the runoff will decline proportionally over the upcoming fifty years (Kalogeropoulos and Chalkias, 2013).

Some of the reviewed studies quantified the effect of anticipated changes in climate variables on the retention rate and lifespan of reservoirs. Using SWAT, Almeida et al. (2019) modeled the Montargil's basin reservoir (Portugal) under two climatic projections. According to their findings, there would be a future decline in reservoir inflows. A SWAT application by Rocha et al. (2020a) predicted that the water content of two Portuguese multifunctional reservoirs would decline due to the effect of climate change. Conversely, SWAT simulation for a set of climate change scenarios performed by Nerantzaki et al. (2016) predicted that siltation rate of the Kremasta dam (Greece) will only reach 6.1% in the year 2100, a proportion substantially lower than the reservoir dead volume.

SWAT allowed outlining the need to take measures in the Thau catchment (France) since simulating the hydrological budget in the context of climate change proved that current uses of water are incompatible with its local management and rather lead to additional vulnerabilities (La Jeunesse et al., 2015). By integrating SWAT with the Princeton Transport Code model, Gamvroudis et al. (2017) indicated that the alluvial plain of Sparta (Greece) is very sensitive to potential future climate changes.

Pulighe et al. (2021) used SWAT + to capture the possible alteration of hydrological components by future climate change in the Sulcis watershed, an agricultural semi-arid area located in Sardinia, Italy. SWAT + uses similar equations but offers more configuration flexibility, allowing a more realistic simulation of water bodies, landscape position, overland routing and floodplain processes. These improvements are expected to yield more accurate results in future applications.

Combined scenarios

The reviewed SWAT simulations of matched scenarios of land use and climate expose their cumulative effects on water supplies and pollutants export. For instance, Pisinaras et al. (2014) first employed SWAT for the identification, conceptualization, quantification, and simulation of the hydrological consequences of turning the agricultural land of the Vosvozis area (Greece) into photovoltaic parks. Dynamically downscaled climate forecasts for the period 2011–2100 were then used to model long-term repercussions. Results allowed to identify the hydrologic parameters that must be considered when locating photovoltaic parks. By applying SWAT to a humid Mediterranean catchment, Serpa et al. (2017) demonstrated that climate change can lead to a decline in nutrient and metal exports. They also showed that the latter highly depends on the land use change type and degree. Furthermore, combined scenarios heavily affected the export of pollutants.

Through a simulation of anticipated changes in water level by coupling SWAT to a Support Vector Regression model in Lake Beys¸ehir, which is the largest Mediterranea freshwater lake, Bucak et al. (2017) concluded that changes in climate have a more significant effect on the lake hydrology compared to land use. They also concluded that the ongoing intense water extraction may cause shallow lakes in the Mediterranean region to experience dramatic drought stress and lose their ecological value in the near future. These results were further investigated by Bucak et al. (2018). Recently, Choukri et al. (2020) projected using SWAT that the consequences of upcoming changes in climate and land use in the Tleta watershed (Morocco) will result in an annual reduction in both water and sediment yields.

A modified SWAT was applied to an intensively managed Mediterranean catchment to evaluate the hydrochemical response of karstic environments to scenarios of climate change and land use management (Nikolaidis et al., 2013). The study demonstrated that the land use change, which occurred in terms of intensity of use rather than composition, has a negative impact on the quality of surface and ground water and that the Koiliaris River basin has already been experiencing climate change impacts during the past fifty years. In a simulation of future conditions for four (climate change and land use) scenarios, SWAT allocated less water for irrigation, successfully accounting for the general water decline resulting from climate change (Ertürk et al., 2014). The results indicated a significant decrease in groundwater recharge and storage, with the agriculture sector being the main consumer of water.

Nunes et al. (2017) applied SWAT to a Mediterranean basin already affected by drought stress and indicated that most simulated future scenarios that involved individual changes in climate, socio-economic conditions, and a combination of both resulted in a decline in water availability. Stefanidis et al. (2018) simulated three future world climate and socio-economic scenarios which were developed as part of the MARS project using SWAT. The findings suggest that consequently to the rise of water temperature and the decrease in nutrient loadings, a decline in the average concentration of surface dissolved oxygen is to be expected.

SWAT studies on Best Management Practices (BMPs)

In several reviewed examples, SWAT proved to be a practical decision-making tool when targeting and implementing BMPs. These SWAT studies include spotting a watershed's critical areas requiring water and soil management and the investigation of its response to alternative management strategies.

In the 34 surveyed studies that applied SWAT to assess the effectiveness of BMPs, 7 articles addressed soil erosion reduction, 20 articles tackled nutrient loads reduction, 4 articles addressed both soil and pollutant losses reduction, and 3 studies implemented BMPs for improving irrigation efficiency. In all of these studies, the assessment of the effectiveness of BMPs was introduced after identifying critical source zones. In terms of soil erosion reduction, the most commonly assessed BMPs are contour farming, no tillage, reforestation, strip cropping, and terracing. Concerning nutrient loads reduction, targeted reduction of fertilizers application was the most assessed BMP. Furthermore, several studies assessed the cost-effectiveness of BMPs to identify optimal management strategies. Many SWAT applications highlighted the importance of combining different BMPs and targeting and prioritizing the most affected regions in the case of erosion for example.

Gikas et al. (2006) demonstrated that SWAT, when accurately validated, can be successfully employed to test different management scenarios in Mediterranean watersheds. SWAT results in the study of Lopez-Ballesteros et al. (2019) ´ showed that dam restoration is the most effective BMP at the El Beal watershed scale (Greece), followed by reforestation and that combined BMPs were the most effective. Malik et al. (2020) applied SWAT to a Spanish irrigated watershed and demonstrated that combined BMPs outperform their individual implementation in terms of benefits to the environment and farmers.

Based on regional agricultural policies, Ricci et al. (2020) used SWAT to implement four management scenarios in the Carapelle basin (Italy) and showed that contour farming and reforestation are the most effective erosion control strategies when combined. More recently, Ricci et al. (2022) further suggested that for the Carapelle watershed, contour farming and no tillage with a 20% reduction of fertilizers represented the best management alternative due to their efficiency in combatting soil and nutrient losses and their reduced farm-level production costs. Mosbahi and Benabdallah (2020) applied SWAT to assess the effectiveness of various land management practices in reducing runoff and erosion in the Sarrath catchment (Tunisia). They concluded that targeting the prioritized sub-catchments and combining different practices resulted in greater reductions than their individual implementation.

Briak et al. (2019) demonstrated through SWAT simulations of the top three useable agricultural BMPs that measurements performed by the contouring are inappropriate for the Kalaya River basin (Morocco) as they have rather increased erosion rates. They also concluded that terracing followed by strip-cropping was the most effective at reducing soil loss at the watershed level.

Mtibaa et al. (2018) used SWAT to identify critical sediment source areas in the Joumine catchment (Tunisia) and investigate the effectiveness of different BMPs in reducing sediment yield. The model results indicated that the cultivated upland area is the primary source of sediment and showed that adequately combining BMPs leads to the most economically beneficial reductions in sediment yield. SWAT was used in the agricultural Nif basin (Turkey) to assess the effects of using vegetated filter strips as nitrogen and phosphorus retention BMPs (Elçi, 2017). SWAT results obtained by Ben Khelifa et al. (2017) confirmed the effectiveness of local terraces, installed on approximately 50% of the Sbaihia watershed (Tunisia), since they decreased surface runoff and sediment yield, limiting thereby the sedimentation of the hill lake.

Bouraoui et al. (2005) used SWAT to investigate the potential impact of land management scenarios on a Mediterranean catchment that is under intensive agriculture and rapidly increasing irrigation. They predicted that increasing the extent of the irrigated area and increasing accordingly the fertilization rate would not lead to a problematic degradation of surface water quality. It was also suggested that a drastic reduction in the load of ammonium and phosphorus could be achieved by treating wastewater from major urban areas. Aouissi et al. (2014) and Malago et al. (2019) ` applied SWAT to test the effectiveness of different agricultural nitrogen reduction BMPs. Panagopoulos et al. (2013) integrated SWAT with a decision support tool to serve as the nonpoint source pollution estimator which enabled the identification of a low cost, and possibly more favorable, compared to previous findings (e.g., Panagopoulos et al., 2011c), combination of BMPs that ensures good quality of river water. Panagopoulos et al. (2014a) made use of SWAT's ability to optimize the cost-effectiveness of landscape approaches to create an effective decision support tool that could recommend the best location for installing irrigation BMPs in a Greek basin with a limited supply of water (Pinios River Basin).

Dechmi and Shiri (2013) tested twenty BMPs scenarios using SWAT-IRRIG in Del Reguero watershed (Spain) and quantified their effects on total suspended sediment, irrigation return flows, and phosphorus yields at the outlet, as well as their economic impacts on crop gross margin. SWAT was also used in a Mediterranean vineyard production area to model soil and nutrient in scenarios in the presence and absence of soil conservation practices for years with different characteristics (Ramos et al., 2015b).

3.6. SWAT studies on environmental risks

Several reviewed papers focused on risk prevention by examining past natural catastrophe scenarios and evaluating the risk management measures through simulating different hypothetical hazard scenarios.

Brouziyne et al. (2020) combined SWAT with meteorological and hydrological drought indices to predict dry years during two future periods in the Moroccan Bouregreg basin, a typical Mediterranean watershed. They noticed that hydrologic systems within ocean or high-altitude influenced sub-watersheds are less vulnerable to drought. In Strohmeier et al. (2020), surface runoff and drought assessment were conducted at Oum Er Rbia watershed and Moroccan country scale. For that, they employed SWAT, as a detailed watershed model, to validate simulation results obtained from linking EO (Earth Observation) products with a global water balance model (PCR-GLOBWB). The study revealed that EO data and PCR-GLOBWB enable the satisfactory simulation of surface runoff spatio-temporal patterns even without the use of in-situ data for calibration. In addition to using streamflow gauges, validation was performed through the spatial overlay with SWAT results.

SWAT was used to model historic floods in a semi-arid intermittent flow watershed from the available rainfall data and succeeded in estimating the frequency of hazardous floods and at identifying the dominant flood type in the basin (Tzoraki et al., 2013). Busico et al. (2020) employed a general approach based on SWAT for flood management that can be adopted in highly anthropized small Mediterranean catchments. The authors considered, among the model's outputs, SURQ which is the surface runoff contribution to streamflow during the time step for four years of simulation. The obtained values were after that reclassified into five qualitative classes using the geometrical interval mostly employed to spatially represent environmental parameters. The method is promising as its application for the Aspio basin (Italy) successfully identified the highly runoff-prone sub-basins.

Boithias et al. (2017) results showed that SWAT, although constrained by rainfall and soil data, properly simulated peak discharge, and timing and volume of floods. Thereby, the authors concluded that SWAT seems to be a trustworthy model to simulate discharge in large basins with frequent flash floods over extended time periods and flash floods. The results found by Jodar-Abellan et al. (2019) from s SWAT simulation for five Mediterranean ravine watersheds highlighted the need for an enhanced risk perception against flash floods effects as changes in land uses, particularly large urbanization, increased flash flood risks in the study basins.

SWAT was used to predict water balance components to evaluate the potential hydrological effect of hypothetical forest fires in a Mediterranean basin located in Greece (Batelis and Nalbantis, 2014). Three scenarios of typical Mediterranean forest fires were constructed, and their effects were quantified. Carvalho-Santos et al. (2019) demonstrated that time series of satellite indices can be employed "to inform SWAT about vegetation growth and post-fire recovery processes".

The number of SWAT applications in assessing drought, flood, and wildfire risks is limited in the Mediterranean region.

4. FURTHER INSIGHTS ON THE REVIEWED PUBLICATIONS

This section discusses SWAT studies that compare watershed responses, the SWAT model comparison to other models, its integration or coupling with other tools and techniques, innovative model modifications and improvement, and the effects of inputs on SWAT outputs.

SWAT helped identify similarities and heterogeneities among hydrologic systems by running the same scenarios in different contexts in terms of climatic setting, hydrologic regime, presence of gauges, scale, and watershed physical features. Table 2 lists some examples of studies that applied SWAT in relatively different contexts to either test its performance, prove the utility of regionalization when facing data availability issues, or demonstrate that land use and climate change effects are specific to the study case.

Table -2:Examples of reviewed SWAT studies comparing different catchment simulations

Criteria	Study	Watersheds/Regions	Outline
Climate	Jimeno-Saez ´ et al. (2018)	Ladra (Atlantic climate) and Segura (Mediterranean climate)	Applying SWAT in watersheds with contrasting climates allowed checking its accuracy under different climatic conditions. SWAT was better at estimating streamflow when the climate was more humid.
	Mourad et al. (2019)	Laou watershed (Northern Morocco): extends over the Mediterranean sub- humid and the semi-arid climates	SWAT model performs well at modeling the portioning of rainfall in the Mediterranean sub-humid and the semi-arid climatic settings.
	Nunes et al. (2008)	18 large watersheds in two Portuguese contrasting regions: Alentejo (semi-arid climate) and Ribatejo (transitional between sub-humid and humid climates)	Mediterranean watersheds with different climates are vulnerable to climate change in terms of water supplies, vegetation growth, and soil loss (especially subsurface runoff).
	Panagopoulos et al. (2011b)	Greek Ali Efenti (Mediterranean climate) and Norwegian Vansjø-Hobølv (typical Scandinavian cold climate)	Differences in geoclimatic conditions should be taken into account when addressing nutrient-related water quality problems.
	Paparrizos and Matzarakis (2017)	Ardas (humid continental climate conditions), Sperchios (Mediterranean conditions with milder mountainous conditions) and Geropotamos (Mediterranean conditions)	Regions under continental climate conditions will be more resistant to projected climate changes than areas with Mediterranean climate.
	Pascual et al. (2015)	Fluvia and Tordera ` (humid) and Siurana (semi-arid)	At the end of the current century and due to the projected changes in climate, Mediterranean watersheds will be dramatically altered, with more pronounced impacts on drier catchments.
	Serpa et al. (2015)	Sao Lourenço ˜ (Mediterranean humid) and Guadalupe (Mediterranean dry)	The catchment's current climate context determines how changes to the land use and climate will affect its hydrology and erosion.
Hydrologic Regimes	Sellami et al. (2016)	Thau (Southern France; groundwater is important because of the presence of the karstic system) and Chiba (Northeastern Tunisia; the hydrologic regime totally depends on surface water contribution)	Watershed characteristics and flow seasonality condition the projected magnitudes of alteration induced by climate change and their associated uncertainty.
Gauged	Bouslihim et al.	Mazer (gauged) and El Himer	Regionalization methods

International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

and ungauged	(2020)	(ungauged)	can be used in physically proximate watersheds with similar characteristics.
	Sellami et al. (2014)	6 gauged and 4 ungauged French watersheds draining to the Thau Lagoon	The prediction of discharge at ungauged watersheds is possible through the regionalization of the SWAT parameters, but its uncertainty is directly proportional to the distance separating the donor and the receptor watersheds.

Seventy out of the 260 studies included in this review either combine or/and compare SWAT with other models or methods. Several SWAT couplings and integrations demonstrated the strength of using combined modeling (Table 3). Comparing SWAT to other models or methods helped highlight its strengths, underscore its limitations, and consequently suggest strategies to overcome them (Table 4).

SWAT coupled/	Study	Study outline
3D Lagoon Model	Plus et al. (2006)	The hydrodynamical-ecological model was forced using SWAT outcomes to estimate the relative relevance of nitrogen sources and assess the impacts of various climatic variables on the primary productivity of the Thau lagoon.
ANN	Essenfelder and Giupponi (2020)	Not only was SWAT-ANN able to accurately replicate the water balance of the study watershed, but it significantly improved SWAT's hydrological modeling performance in a challenging setting.
Aquatool	Haro-Monteagudo et al. (2020).	Coupled Aquatool and SWAT was used to the largest irrigated system in the EU to assess water resource management process and the results highlighted the need to implement further climate adaptation measures.
AQUATOX	Pesce et al. (2019)	Coupled SWAT and the ecological model AQUATOX was used to explore how coastal aquatic ecosystems are impacted by climate change.
Biotic indicators	Segurado et al. (2018)	The potentialities of coupling process-based modeling with empirical modeling was demonstrated by a applying this combination to a Mediterranean water-scarce and diffuse pollution-prone system and showed that the biotic state is significantly affected by agriculture and nutrient enrichment.
CMB method	Choukri et al. (2020)	Since interbasin groundwater flow (IGF) is so challenging to identify and quantify, most hydrological models conveniently ignore it. In highly permeable bedrock watersheds receiving IGF, SWAT and the Chloride Mass Balance (CMB) approach were coupled to enhance streamflow modeling.
CMM	Kaffas et al. (2018)	SWAT and the Composite Mathematical Model (three sub- models of rainfall-runoff, soil erosion and stream sediment transport) were used to continuously simulate hydromorphological processes (hydrologic, soil erosion and streambed erosion processes) at the basin scale.

Given the fact that the digital elevation model, land use/land cover, soil and weather data are important representatives of major drivers of the processes simulated by the SWAT model, research works assessing the impact of these inputs on simulations are receiving more attention in the Mediterranean region (Table 5). Better input resolution does not necessarily yield more accurate results and better model performance. Although the model outputs in some cases are judged more accurate when using finer input resolutions (e.g., Rocha et al., 2020b), it is not a general rule as evidenced by Busico et al. (2020) for instance.

Several reviewed studies included SWAT adjustments and/or innovative strategies to improve its performance under specific conditions:

- Ouessar et al. (2009) adjusted and applied SWAT (dubbed "SWAT-WH") to a dry Mediterranean catchment by incorporating water-harvesting systems and modifying the crop growth processes. They indicated that the evaluation coefficients for calibration and validation confirmed the model's reasonable reproduction of the observed events.

Dechmi et al. (2012) modified the SWAT2005 version to correctly simulate the main hydrological processes in a watershed where irrigation is intense, and its source is outside of the drainage boundary. Streamflow and total phosphorus loads were accurately simulated by the "SWAT-IRRIG" model.

- Nikolaidis et al. (2013) modified SWAT to model karstic systems' hydrochemical response and demonstrated, using high-frequency monitoring data, its ability to detect the temporal variability of surface runoff and karst flow. The modified tool was also used to evaluate the effects of land use management and climate change on a highly managed Greek catchment.
- Abouabdillah et al. (2014) innovatively used the existing technical capabilities of SWAT, by modeling large dams,

small dams, and contour ridges as reservoirs, ponds, and potholes, respectively.

Galvan et al. (2014) ´ carefully revised the estimation of rainfall in SWAT. Their results showed that SWAT does not reflect realistically the spatial distribution of rainfall in the basin as it tends to overestimate lower daily precipitation and to underestimate more intense rainfall. They suggested a new methodology for better presenting orographic precipitation's distribution in time based on multiplying the recorded precipitation by a ratio, instead of adding a constant amount to the daily precipitation. After simulation, the deviation of runoff volume using the proposed approach was appreciably lower than that obtained with SWAT. Although the applicability of the introduced methodology is still to be verified for complex basins, the estimation of precipitation can be improved by including the proposed procedure in SWAT's source code.

- Napoli and Orlandini (2015) introduced an improved ArcSWAT2009 sub-model ("SWAT-GC") that, compared to the standard SWAT calibrated in situ, provided very good predictions of average daily runoff and soil and nutrient loss during calibration and validation periods. The sub-routine was used to perform daily growth models of both tree and grass covered areas was used in order to evaluate the soil ground cover, the soil water balance, and residue effects on daily water runoff, as well as sediment, N, and P runoff yields. Multiple modifications were introduced in terms of canopy height, leaf area index, residues left after harvesting, etc. SWAT-GC was capable of adequately modeling differences in nutrient yields between the different tillage practices by only calibrating crop growth, runoff, and sediment yields. Daily performance of the standard SWAT model was unsatisfactory during validation, whereas the SWAT-GC model provided very good predictions of average daily runoff and soil and nutrient loss during both the calibration and validation periods.

- Meaurio et al. (2015) included field data obtained from electrical conductivity, uncommonly used in model calibration, in the process in order to obtain a more realistic hydrological simulation. Satisfactory simulation of outlet-discharge and sub-watersheds contribution was achieved. The model-field combined approach performed well and allowed detecting spatial–temporal uncertainties.

- Ozdemir and Leloglu (2019) developed a software package ("FACT"), built on SUFI-2, that works on SWAT to decrease the computational complexity and improve the calibration procedure performance. Results showed improved statistical indexes (i.e., R^2, NSE, p-factor, and r-factor) values. Moreover, the new calibration methodology took a shorter time compared to SWAT-CUP with minimum user involvement.

Samarinas et al. (2020) introduced the first insights into achieving annually revised and accurate parameterization of SWAT through the model synergy with deep learning classification algorithms.

SWAT compared to	Study	Comparison outcomes
AnnAGNPS	Abdelwahab et al. (2018)	With a higher gap between simulated and observed sediment load for AnnAGNPS, the two models tended to underestimate sediment load in very wet periods and to overestimate sediment load in the dry season. The setting up of SWAT requires a large set of inputs and more time and its calibration requires a specific knowledge.
ANNs	Demirel et al. (2009)	The ANN models better predicted peak flow than SWAT, although the mean squared error was better in SWAT results.
	Jimeno-Saez et al. ´ (2018)	Daily streamflow modeling by SWAT and ANNs was judged as generally good. Lower flows were better estimated by SWAT, whereas higher flows were better simulates by ANNs.
CATHY, TOPKAPI, tRIBS and WASIM	Perra et al. (2018)	The analysis reflected the major differences between the structures of five hydrologic models. For example, CATHY, TOPKAPI, and tRIBS offer a representation of both vertical and lateral subsurface flow, while SWAT and WASIM provide thorough treatment of vegetation processes.
MARINE EveNFlow, NL-CAT and TRK	Boithias et al. (2017)	Although constrained by soil and rainfall data, both SWAT and MARINE were capable of reproducing peak discharge, and the timing and volume of flooding. SWAT proved to be reliable in terms of discharge modeling even in large scale watersheds and in the presence of flash floods.
	Silgram et al. (2009a)	When predicting river flows, and subannual nitrogen and phosphorus concentrations and loads, the four models generally performed satisfactorily. Discrepancies between measured and predicted values were mostly attributed to constraints in input data (e.g., weather in the Italian Enza watershed).

Type of input data	Study	Compared values	Effect on SWAT outputs
DEM	Rocha et al. (2020b)	3 DEM resolutions (1 m, 10 m and 30 m)	Using different DEM resolutions led to noticeable differences in the hierarchy, length, and total number of channels. The simulations revealed that model performance gradually declined as DEM resolution increased. Intense rainfall events are better modeled by SWAT when employing high resolution DEM, whether prior to or post calibration.
Land Use/ Land Cover	El-Sadek and Irevem (2014)	- COR INE; CLC2006 - GLCC - GlobCover	Simulations of monthly streamflow and sediment in the Seyhan River basin showed relatively minor sensitivity of SWAT to different land cover datasets varying in terms spatial resolution and time periods.
Soil	Azimi et al. (2020)	SMA Enhanced L3 Radiometer Global Daily 9 km EASE-Grid Advanced SCATterometer (ASCAT) H113 A fused ASCAT/ Sentinel-1 satellite	The assimilation of these three different satellite soil moisture products into SWAT via the Ensemble Kalman Filter (EnKF) showed a general improvement of SWAT daily discharge simulations for all products in terms of error and NSE.

5. ACHIEVEMENTS, CHALLENGES, AND FUTURE RECOMMENDATIONS

General insights on the current SWAT modeling status in the mediterranean region

Mediterranean watersheds have diverse aspects such as mountainous to plain topographies, humid to arid climates, agricultural to urbanized land uses, different soil compositions, etc. Hence, only a flexible modeling tool can be adequately applied to many of them. The SWAT performance results in the reviewed studies as well as its recurrent use in the same catchments or by the same modelers is evidence of its reliability for watershed modeling in different settings.

Mediterranean catchments form a research hotspot for climate change and/or land use change impacts on hydrology and the environment as attested by the many examples of SWAT applications. Mediterranean watersheds are expected to be extremely vulnerable to future climate change. A reduction in water resources due to anthropogenic and climatic pressures is anticipated in many studies.

Comparing the SWAT model results for different watersheds (in terms of size, climate setting, etc.) or for the same watershed (in different simulation periods, with different input data, by different research teams, etc.) helps to identify regional patterns and tendencies and allows the identification of uncertainty origins to enhance the model performance. Similarities between catchments can allow hydrological responses transference from gauged to ungauged basins.

Opting for SWAT combination with other models and techniques can reduce uncertainties and lead to satisfactory results for different applications even under difficult settings.

It is noticeable how only very few studies have been conducted exclusively on crop management even though the Mediterranean region beholds a huge amount of agricultural lands (e.g., De Girolamo et al., 2010; Nkwasa et al., 2022; Panagopoulos et al., 2012; Udias et al., 2018). Modelers should take advantage of SWAT's ability to simulate crop yields.

Mediterranean catchments exhibit extremely diverse responses over time and space, inducing hydrological modeling difficulties and introducing prediction uncertainties.

Differentiating the northern and southern Mediterranean regions might help pinpoint further tendencies since these sub-regions reflect more common points and less contrast in natural features and in development indexes. The number of SWAT studies which is much higher in the northern regions highlighting how southern regions are lacking in terms of SWAT applications. This can be mainly due to model promotion, data availability, and financial support.

SWAT was successfully used in multiple data-scarce reviewed study cases. Panagopoulos et al. (2011a) used SWAT to identify high risk areas of pollution in a data scarce catchment for management planning. They performed a justified SWAT parameterization and suggested a guided limited data exploitation for modeling without neglecting possible deficiencies. Abouabdillah et al. (2014) demonstrated that SWAT is still useful for understanding hydrological processes, even in the case of observed data scarcity. Sellami et al. (2014) and Bouslihim et al. (2020)

applied regionalization methods by transferring SWAT parameters from the gauged to the ungauged watersheds. Ben Khelifa et al. (2021) transferred Bench Terrace parameter from an experimental catchment to another catchment lacking monitoring data using SWAT. The transfer can be judged successful as NSE for daily runoff in the receiver watershed went from negative to 0.5.

SWAT can be used to fill the data gaps. Data shortcomings existed in all types of datasets and the various assumptions and gap filling approaches varied.The model can be used to create sets of simulated hydrological data. Astudy by Esen and Hein (2021) showed how the gaps in critical data for water accounting development can be filled using SWAT case-specific outputs. In order to accurately estimate the metal loadings in the Odiel watershed (Spain), Galvan et al. (2016) ´ also used SWAT to address the lack of gauging stations in the study area.

In terms of technical limitations, Panagopoulos et al. (2014b) related potential limitations in the cost-effectiveness predictions to SWAT outputs being sensitive to the schematization of the catchment and its division into sub-basins or to SWAT routines for the simulation of irrigation conveyance efficiency having still bugs/errors preventing the "direct" representation of water losses in some situations for example.

Many of the reviewed works only relied on streamflow for SWAT performance assessment even when it is not the component of interest. For instance, Chaponniere et al. (2008) ` implemented SWAT for the complex semi-arid mountainous Rehraya watershed (Morocco) and concluded that it is not sufficient to only consider simulated and observed streamflow comparison in model performance assessment, particularly in the case of parameter intercorrelation. During the calibration procedure, all available data should be considered and the parameters related to the evaluated constituents should be calibrated sequentially because of the constituents' inter-dependencies.

The problem of data availability is not Mediterranean-specific, all previous global sub-regional SWAT reviews mentioned this issue and suggested strategies to relatively overcome it. Similarly to most of watershed-scale complex models, SWAT is comprehensive in terms of set up data and calibration measured field data. Many reviewed publications reported issues relating to data quality and quantity that influenced the modeling results to various degrees. For example, Conan et al. (2003) reported that the details of some hydrologic processes were not adequately represented by SWAT due to a lack of rainfall information. The SWAT in Bouraoui et al. (2005) was rather successful in reproducing water flow, however the limited detailed rainfall data availability and the lack of information on reservoir management degraded the quality of the simulation. In the case of the Italian Enza catchment, the precipitation stations were located at relatively low altitudes, which contributed to under estimations of rainfall, and therefore, of flow (Silgram et al., 2009a). In another example, De Girolamo et al. (2010) specified that measured data scarcity during the main runoff events did not allow an in-depth evaluation of the model performance in predicting nutrient loads during these events. De Girolamo and Lo Porto (2012) were unable to carry out a case-specific flow calibration because of insufficient streamflow data in the case of the Rio Mannu catchment. Specific strategies were employed to generate model parameters' estimates in the absence of flow data. The authors developed and tested a regional parameter estimation methodology to calibrate hydrological processes based on the transposition of a parameter set from a gauged catchment located in the same region. To generate flow rates, they considered the results of a series of previous studies.

Future SWAT research challenges in mediterranean catchments

Modeling large-scale Mediterranean watersheds: the spatial and temporal heterogeneities in the entire region makes large scale watershed modeling difficult, but this would provide a common framework for studying the hydrological behavior of watersheds and further enhancing regionalization strategies. For example, in Pagliero et al. (2019), four variants of the similarity-based regionalization approach for large-scale model (a 736 780 km^2 Western European drainage area) applications were compared using SWAT.

Improving data availability for SWAT modeling: improving the model performance can be achieved through the acquisition of new data with spatio-temporal characteristics. The implementation of long-term environmental stations and dense networks of rainfall and streamflow gauges can help to improve measuring flash flood occurrences, droughts, long-term changes in land use and climate. Other promising data sources include Radar and remote sensing approaches (e.g., Chaponni`ere et al., 2008; Rocha et al., 2020b). Machine learning models and deep learning methods can also be very useful. Coupling the SWAT with these techniques can be practical in case of data scarcity and under complex environments (e.g., Essenfelder and Giupponi, 2020; Samarinas et al., 2020). Being specific and detailed in reporting the tools, code and datasets used for hydrological modeling is very important to achieve reproducible models. Spotting commonly used data sources and evaluating their reliability in Mediterranean catchments is needed to accurately simulate their hydrological behavior.

A comparison of data from different Mediterranean basins can contribute to develop a standardized protocol. Sharing data and research collaborations can be a step forward in enhancing data availability for SWAT applications in Mediterranean watersheds.

6. CONCLUSIONS

Due to their unique features, Mediterranean watersheds require suitable and specific modeling methodologies and adaptive management strategies. These cannot be simply transposed from studies conducted in other regions of the world. The Soil and Water Assessment Tool (SWAT) proved to be adaptive and flexible enough to simulate various Mediterranean watersheds hydrologic and environmental processes.

This paper presented the main applications and challenges involved in modeling watersheds using the SWAT model in the Mediterranean region through a comprehensive review of literature. The reviewed SWAT applications showcase the model's adaptability to different temporal and spatial scales, its interdisciplinary capacities, its versatility, its combination feasibility, and its robustness as a watershed modeling tool.

This review therefore highlights the SWAT model's contribution to develop a comprehensive knowledge of Mediterranean watersheds' specific features and to better understand their behavior under dynamics driven by internal and external factors. More SWAT studies of Mediterranean watersheds can be expected as the reviewed literature offers evidence of the utility of the SWAT model to assess and solve a variety of scientific, economic, and environmental concerns in the rapidly changing Mediterranean region.

REFERENCES

[1] Abdelwahab, O.M.M., Ricci, G.F., De Girolamo, A.M., Gentile, F., 2018. Modelling soil erosion in a Mediterranean watershed: comparison between SWAT and AnnAGNPS models. Environ. Res. 166, 363–376. https://doi.org/10.1016/j.envres.2018.06.029

[2] Akoko, G., Le, T.H., Gomi, T., Kato, T., 2021. A review of SWAT model application in Africa. Water 139, 1313. https://doi.org/10.3390/w13091313.

[3] Bouraoui, F., Benabdallah, S., Jrad, A., Bidoglio, G., 2005. Application of the SWAT model on the medjerda River Basin (Tunisia). Phys. Chem. Earth 30, 497–507. https://doi.org/10.1016/j.pce.2005.07.004.

[4] Brouziyne, Y., Abouabdillah, A., Bouabid, R., Benaabidate, L., 2018. SWAT streamflow modeling for hydrological components' understanding. J. Mater. Environ. Sci. 9, 128–138. https://doi.org/10.26872/jmes.2018.9.1.16.

[5] Candela, A., Freni, G., Mannina, G., Vivianiet, G., 2012. Receiving water body quality assessment: an integrated mathematical approach applied to an Italian case study. J. Hydroinf. 14, 30–47. https://doi.org/10.2166/hydro.2011.099.

[6] Choukri, F., Raclot, D., Naimi, M., Chikhaoui, M., Nunes, J.P., Huar, F., et al., 2020.Distinct and combined impacts of climate and land use scenarios on water availability and sediment loads for a water supply reservoir in northern Morocco. Int. Soil Water Conserv. Res. 8, 141–153. https://doi.org/10.1016/j.iswcr.2020.03.003.

[7] D'Ambrosio, E., Ricci, G.F., Gentile, F., De Girolamo, A.M., 2020. Using water footprint concepts for water security assessment of a basin under anthropogenic pressures. Sci. Total Environ. 748, 141356 https://doi.org/10.1016/j.scitotenv.2020.141356.

[8] Darwiche-Criado, N., Comín, A.F., Masip, A., Garcíaet, M., Eismann, S.G., Sorando, R., 2017. Effects of wetland restoration on nitrate removal in an irrigated agricultural area: the role of in-stream and off-stream wetlands. Ecol. Eng. 103, 426–435. https://doi.org/10.1016/j.ecoleng.2016.03.016.

[9] De Girolamo, A.M., Lo Porto, A., 2012. Land use scenario development as a tool for watershed management within the Rio Mannu Basin. Land Use Pol. 29 (3), 691–701. https://doi.org/10.1016/j.landusepol.2011.11.005

[10] De Girolamo, A.M., Lo Porto, A., 2020. Source apportionment of nutrient loads to a Mediterranean river and potential mitigation measures. Water 12 (2), 577. https:// doi.org/10.3390/w12020577.

[11] Efthimiou, N., 2018. Hydrological simulation using the SWAT model: the case of Kalamas River Catchment. J. Appl. Water Eng. Res. 6, 210–227. https://doi.org/10.1080/ 23249676.2016.1265471.

[12] El-Sadek, A., Irevem, A., 2014. Evaluating the impact of land use uncertainty on the simulated streamflow and sediment yield of the Seyhan River basin using the SWAT model. Turk. J. Agric. For. 38, 515–530. https://doi.org/10.3906/tar-1309-89.

[13] Elçi, A., 2017. Evaluation of nutrient retention in vegetated filter strips using the SWAT model. Water Sci. Technol. 76, 2742–2752. https://doi.org/10.2166/wst.2017.448

[14] Fader, M., Giupponi, C., Burak, S., Dakhlaoui, H., Koutroulis, A., Lange, M.A., et al., 2020. Water. In: Guiot, J., Marini, K. (Eds.), Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First

[15] Juma, L. A., Nkongolo, N. V., Raude, J. M., & Kiai, C. (2022). Assessment of hydrological water balance in Lower Nzoia Sub-catchment using SWAT-model: towards improved water governance in Kenya. *Heliyon*, *8*(7), e09799.Shivhare, N., Dikshit, P. K. S., & Dwivedi, S. B. (2018).

[16] Lirong, S., & Jianyun, Z. (2012). Hydrological response to climate change in Beijiang River Basin based on the SWAT model. *Procedia Engineering*, *28*, 241-245.Darbandsari, P., & Coulibaly, P. (2020).

[17] Mediterranean Assessment Report [Cramer W. Union for the Mediterranean, Plan Bleu, UNEP/MAP, 2020, Marseille, France, p. 57 (in press). https://www.medecc.org/wp-content/uploads/2020/11/MedECC_MAR1_3_1_Water.pdf.

[18] Mtibaa, S., & Asano, S. (2022). Hydrological evaluation of radar and satellite gauge-merged precipitation datasets using the SWAT model: Case of the Terauchi catchment in Japan. *Journal of Hydrology: Regional Studies*, *42*, 101134.Guug, S. S., Abdul-Ganiyu, S., & Kasei, R. A. (2020).

[19] Ouessar, M., Bruggeman, A., Abdelli, F., Mohtaret, R.H., Gabriels, D., Cornelis, W.M., 2009. Modelling water-harvesting systems in the arid south of Tunisia using SWAT. Hydrol. Earth Syst. Sci. 13, 2003–2021. https://doi.org/10.5194/hess-13-2003- 2009.

[20] Ozdemir, A., Leloglu, U.M., 2019. A fast and automated hydrologic calibration tool for SWAT. Water Environ. J. 33, 488–498. https://doi.org/10.1111/wej.12419.

[21] Pacetti, T., Lompi, M., Petri, C., Caporali, E., 2020. Mining activity impacts on soil erodibility and reservoirs silting: evaluation of mining decommissioning strategies. J. Hydrol. 589, 125107 https://doi.org/10.1016/j.jhydrol.2020.125107.

[22] Perez-Valdivia, C., Cade-Menun, B., & McMartin, D. W. (2017). Hydrological modeling of the pipestone creek watershed using the Soil Water Assessment Tool (SWAT): Assessing impacts of wetland drainage on hydrology. *Journal of Hydrology: Regional Studies*, *14*, 109-129.Vilaysane, B., Takara, K., Luo, P., Akkharath, I., & Duan, W. (2015).

[23] Vilaysane, B., Takara, K., Luo, P., Akkharath, I., & Duan, W. (2015). Hydrological stream flow modelling for calibration and uncertainty analysis using SWAT model in the Xedone river basin, Lao PDR. *Procedia Environmental Sciences*, *28*, 380-390

[24] Worldmeter, 2022. Data based on the latest United Nations population division estimates. Countries in the world by population. https://www.worldometers.info/po pulation/. (Accessed 7 April 2022).

[25] Xoplaki, E., Gonzalez-Rouco, J.F., Luterbacher, J., 2004. Wet season Mediterranean precipitation variability: influence of large-scale dynamics and predictability. Clim. Dynam. 23, 63–78. https://doi.org/10.1007/s00382-004-0422-0.

[26] Yen, H., Park, S., Arnold, J.G., Srinivasan, R., Chawanda, C.J., Wang, R., et al., 2019. IPEAT+: a built-in optimization and automatic calibration tool of SWAT+. Water 11 (8), 1681. https://doi.org/10.3390/w11081681.

[27] Zettam, A., Taleb, A., Sauvage, S., Boithias, L., Belaidi, N., Sanchez-Perez, J.M., 2020. Applications of a SWAT model to evaluate the contribution of the Tafna Catchment (north-west Africa) to the nitrate load entering the Mediterranean Sea. Environ. Monit. Assess. 192, 510. https://doi.org/10.1007/s10661-020-08482-0.