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From SWAT to Hybrid SWAT+: A Conceptual Review of the Evolution of Watershed Modelling towards AI-Enhanced Environmental Informatics

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Abstract

The escalating complexity of global water resource challenges driven by climate change, land-use transformation, and intensifying anthropogenic pressures has reinforced the strategic importance of physically based hydrological models as critical decision-support tools. This review synthesises the conceptual evolution of the Soil and Water Assessment Tool (SWAT), tracing its transition from a subbasin-centric, file-based architecture to the modular, object-oriented environmental informatics framework of SWAT+. Central to this evolution is the replacement of proprietary MS Access databases with open-source SQLite and the introduction of Landscape Units (LSUs), which improve spatial representation by organising Hydrologic Response Units (HRUs) within geomorphologically meaningful landscape hierarchies. Global evaluations indicate that SWAT+ generally provides improved hydrological performance over legacy SWAT, particularly in representing spatial connectivity and baseflow processes, although challenges remain in small headwater catchments and arid regions. Beyond reviewing this technological evolution, the principal contribution of this article is the development of a conceptual Hybrid SWAT+ Modelling Framework. The proposed framework integrates the physically based modelling core with artificial intelligence and real-time environmental data across three complementary levels: pre-processing for input enhancement, in-simulation via rule-based decision tables, and post-processing for residual correction. By addressing parameter non-stationarity while preserving mass balance and process interpretability, this hybridisation enables adaptive learning under changing environmental conditions. The proposed framework provides a conceptual pathway toward adaptive watershed modelling and next-generation environmental informatics, supporting more climate-resilient and evidence-based water resources management.

Keywords: *SWAT+, hybrid modelling, environmental informatics, AI-enhanced watershed modelling, conceptual review*

INTRODUCTION

Global Water Challenges and the Strategic Role of Hydrological Modelling

Global water resource systems are under intense pressure from accelerating climate variability, rapid land-use transformations, and the intensification of agricultural production. Together, these stressors have altered hydrological regimes, bringing more frequent floods and droughts while degrading water quality in both developed and developing regions (Arnold et al., 1998; Gassman et al., 2007; IPCC, 2008; OECD, 2014). Within this context, hydrological modelling has become a cornerstone of evidence-based water governance, providing the necessary framework for scenario analysis and risk assessment under deep uncertainty (Mensah et al., 2022; Neitsch et al., 2011; Ortiz-Partida et al., 2023).

Physically based, semi-distributed watershed models occupy a vital middle ground between simplistic lumped approaches and computationally demanding fully distributed models. They offer a pragmatic balance between physical realism and data availability, making them particularly effective for managing large, heterogeneous basins (Beven, 2012; Veettil et al., 2021). The Soil and Water Assessment Tool (SWAT) has achieved global prominence in this field due to its process-based structure and its ability to simulate long-term interactions between hydrology, land management, and biogeochemical cycles (Arnold, Moriasi, et al., 2012; Moriasi et al. 2007; Gassman et al., 2007).

Overview of SWAT Modelling Philosophy

Developed by the USDA Agricultural Research Service, SWAT was designed to evaluate how land management affects water, sediment, and chemical yields in complex watersheds (Arnold et al., 1998).

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Unlike models focused on short-term flood events, SWAT operates on a continuous daily time step. This allows for the detailed analysis of cumulative processes, such as soil moisture dynamics, groundwater recharge, and vegetation growth over decadal scales (Aloui et al., 2023; Neitsch et al., 2011; Tan et al., 2020; Wang et al., 2019).

The model's conceptual foundation is the water balance equation, which ensures mass balance consistency across all simulated processes:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right)$$

This framework allows SWAT to represent the intricate links between climate forcing, surface processes, and subsurface hydrology in a physically coherent manner.

Spatial Discretisation and the Hydrologic Response Unit Concept

A hallmark of the legacy SWAT framework is its discretisation strategy, where watersheds are partitioned into subbasins and then further divided into Hydrologic Response Units (HRUs). These HRUs represent unique combinations of land use, soil type, and slope (Arnold et al., 1998; Neitsch et al., 2011; Volk et al., 2007). However, in the legacy version, HRUs are non-spatial entities; while they capture landscape heterogeneity, their exact physical location within a subbasin is not explicitly defined.

While this HRU-centric approach is efficient for large-scale simulations, it has been criticised for its inability to represent lateral connectivity and hillslope-to-floodplain processes (Gassman et al., 2007; Malagó et al., 2017; Neitsch et al., 2011). This limitation often oversimplifies how water and constituents move across the landscape, particularly in highly managed or riparian systems (Beven, 2012; Chawanda et al., 2025; Gunnell et al., 2019).

From SWAT to SWAT+: A Paradigm Shift

The transition to SWAT+ represents a fundamental architectural shift rather than a minor update. The legacy versions (e.g., SWAT2012) were often constrained by rigid routing logic and a dependence on Microsoft Access, which limited scalability and deployment in high-performance computing environments (Arnold, Kiniry, et al., 2012; Chawanda et al., 2025; Seo et al., 2014).

SWAT+ overcomes these hurdles by adopting a modular, object-oriented framework supported by open-source SQLite databases. The introduction of Landscape Units (LSUs) allows for a more realistic spatial hierarchy, enabling the model to represent complex hydrological connectivity and adaptive management logic (Bieger et al., 2017; Chawanda et al., 2025; USDA-ARS & Texas A&M, 2016). This modularity is a critical prerequisite for integrated environmental informatics, where physical simulations can be coupled with data-driven intelligence.

Expanding Applications and Emerging Research Frontiers

Over recent decades, SWAT-based models have been applied to diverse domains, from agricultural water management to climate change impact assessments (Aloui et al., 2023; Gassman et al., 2007; Hermassi et al., 2025; Koltsida et al., 2023). Recent advancements in GIS integration and remote sensing have further refined these simulations (Arnold, Moriasi, et al., 2012; Chiang et al., 2023; Moriasi et al., 2007).

More recently, there has been growing interest in coupling SWAT-based models with artificial intelligence, machine learning, and global climate model outputs to address non-stationarity and deep uncertainty in future hydrological regimes (Barso & Negasa, 2022; Brigode et al., 2013; Dile et al., 2016; Santos et al., 2019). These developments signal a shift towards integrated, data-driven watershed modelling frameworks capable of supporting adaptive and resilient water governance.

Objectives and Structure of This Review

This review synthesises the conceptual journey of SWAT and SWAT+ into a unified narrative. The primary objective of this article is to develop and articulate a conceptual Hybrid SWAT+ Modelling Framework that integrates physically based watershed simulation with artificial intelligence and adaptive environmental informatics. To achieve this objective, the review synthesises the evolution of SWAT and SWAT+, critically evaluates their strengths and limitations, identifies emerging methodological gaps under non-stationary environmental conditions, and explores how AI-based approaches can be integrated into future watershed modelling systems while preserving physical consistency and interpretability.

The remainder of this article is organised as follows: Section 2 presents the modelling methods and frameworks, Section 3 synthesises results and discussions from global applications, Section 4 provides conclusions and strategic recommendations, followed by a comprehensive list of references.

METHODS AND FRAMEWORK

Conceptual Narrative Review Approach

This study adopts a conceptual narrative review approach rather than a formal systematic review. The purpose of the review is not to quantify evidence through meta-analysis, but to synthesise the intellectual and methodological evolution of SWAT and SWAT+ and to develop a conceptual framework for Hybrid SWAT+ modelling. Literature was selected purposively from highly cited peer-reviewed publications, official SWAT and SWAT+ documentation, and recent studies on artificial intelligence applications in hydrological modelling. The review focuses on identifying conceptual transitions, structural innovations, methodological limitations, and future integration pathways.

Core Modelling Philosophy and Principles

The SWAT and SWAT+ ecosystems are built upon a physically based, semi-distributed framework designed for continuous-time simulation. Unlike models that focus on isolated storm events, these tools aim to capture the long-term interaction of hydrological and biogeochemical processes under varying environmental and management conditions (Abbaspour et al., 2015; Arnold et al., 1998; Krysanova & White, 2015; Neitsch et al., 2011; USDA-ARS & Texas A&M, 2016).

Both SWAT and SWAT+ are underpinned by three core methodological principles: mass-balance consistency, physically interpretable process equations, and a discretisation strategy that balances spatial detail with computational efficiency (Arnold, Moriasi, et al., 2012; Gassman et al., 2007).

While these principles are enduring, their technical execution has evolved significantly from the legacy versions to the modular SWAT+ architecture (Chawanda et al., 2025).

Spatial Discretisation Frameworks

In the legacy SWAT framework (up to SWAT2012), watershed discretisation follows a fixed hierarchical structure:

[Watershed → Subbasin → Hydrologic Response Unit (HRU)]

Subbasins are delineated using a Digital Elevation Model (DEM) and stream threshold parameters. Each subbasin is then subdivided into HRUs, defined as unique combinations of land use, soil type, and slope class (Chen et al., 2021; Neitsch et al., 2011).

HRUs are conceptual units, not spatially explicit polygons. As a result, lateral interactions between HRUs within a subbasin are not directly simulated. Instead, all HRU outputs are aggregated at the subbasin outlet before being routed downstream (Arnold, Moriasi, et al., 2012; Moriasi et al., 2007; Pignotti et al., 2017). This simplifies computation but limits the model's ability to represent landscape connectivity, particularly in riparian or floodplain zones (Beven, 2012).

SWAT+ introduces a fundamentally revised spatial hierarchy:

[Watershed → Subbasin → Landscape Unit (LSU) → HRU]

Landscape Units (LSUs) represent geomorphologically meaningful entities, typically separating upland hillslopes from valley bottoms or floodplains (Chawanda et al., 2025). LSUs are generated using an "inverted DEM" logic, where ridgelines rather than streams are used as primary boundaries (Macmillan et al., 2000).

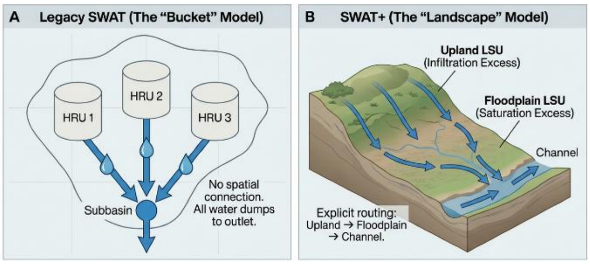

Figure 1 The Bucket Model and the Landscape Model (Source: Developed by the authors based on the literature synthesis presented in this review)

This allows for a more realistic representation of water and nutrient routing across the landscape while maintaining the HRU as the primary unit for process calculations (Chawanda et al., 2025; WMO, 2011).

Table 1 Comparison of Spatial Discretisation Frameworks

Aspect	Legacy SWAT (≤2012)	SWAT+
Primary spatial units	Subbasin, HRU	Subbasin, LSU, HRU
HRU spatial explicitness	Conceptual (non-spatial)	Nested within LSUs
Floodplain representation	Implicit	Explicit
Hillslope–channel connectivity	Simplified	Physically differentiated
Scalability	Moderate	High (HPC-ready)

Sources: (Arnold, Kiniry, et al., 2012; Chawanda et al., 2025; Neitsch et al., 2011; USDA-ARS & Texas A&M, 2016)

Hydrological Process Representation

The ability to represent watershed hydrology has been a defining characteristic of the SWAT modelling framework since its initial development. Both SWAT and SWAT+ simulate key hydrological processes, including precipitation partitioning, surface runoff generation, evapotranspiration, infiltration, percolation, lateral flow, groundwater recharge, and streamflow routing. These processes are represented through physically based formulations that maintain mass balance consistency across the watershed system (Allen et al., 1998; Neitsch et al., 2011; USDA-ARS & Texas A&M, 2016).

Although the fundamental hydrological concepts remain largely unchanged between SWAT and SWAT+, important differences emerge in model structure and spatial representation. Legacy SWAT relies on a subbasin and Hydrologic Response Unit (HRU) configuration in which hydrological processes are simulated within spatially disconnected units. This approach proved computationally efficient and supported widespread application across a broad range of climatic and geographical settings. However, the inability of HRUs to exchange water, sediment, and nutrients directly limits the representation of landscape connectivity and localised hydrological interactions (Allen et al., 1998; USDA-ARS & Texas A&M, 2016).

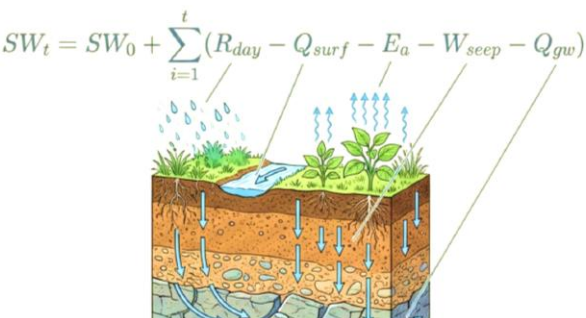

Figure 2 The Water Balance Equation (Source: Developed by the authors based on the literature synthesis presented in this review)

SWAT+ addresses this limitation through an object-oriented architecture that explicitly represents landscape elements and their interactions. The introduction of Landscape Units (LSUs), channels, reservoirs, aquifers, and other connected spatial objects allows more realistic simulation of flow pathways and watershed connectivity. Consequently, hydrological responses can be represented in a manner that better reflects actual watershed processes, particularly in heterogeneous environments where spatial interactions strongly influence runoff generation and water movement (Neitsch et al., 2011; USDA-SCS, 1972).

From a conceptual perspective, the transition from SWAT to SWAT+ is more than a software upgrade; it marks a move away from simplified semi-distributed modelling toward a more flexible environmental informatics framework capable of supporting future integration with advanced data streams, adaptive management strategies, and hybrid modelling approaches (Abbaspour et al., 2015; Neitsch et al., 2011).

Sediment and Erosion Modelling

Sediment transport and erosion simulation constitute important components of the SWAT modelling framework because they directly influence watershed sustainability, reservoir sedimentation, river morphology, and water quality. Since its early development, SWAT has incorporated process-based approaches to estimate sediment generation from upland areas and its subsequent transport through river networks (Neitsch et al., 2011; USDA-ARS & Texas A&M, 2016; Williams, 1975).

Numerous studies have demonstrated the effectiveness of SWAT in evaluating erosion risks under varying land-use, climate, and management scenarios. The model has been widely applied to assess the impacts of agricultural practices, conservation measures, watershed restoration programs, and land-use change on sediment yield across different spatial scales (Abbaspour et al., 2015; Neitsch et al., 2011; USDA-ARS & Texas A&M, 2016).

Despite its broad applicability, several limitations have been reported. Sediment predictions are often sensitive to parameter calibration, input data quality, and watershed discretisation schemes. In complex landscapes, uncertainties associated with erosion processes may increase substantially, particularly when high-resolution spatial information is unavailable. These challenges become more pronounced under rapidly changing environmental conditions where historical relationships between rainfall, runoff, and sediment production may no longer remain stable.

The enhanced spatial connectivity introduced in SWAT+ improves the representation of sediment transfer pathways and landscape interactions. Nevertheless, uncertainties related to parameter estimation and environmental non-stationarity continue to present significant challenges. These limitations provide a strong rationale for exploring hybrid modelling approaches in which physically based sediment simulations are complemented by data-driven learning algorithms capable of identifying emerging patterns and reducing predictive uncertainty.

Nutrient and Biogeochemical Cycling

Beyond hydrological simulation, SWAT and SWAT+ provide integrated representations of nutrient dynamics and biogeochemical processes within watershed systems. These capabilities have enabled extensive applications in water quality assessment, agricultural management, eutrophication studies, and ecosystem restoration planning (Neitsch et al., 2011).

The modelling framework simulates nutrient transport and transformation processes across terrestrial and aquatic environments, linking land management activities with downstream water quality outcomes. This integration has made SWAT one of the most widely used watershed models for evaluating the environmental consequences of agricultural intensification, fertiliser application, and land-use change.

However, biogeochemical processes are inherently complex and often characterised by considerable spatial and temporal variability. The accuracy of nutrient simulations depends heavily on the availability of monitoring data, calibration quality, and the representation of local environmental conditions. In many regions, particularly those with limited observational data, uncertainty remains a significant concern (Rathjens et al., 2025).

The evolution toward SWAT+ has improved flexibility in representing management operations and spatial interactions among watershed components. Nevertheless, the increasing complexity of environmental systems, coupled with climate change and rapidly evolving land-use patterns, suggests that future modelling frameworks may require greater adaptability than conventional deterministic approaches can provide. This challenge has stimulated growing interest in integrating artificial intelligence and machine learning techniques with physically based watershed models to enhance predictive capability while preserving process understanding.

Management Representation and Decision Logic

In legacy SWAT, management operations (planting, fertilisation, irrigation, tillage) are defined chronologically in .mgt files, using fixed dates or accumulated heat units (Neitsch et al., 2011). This approach limits adaptive decision-making capability and partly motivates the architectural redesign introduced in SWAT+.

SWAT+ introduces Decision Tables, enabling rule-based adaptive management. Each table consists of four quadrants: conditions, alternatives, action entries, and actions. This framework allows the simulation of human decision-making under environmental feedback, significantly enhancing realism (Chawanda et al., 2025; USDA-ARS & Texas A&M, 2016).

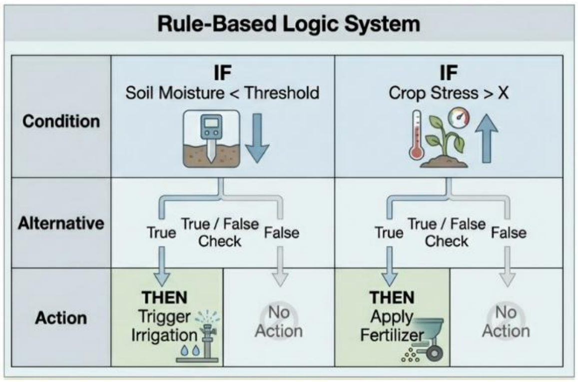

Figure 3 Adaptive Management with Decision Table (Source: Developed by the authors based on the literature synthesis presented in this review)

Data Architecture and Computational Framework

SWAT2012 relies on text-based input files, Microsoft Access databases, and sequential processing. This architecture imposes size and performance limitations (Arnold, Kiniry, et al., 2012).

Meanwhile, SWAT+ replaces legacy structures with SQLite databases, object-based connection files, and parallel processing compatibility. This enables large-scale, high-resolution modelling and integration with external models and datasets (Chawanda et al., 2025).

Taken together, the shift from text-based, Access-dependent storage to an open, object-oriented SQLite architecture is not merely a technical upgrade; it is the structural precondition that makes hybridisation feasible. Without modular connection files and queryable databases, coupling SWAT-class models with external AI components, remote sensing feeds, or real-time IoT streams would be considerably more cumbersome.

Calibration, Validation, and Uncertainty Analysis

Model credibility relies on rigorous calibration and validation. Performance is commonly evaluated using Nash–Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), and Percent Bias (PBIAS).

SWAT+ integrates IPEAT+, enabling automated sensitivity analysis and multi-objective calibration (Chawanda et al., 2025; USDA-ARS & Texas A&M, 2016).

Automated tools such as IPEAT+ improve the efficiency of calibration, but they still operate within a stationary-parameter paradigm: a single optimised parameter set is assumed to remain valid for the simulation period. This is precisely the assumption that becomes questionable under non-stationary climate and land-use trajectories, and it is the gap that the hybrid framework proposed later in this review is designed to address.

Table 2 Comparison of System Architectures

Component	SWAT2012	SWAT+
Database	MS Access	SQLite
Routing	Fixed (.fig)	Flexible (connections)
Management logic	Chronological	Rule-based
HPC compatibility	Limited	High
Model coupling potential	Low	High

Sources: (Arnold, Kiniry, et al., 2012; Chawanda et al., 2025)

Methodological Implications for Integrated Watershed Modelling

The methodological evolution from SWAT to SWAT+ represents a transition from structural hydrological modelling to modular environmental informatics. This shift enhances physical realism, scalability, and policy relevance, as well as integration with climate, socio-economic, and decision-support systems.

These methodological foundations provide the basis for the synthesis of empirical results and applications discussed in the following section.

SYNTHESIS AND CRITICAL DISCUSSION

The reviewed literature compares legacy SWAT and the modular SWAT+ architecture, highlighting how each framework addresses specific watershed challenges. The synthesis indicates that while both versions maintain robust performance in stable climatic regimes, the modularity of SWAT+ provides superior flexibility for the thematic areas of complex routing and adaptive management.

Global Patterns of SWAT and SWAT+ Applications

Since its initial release in the mid-1990s, SWAT has been applied in thousands of peer-reviewed studies across all inhabited continents, encompassing climatic zones ranging from humid tropics to semi-arid and cold regions (Arnold, Moriasi, et al., 2012; Moriasi et al., 2007; Gassman et al., 2007). The breadth of applications reflects the model's flexibility in addressing diverse research objectives, including streamflow simulation, sediment yield estimation, nutrient transport analysis, and assessment of land management scenarios (Gassman et al., 2014).

A synthesis of the literature indicates that applications typically cluster into five primary domains: hydrological regime simulation, agricultural management assessment, water quality and sediment transport, climate change impact studies, and decision-support for watershed policy (Chiang et al., 2023; Gassman et al., 2007; Koltsida et al., 2023).

More recent studies increasingly employ SWAT+ to overcome structural limitations of legacy SWAT, particularly in complex landscapes and large-scale basins (Chawanda et al., 2025; Gassman et al., 2014; USDA-ARS & Texas A&M, 2016).

Hydrological Performance across Climatic and Physiographic Contexts

Across diverse basins, SWAT has consistently demonstrated satisfactory to very good performance in simulating daily and monthly streamflow when appropriately calibrated. Meta-analyses report Nash–Sutcliffe Efficiency (NSE) values typically ranging from 0.60 to 0.85 for monthly flows, with slightly lower performance at daily scales (Arnold, Moriasi, et al., 2012; Moriasi et al., 2007; Dile et al., 2016; Gassman et al., 2007).

Performance is generally most reliable in medium-to-large basins (>500 km^2) with stable climatic regimes. However, challenges often persist in small headwater catchments and highly urbanised areas where rapid runoff responses are difficult to capture with daily time steps (Beven, 2012; Brigode et al., 2013; Santos et al., 2019).

A significant finding in recent SWAT+ studies is its improved representation of baseflow, particularly in floodplain-dominated systems (Aloui et al., 2023; Chawanda et al., 2025; Hermassi et al., 2025). This is largely attributed to the explicit use of

Landscape Units (LSUs), which allow the model to differentiate between recharge-heavy uplands and discharge-dominated lowlands. While legacy SWAT often relied on lumped groundwater parameters like ALPHA_BF, GW_DELAY, and GWQMN, the spatial attribution in SWAT+ provides a more physically grounded representation of aquifer–river interactions (Brigode et al., 2013; Chawanda et al., 2025; Me et al., 2015; Neitsch et al., 2011; Santos et al., 2019; USDA-ARS & Texas A&M, 2016).

Sediment, Nutrients, and Water Quality

The application of MUSLE within SWAT has yielded robust sediment yield estimates in agricultural and mixed land-use watersheds, particularly where erosion is runoff-driven rather than rainfall-intensity-driven (Gassman et al., 2007; Zhang et al., 2019). Reported sediment NSE values commonly range between 0.50 and 0.80, although uncertainty increases significantly at daily time steps due to the episodic nature of erosion events (Arekhi et al., 2012; Neitsch et al., 2011). Similarly, nitrogen and phosphorus modules have been instrumental in assessing diffuse agricultural pollution (Beven, 2012).

SWAT's nitrogen and phosphorus modules have been widely used to evaluate diffuse agricultural pollution and eutrophication risk. Studies consistently show reasonable agreement between observed and simulated nutrient loads at monthly and annual scales (Arnold, Moriasi, et al., 2012; Chiang et al., 2023; Cui et al., 2021; Moriasi et al., 2007). Denitrification and plant uptake parameters often emerge as dominant sources of uncertainty, particularly in tropical and irrigated systems where nutrient cycling rates are highly dynamic (Del Grosso et al., 2020; Koltsida et al., 2023).

SWAT+ enhances nutrient routing realism by allowing nutrient transformation and retention processes to occur within landscape positions, rather than exclusively at HRU outlets, improving load attribution at subbasin scales (Chawanda et al., 2025).

Evaluating Management Practices and Land-Use Change Applications

One of the most influential application domains of SWAT is the evaluation of Best Management Practices (BMPs), including conservation tillage, buffer strips, contour farming, and nutrient management (Gassman et al., 2007; Gitau et al., 2008). Results across several studies indicate sediment reduction potentials of 20–60% and nutrient load reductions of 15–50%, depending on BMP type and spatial targeting.

SWAT+ decision tables significantly improve BMP realism by enabling conditional implementation based on soil moisture, crop stage, or climatic thresholds, thus better reflecting farmer decision-making behaviour (Arnold et al., 2018; Chawanda et al., 2025). SWAT applications assessing deforestation, afforestation, and urban expansion consistently report increased surface runoff and reduced baseflow following impervious surface expansion (Brigode et al., 2013; Santos et al., 2019).

However, legacy SWAT tends to overgeneralise urban hydrological responses due to limited representation of stormwater infrastructure. SWAT+ provides partial improvements through flexible routing but still requires coupling with specialised urban models for high-resolution urban hydrology (Abbaspour et al., 2015; Arnold et al., 2018).

Climate Change Impact Assessments

SWAT has been extensively coupled with Global and Regional Climate Models (GCMs and RCMs) to assess climate change impacts on water availability, flood risk, and agricultural productivity (Barso & Negasa, 2022; Brigode et al., 2013; Santos et al., 2019). Results indicate increased runoff variability, more frequent extreme flow events, and seasonal shifts in water availability.

Model sensitivity is particularly pronounced for precipitation inputs, with temperature-driven ET changes playing a secondary but non-negligible role (Brigode et al., 2013; Santos et al., 2019). Climate impact studies highlight significant uncertainty stemming from climate model selection, bias correction techniques, and parameter non-stationarity.

SWAT's traditional calibration paradigm assumes stationary parameters, which may not hold under future climate regimes. Emerging studies propose adaptive calibration and hybrid SWAT–machine learning frameworks to address this limitation (Abbaspour et al., 2015; Arnold et al., 2018; Arnold, Moriasi, et al., 2012; Barso & Negasa, 2022).

Comparative Performance: SWAT versus SWAT+

Empirical comparisons between SWAT2012 and SWAT+ remain relatively limited but reveal several consistent trends:

- Hydrological performance: Comparable NSE and R^2 values under identical calibration datasets.

- Spatial realism: SWAT+ outperforms legacy SWAT in representing floodplain processes and landscape connectivity.
- Model transparency: Object-based routing in SWAT+ enhances diagnostic capability.
- Computational efficiency: SWAT+ scales more effectively in large basins and parallel computing environments (Aloui et al., 2023; Chawanda et al., 2025; Hermassi et al., 2025).

Table 3 Synthesis of SWAT and SWAT+ Application Outcomes

Model	Study (Representative Application)	Basin Type	Temporal Scale	Performance Metric	Source & Location
SWAT	Global and regional watershed applications	Mixed/varied	Monthly	NSE ≈ 0.60–0.85	(Arnold, Kiniry, et al., 2012), Ch. 12
SWAT	Large-basin and continental-scale studies	Mixed/large	Monthly	Robust long-term performance	(Gassman et al., 2007), Sec. 4.2
SWAT	Climate change impact assessments	Climate change focus	Monthly	~0.65–0.75	(Krysanova & White, 2015), Sec. 3.1–3.3
SWAT	Non-stationary hydrological analyses	Non-stationary systems	Monthly	~0.65–0.70	(Abbaspour et al., 2015), Sec. 4
SWAT	Sediment and erosion modelling studies	Sediment-dominant basins	Monthly	0.60–0.75	(Tan et al., 2020), Table 5
SWAT+	Structural & architectural redesign	Conceptual / multi-scale	object-based routing	Architecture-focused (modular design)	(Bieger et al., 2017), Sec. 2–5
SWAT+	Managed watershed and reservoir operations	Managed basins	Monthly	NSE ≈ 0.70–0.85	(Arnold et al., 2018), Sec. 4
SWAT+	Advanced routing and landscape connectivity	Mixed / Mediterranean	Monthly	~0.75–0.80	(Dile et al., 2016), Sec. 3.4
SWAT+	Semi-arid and regulated basin application	Semi-arid / managed	Monthly	0.72–0.86	(Arnold et al., 2018), Sec. 4
SWAT+	Global high-resolution implementation (CoSWAT)	Global	Monthly	KGE-based discharge performance	(Chawanda et al., 2025), Sec. 2–3

The studies cited in Table 3 are intentionally selected as representative and authoritative examples rather than exhaustive listings. Performance metrics are synthesised from review studies, model documentation, and large-scale applications to illustrate typical performance ranges and modelling capabilities.

Table 3 synthesises representative application outcomes of SWAT and SWAT+ across diverse basin types and modelling objectives, highlighting both quantitative performance ranges and qualitative modelling implications. From a purely statistical perspective, monthly streamflow performance indicators for SWAT and SWAT+ frequently overlap, with reported NSE values commonly ranging between approximately 0.60 and 0.85, and in some cases exceeding 0.85 in well-instrumented or managed basins. This convergence indicates that the principal advancement of SWAT+ does not primarily lie in systematic improvements of traditional goodness-of-fit metrics, but rather in its redesigned model architecture and enhanced spatial and operational realism.

In contrast to legacy SWAT, SWAT+ consistently demonstrates improved representation of landscape connectivity, routing logic, and management interventions, particularly in complex, regulated, and semi-arid systems. These characteristics suggest that SWAT+ is best regarded as a structurally enabling platform for hybrid modelling, where physically based simulation can be coherently coupled with data-driven, remote sensing, and adaptive decision-support components without compromising process transparency or mass balance consistency. This confirms that the scientific value of SWAT+ lies primarily in its structural and representational advances, rather than in marginal improvements of traditional goodness-of-fit metrics.

Critical Discussion and Research Gaps

Despite its global success, SWAT-based modelling faces persistent challenges: (1) Equifinality and parameter non-uniqueness, particularly in data-scarce regions (Beven, 2012). (2) Limited socio-economic representation, restricting integration with governance and behavioural models. (3) Urban hydrology simplifications require external coupling. (4) Climate non-stationarity challenges conventional calibration frameworks.

SWAT+ addresses structural issues but does not fully resolve conceptual limitations related to human–water system interactions (USDA-ARS & Texas A&M, 2016). It is worth noting that the shift from SWAT to SWAT+ does not fully address the underlying conceptual problem. Moving to SQLite, introducing Landscape Units, and adopting object-based routing solve genuine technical issues, and this results in improved floodplain representation. However, the core assumption remains unchanged: that a fixed, calibrated set of parameters can keep describing watershed behaviour over time.

SWAT+ modularity, including decision tables, object-based connections, and open databases, provides natural entry points for external data-driven information without compromising the model's physical basis (Jeong et al., 2024). Therefore, the rationale for a hybrid framework does not stem from poor SWAT+ performance, as its fit is broadly comparable to legacy SWAT, but from the need to fully exploit these new capabilities

Conceptualising Hybrid SWAT+ Modelling

The transition from SWAT to SWAT+ marks a shift from static watershed simulation towards adaptive environmental informatics platforms. When coupled with remote sensing, artificial intelligence, and decision-support systems, SWAT+ has the potential to evolve into a core engine for integrated river basin management under climate uncertainty (Arnold et al., 2018; Ortiz-Partida et al., 2023; Zamani et al., 2021). This evolution positions SWAT+ not merely as a hydrological model, but as a boundary object linking science, policy, and practice.

The increasing complexity of hydrological systems under climate change, land-use dynamics, and socio-environmental feedback exposes fundamental limitations of purely process-based modelling paradigms. While SWAT and SWAT+ provide physically interpretable and policy-relevant simulations, their predictive capacity is constrained by parameter stationarity assumptions, structural simplifications, and data scarcity in many regions. These limitations motivate the development of hybrid modelling frameworks, in which physically based models are systematically coupled with data-driven methods.

In the proposed hybrid modelling concept, SWAT+ functions as the core deterministic engine, preserving mass balance, process realism, and interpretability, while artificial intelligence (AI) components operate as adaptive layers rather than replacements. Machine learning algorithms, such as artificial neural networks, recurrent neural networks, or tree-based learners, are employed to learn systematic residuals between observed and simulated outputs, detect non-linear process interactions, and dynamically adjust sensitive parameters under changing boundary conditions. This positioning is not an isolated proposition: it builds directly on the recurring evidence, synthesised in the preceding sections, that legacy SWAT and SWAT+ remain constrained by stationary-parameter assumptions even as their structural flexibility (decision tables, object-based connections, open databases) creates the technical entry points needed for such coupling.

The modular architecture of SWAT+ enables such coupling through its object-based routing, open SQLite databases, and decision-table logic. Remote sensing products (e.g. satellite-derived precipitation, evapotranspiration, soil moisture) and Internet of Things (IoT) sensor networks can be assimilated as near-real-time inputs, while AI modules update correction functions or decision thresholds without violating the underlying physical constraints of the model.

Within this framework, hybridisation occurs at three complementary levels:

1. Pre-processing hybridisation, where AI enhances climate input bias correction, land-use classification, and parameter regionalisation.
2. In-simulation hybridisation, where machine learning augments SWAT+ decision tables and adaptive management rules.
3. Post-processing hybridisation, where neural networks correct output residuals, improve extreme event representation, and quantify uncertainty.

Each maintains a clear functional boundary between physical consistency and data-driven learning.

Rather than transforming SWAT+ into a black-box predictor, this hybridisation preserves transparency while extending model adaptability. Hybridisation can thus be seen as a layered augmentation process, not a substitution of physical process representation, marking a conceptual shift from static calibration towards learning watershed systems capable of evolving alongside environmental and socio-economic change. The hybrid SWAT+ framework offers a promising pathway for future research in climate impact assessment, adaptive water management, and digital twin development for river basins.

This study goes beyond conventional model comparison by proposing a conceptual Hybrid SWAT+ Modelling Framework, positioning SWAT+ as a process-based backbone for AI-enhanced environmental informatics. The contribution should be read as an open research architecture for future methodological development.

The Frontier of Hybrid SWAT+ Modelling

While SWAT and SWAT+ provide robust, physically interpretable representations of hydrological and biogeochemical processes, their predictive performance and decision relevance remain constrained by parameter stationarity assumptions, data scarcity, and limited adaptive capability under rapidly changing environmental conditions. Conversely, artificial intelligence and machine learning models exhibit strong pattern recognition and predictive capacity but often lack physical consistency and interpretability.

A hybrid modelling paradigm seeks to combine the complementary strengths of both approaches: process realism and mass balance consistency from SWAT+, and adaptive intelligence and data-driven learning from AI-based systems.

In the proposed framework, SWAT+ functions as the core physical engine, while AI-based modules operate as external or semi-embedded components responsible for learning, correction, and adaptive control. Figure 4 presents the conceptual diagram of a hybrid SWAT+ modelling framework integrating process-based hydrological simulation with artificial intelligence, remote sensing, and real-time data streams to support adaptive and climate-resilient watershed management.

In the proposed hybrid SWAT+ modelling framework, the physically based process engine of SWAT+ is augmented by artificial intelligence and data-driven modules. Rather than replacing hydrological process representation, these modules instead function as an adaptive intelligence layer, enabling dynamic parameter learning, bias correction, and non-stationarity detection. The framework integrates multi-source data streams, including remote sensing and IoT-based observations, to support continuous model updating and decision-oriented scenario evaluation.

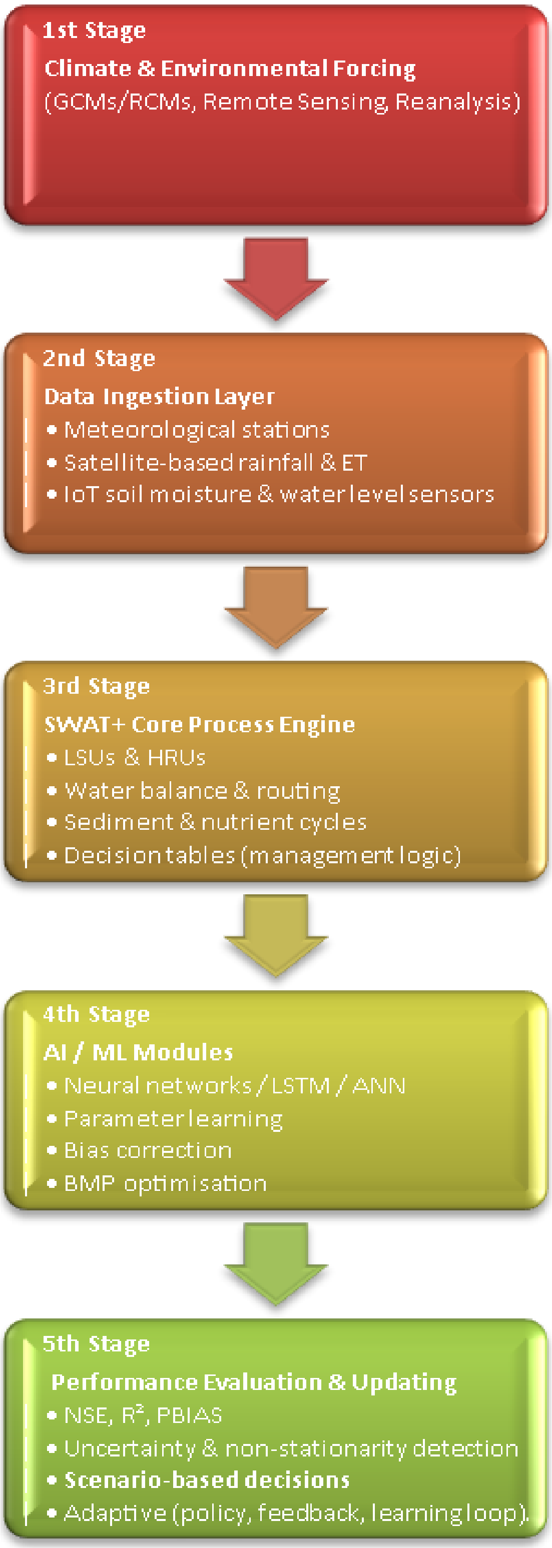

Figure 4 Conceptual Diagram of Hybrid SWAT+ (Source: Developed by the authors based on the conceptual synthesis of this review.)

CONCLUSIONS

This review has synthesised the conceptual evolution and global applications of the Soil and Water Assessment Tool (SWAT) and its successor, SWAT+, framing them within the broader trajectory of modern hydrological modelling. Over three decades, the framework has transitioned from a pragmatic, subbasin-centric tool into a modular, object-oriented environmental informatics platform. This transition represents not merely an incremental update, but a paradigm shift that enhances the model's capacity to support resilient water resource management in an increasingly complex world.

The enduring relevance of SWAT-based modelling stems from several core contributions. Firstly, it offers a coherent integration of hydrology, land management, and biogeochemical cycles within a single framework. Secondly, its operational scalability allows for consistent analysis across scales, from small experimental plots to continental basins. Finally, the transition to SWAT+ has introduced structural transparency through object-based routing and rule-based management via decision tables, facilitating a more realistic representation of human–environment interactions.

Despite these advances, certain methodological hurdles remain. Issues such as parameter equifinality, particularly in data-scarce regions, continue to complicate model inference and policy interpretation. Furthermore, the simplified representation of groundwater in karstic systems and the overgeneralisation of urban hydrological responses are areas requiring ongoing refinement through model coupling. Perhaps most critically, the traditional assumption of parameter stationarity is increasingly untenable under the non-stationary conditions of climate change and rapid land-use transformation.

The future of watershed modelling lies in the strategic integration of physically based simulations with adaptive, data-driven technologies. SWAT+ is uniquely positioned to serve as the deterministic backbone for such hybrid frameworks. By layering artificial intelligence (AI) and machine learning (ML) onto the modular core of SWAT+, researchers can enhance model adaptability by learning non-linear residual structures and dynamically updating sensitive parameters in response to environmental change. This integration also enables the assimilation of remote sensing and Internet of Things (IoT) data streams for near-real-time state updating and early warning capabilities. Furthermore, it supports the development of digital twins by coupling hydrological processes with socio-economic and governance rules through object-oriented logic, thereby enabling multi-objective decision-making.

In closing, the next generation of watershed science will be defined by the convergence of physical theory and data-driven learning. By embracing this hybrid paradigm, SWAT+ can evolve into a ‘living’ watershed model, providing the scientific foundation needed for adaptive and resilient governance in an era of accelerating environmental change. The proposed conceptual framework is intended to guide future research, innovation, and practical applications in integrated watershed modelling.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this article.

AI DISCLOSURE STATEMENT

AI-assisted tools were used solely to support language refinement, grammar checking, and editorial improvement. All interpretations, analysis, and content were developed and evaluated by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the work. In addition, Figures 1–3 were initially produced with the assistance of generative AI image-creation tools, based entirely on the conceptual content and literature synthesis developed by the authors, and were subsequently edited and finalised by the authors using the Windows Photos/Picture Editor application to ensure accuracy, labelling consistency, and presentation quality. Figure 4 was developed entirely by the authors without the use of any generative AI tool, and was prepared and finalised using Microsoft Word’s built-in editing tools.

REFERENCES

Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., & Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, *524*, 733–752. https://doi.org/10.1016/j.jhydrol.2015.03.027

Allen, R. G., Pereira, L. S., Raes, D., Smith, M., & W, a B. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. *Irrigation and Drainage*. https://doi.org/10.1016/j.eja.2010.12.001

Aloui, S., Mazzoni, A., Elomri, A., Aouissi, J., Boufekane, A., & Zghibi, A. (2023). A review of Soil and Water Assessment Tool (SWAT) studies of Mediterranean catchments: Applications, feasibility, and future directions. *Journal of Environmental Management*, *326*(116799), 1–20. https://doi.org/10.1016/j.jenvman.2022.116799

Arekhi, S., Shabani, A., & Rostamizad, G. (2012). Application of the modified universal soil loss equation (MUSLE) in prediction of sediment yield (Case study: Kengir Watershed, Iran). *Arabian Journal of Geosciences*, *5*, 1259–1267. https://doi.org/10.1007/s12517-010-0271-6

Arnold, J. G., Bieger, K., White, M. J., Srinivasan, R., Dunbar, J. A., & Allen, P. M. (2018). Use of Decision Tables to Simulate Management in SWAT+. *Water (Switzerland)*, *10*(6), 713. https://doi.org/10.3390/w10060713

Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., & Neitsch, S. L. (2012). Soil & Water Assessment Tool: Input/Output Documentation. Version 2012. *Texas Water Resources Institute, TR-439*. https://swat.tamu.edu/media/69296/swat-io-documentation-2012.pdf

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., Van Griensven, A., Van Liew, M. W., Kannan, N., & Jha, M. K. (2012). SWAT: Model Use, Calibration, and Validation. *Transactions of the ASABE*, *55*(4), 1491–1508. https://swat.tamu.edu/media/99051/azdezasp.pdf

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*(1). https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Barso, G., & Negasa, T. (2022). Runoff and Sediment Yield Modeling Using ArcSWAT -A Case of Meki River Watershed. *Research Square*, 1–12. https://doi.org/10.21203/rs.3.rs-1245203/v1

Beven, K. (2012). *Rainfall-Runoff Modelling: The Primer: Second Edition*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119951001

Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., Allen, P. M., Volk, M., & Srinivasan, R. (2017). Introduction to SWAT+, A Completely Restructured Version of the Soil and Water Assessment Tool. *Journal of the American Water Resources Association*, *53*(1), 115–130. https://doi.org/10.1111/1752-1688.12482

Brigode, P., Oudin, L., & Perrin, C. (2013). Hydrological model parameter instability: A source of additional uncertainty in estimating the hydrological impacts of climate change? *Journal of Hydrology*, *476*, 410–425. https://doi.org/10.1016/j.jhydrol.2012.11.012

Chawanda, C. J., Van Griensven, A., Nkwasa, A., Teran Orsini, J. P., Jeong, J., Choi, S.-K., Srinivasan, R., & Arnold, J. G. (2025). CoSWAT Model v1: A high-resolution global SWAT+ hydrological model. *Hydrol. Earth Syst. Sci. EGUsphere*, *29*, 6901–6916. https://doi.org/10.5194/hess-29-6901-2025

Chen, M., Cui, Y., Gassman, P. W., & Srinivasan, R. (2021). Effect of watershed delineation and climate datasets density on runoff predictions for the upper mississippi river basin using SWAT within HAWQS. *Water (Switzerland)*, *13*(4), 422. https://doi.org/10.3390/w13040422

Chiang, L. C., Shih, P. C., Lu, C. M., & Jhong, B. C. (2023). Strategies Analysis for Improving SWAT Model Accuracy and Representativeness of Calibrated Parameters in Sediment Simulation for Various Land Use and Climate Conditions. *Journal of Hydrology*, *626*(130124), 1–17. https://doi.org/10.1016/j.jhydrol.2023.130124

Cui, J., Zhao, Y., Sun, W., Chen, Y., Wu, B., Xue, B., Chen, H., Li, Z., & Tian, Z. (2021). Evaluating the influence of hydrological condition on the phosphorus loads in an agricultural river basin using the SWAT model. *Hydrology Research*, *52*(5), 1143–1158. https://doi.org/10.2166/nh.2021.165

Del Grosso, S. J., Smith, W., Kraus, D., Massad, R. S., Vogeler, I., & Fuchs, K. (2020). Approaches and concepts of modelling denitrification: increased process understanding using observational data can reduce uncertainties. *Current Opinion in Environmental Sustainability*, *47*, 37–45. https://doi.org/10.1016/j.cosust.2020.07.003

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 and Software*, *85*, 129–138. https://doi.org/10.1016/j.envsoft.2016.08.004

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE*, *50*(4), 1211–1250. https://doi.org/10.13031/2013.23637

Gassman, P. W., Sadeghi, A. M., & Srinivasan, R. (2014). Applications of the SWAT Model Special Section: Overview and Insights. *Journal of Environmental Quality*, *43*, 1–8. https://doi.org/10.2134/jeq2013.11.0466

Gitau, M. W., Gburek, W. J., & Bishop, P. L. (2008). Use of the SWAT Model to Quantify Water Quality Effects of Agricultural BMPs at the Farm-Scale Level. *Transactions of the ASABE*, *51*(6), 1925–1936. https://doi.org/10.13031/2013.25398

Gunnell, K., Mulligan, M., Francis, R. A., & Hole, D. G. (2019). Evaluating natural infrastructure for flood management within the watersheds of selected global cities. *Science of the Total Environment*, *670*, 411–424. https://doi.org/10.1016/j.scitotenv.2019.03.212

Hermassi, T., Jarray, F., Tlili, W., & Achour, I. (2025). Integrative Hydrologic Modelling of Soil and Water Conservation Strategies: a SWAT-Based Evaluation of Environmental Resilience in the Merguellil Watershed, Tunisia. *Frontiers in Water*, *7*, 1–15. https://doi.org/10.3389/frwa.2025.1521812

IPCC. (2008). Climate change and water resources in systems and sectors. In *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change.* (pp. 55–75). IPCC.

Jeong, H., Lee, B., Kim, D., Qi, J., Lim, K. J., & Lee, S. (2024). Improving estimation capacity of a hybrid model of LSTM and SWAT by reducing parameter uncertainty. *Journal of Hydrology*, *633*, 130942. https://doi.org/10.1016/j.jhydrol.2024.130942

Koltsida, E., Mamassis, N., & Kallioras, A. (2023). Hydrological Modeling Using the Soil and Water Assessment Tool in Urban and Peri-Urban Environments: the Case of Kifisos Experimental Subbasin (Athens, Greece). *Hydrology and Earth System Sciences*, *27*(4), 917–931. https://doi.org/10.5194/hess-27-917-2023

Krysanova, V., & White, M. (2015). Advances in Water Resources Assessment with SWAT— An Overview. *Hydrological Sciences Journal*, *60*(5), 771–783. https://doi.org/10.1080/02626667.2015.1029482

Macmillan, R. A., Mcnabb, D. H., & Jones, R. K. (2000). Automated landform classification using DEMs: a conceptual framework for a multi-level, hierarchy of hydrologically and geomorphologicaly oriented physiographic mapping units. *4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4): Problems, Prospects and Research Needs. Banff, Alberta, Canada, September 2 - 8, 2000.*, 1–16.

Malagó, A., Bouraoui, F., Vigiak, O., Grizzetti, B., & Pastori, M. (2017). Modelling water and nutrient fluxes in the Danube River Basin with SWAT. *Science of the Total Environment*, *603*, 196–218. https://doi.org/10.1016/j.scitotenv.2017.05.242

Me, W., Abell, J. M., & Hamilton, D. P. (2015). Effects of hydrologic conditions on SWAT model performance and parameter sensitivity for a small, mixed land use catchment in New Zealand. *Hydrology and Earth System Sciences*, *19*, 4127–4147. https://doi.org/10.5194/hess-19-4127-2015

Mensah, J. K., Ofosu, E. A., Yidana, S. M., Akpoti, K., & Kabo-bah, A. T. (2022). Integrated modeling of hydrological processes and groundwater recharge based on land use land cover, and climate changes: A systematic review. *Environmental Advances*, *8*(100224), 1–16. https://doi.org/10.1016/j.envadv.2022.100224

Moriasi, D. N., Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, & T. L. Veith. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE, 50*(3), 885-900. https://doi.org/10.13031/2013.23153

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 Technical Report no. 406. In *Texas Water Resources Institute, TR-406*. https://doi.org/10.1016/j.scitotenv.2015.11.063

OECD. (2014). *Climate Change, Water and Agriculture: Towards Resilient Systems*. OECD Publishing. https://doi.org/10.1787/9789264209138-en

Ortiz-Partida, J. P., Fernandez-Bou, A. S., Maskey, M., Rodríguez-Flores, J. M., Medellín-Azuara, J., Sandoval-Solis, S., Ermolieva, T., Kanavas, Z., Sahu, R. K., Wada, Y., & Kahil, T. (2023). Hydro-Economic Modeling of Water Resources Management Challenges: Current Applications and Future Directions. *Water Economics and Policy*, *9*(1), 2340003.

https://doi.org/10.1142/S2382624X23400039

Pignotti, G., Rathjens, H., Cibin, R., Chaubey, I., & Crawford, M. (2017). Comparative analysis of HRU and grid-based SWAT models. *Water (Switzerland)*, *9(4)*(272), 1–20. https://doi.org/10.3390/w9040272

Rathjens, H., Kiesel, J., Arnold, J., Reinken, G., & Sur, R. (2025). Technical note: Extending the SWAT2012 and SWAT+ models to simulate pesticide plant uptake processes. *Hydrology and Earth System Sciences*, *29*(22), 6703–6714. https://doi.org/10.5194/hess-29-6703-2025

Santos, R. M. B., Fernandes, L. F. S., Cortes, R. M. V., & Pacheco, F. A. L. (2019). Hydrologic Impacts of Land Use Changes in the Sabor River Basin: A Historical View and Future Perspectives. *Water (Switzerland)*, *11*(1464), 1–26. https://doi.org/10.3390/w11071464

Seo, M., Yen, H., Kim, M.-K., & Jeong, J. (2014). Transferability of SWAT Models between SWAT2009 and SWAT2012. *Journal of Environmental Quality*, *43*(3), 869–880. https://doi.org/10.2134/jeq2013.11.0450

Tan, M. L., Gassman, P. W., Yang, X., & Haywood, J. (2020). A Review of SWAT Applications, Performance and Future Needs for Simulation of Hydro-Climatic Extremes. *Advances in Water Resources*, *143*(103662), 1662–1669. https://doi.org/10.1016/J.ADVWATRES.2020.103662

USDA-ARS, & Texas A&M. (2016). *SWAT+ Documentation*. USDA-ARS and Texas A&M. https://swatplus.gitbook.io/io-docs/

USDA-SCS. (1972). Section 4: Hydrology. In *National Engineering Handbook* (p. 734). United States Department of Agriculture, Soil Conservation Service.

Veettil, A. V., Green, T. R., Kipka, H., Arabi, M., Lighthart, N., Mankin, K., & Clary, J. (2021). Fully distributed versus semi-distributed process simulation of a highly managed watershed with mixed land use and irrigation return flow. *Environmental Modelling and Software*, *140*(105000), 1–18. https://doi.org/10.1016/j.envsoft.2021.105000

Volk, M., Arnold, J. G., Bosch, D. D., Allen, P. M., & Green, C. H. (2007). Watershed configuration and simulation of landscape processes with the SWAT model. *MODSIM07 - Land, Water and Environmental Management: Integrated Systems for Sustainability, Proceedings*, 2383–2389. https://www.ars.usda.gov/ARSUserFiles/36627/Watersheds47_Volk_.pdf

Wang, Y., Jiang, R., Xie, J., Zhao, Y., Yan, D., & Yang, S. (2019). Soil and Water Assessment Tool (SWAT) Model: A Systemic Review. *Journal of Coastal Research*, *93*, 22–30. https://doi.org/10.2112/SI93-004.1

Williams, J. R. (1975). Sediment Routing for Agricultural Watersheds. *JAWRA Journal of the American Water Resources Association*, *11*(5), 965–974. https://doi.org/10.1111/j.1752-1688.1975.tb01817.x

WMO. (2011). *Manual on flood forecasting and warning WMO-No. 1072*. WMO. https://doi.org/10.1016/j.transproceed.2010.08.027

Zamani, M., Shrestha, N. K., Akhtar, T., Boston, T., & Daggupati, P. (2021). Advancing model calibration and uncertainty analysis of SWAT models using cloud computing infrastructure: LCC-SWAT. *Journal of Hydroinformatics*, *23*(1), 1–15. https://doi.org/10.2166/hydro.2020.066

Zhang, L., Meng, X., Wang, H., & Yang, M. (2019). Simulated runoff and sediment yield responses to land-use change using the SWAT model in Northeast China. *Water (Switzerland)*, *11*(5), 915. https://doi.org/10.3390/w11050915