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Advances in SWAT Applications for Investigating Spatiotemporal Changes in Multiple Hydrological Components and Implications for the Liao River Basin

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Abstract

SWAT studies increasingly examine evapotranspiration, soil water and groundwater alongside streamflow. The difficulty is assessing which of these simulated components are supported by observations. This narrative review compares evidence from meteorological forcing studies, multivariable calibration and management representations, with particular attention to applications in the Liao River region. The regional scope includes the West Liao and East Liao rivers, the Liao River mainstem and the Hun-Taizi-Daliao system, while retaining the distinct outlets and periods used in individual studies. The reviewed results show that the benefits of additional data depend on the variable and location evaluated. Meteorological products that perform well at one gauge can perform less well downstream, and joint calibration can improve process constraints without improving every streamflow metric. Regional SWAT applications provide evidence on runoff, landscape change, wetlands, water retention and water-resource vulnerability, but offer limited joint validation of evapotranspiration and storage. These findings favour a subregional research design: test meteorological inputs against local observations, select calibration data for the process in question, and evaluate reservoir operations and water use explicitly. Cold-season performance also requires separate assessment. By distinguishing direct regional results from transferable methods and proposed experiments, the review identifies what can currently be inferred about water partitioning and where additional observations are needed.

Keywords

SWAT Model, Hydrological Components, Spatiotemporal Changes, Multivariable Analysis, Liao River Basin

1. Introduction

The basin hydrological cycle connects precipitation, land surface evapotranspiration, soil water storage, groundwater recharge, and streamflow. These processes govern the generation and distribution of water resources. Discharge at a river cross-section reflects variations in the combined flow from upstream areas. However, it does not directly reveal where water is consumed, which areas contribute runoff, or how seasonal changes in storage influence subsequent flows. With the growing use of spatial data and hydrological models, basin hydrological studies have broadened their focus from outlet streamflow to multiple hydrological processes. SWAT integrates information on topography, land use, soils, and meteorological conditions and divides a basin into sub-basins and hydrological response units, providing a means of analysing water partitioning within the basin [1]. Previous studies have used the model to assess water resources, land management, and environmental change across a range of spatial scales [2].

Studies of multiple hydrological components must evaluate whether the model realistically represents the partitioning of water among processes. Increasing the number of output variables is only one aspect of this task. Even when simulated total streamflow closely matches observations, substantial biases may persist in evapotranspiration or changes in water storage. Parameter adjustments may compensate for some errors, yielding satisfactory simulations of outlet streamflow. Model applications should therefore combine statistical performance metrics with assessments of the plausibility of simulated hydrological processes and clearly define the conditions under which their findings are applicable [3]. Studies of the Liao River Basin have focused on different mainstem and tributary reaches, gauging stations, and time periods, reaching differing conclusions [4] [5]. A comparison must first establish what each study actually represents before asking why its conclusions differ.

This review examines whether advances in forcing data and calibration provide stronger evidence for internal water partitioning, and how that evidence can inform research in the Liao River region. The comparison records the model configuration, target variable, temporal scale and evaluation stage of each selected application. Particular attention is given to the distinction between a result obtained during calibration and one tested against withheld observations. Regional findings are then used to identify suitable observations and experiments for the West Liao River, the mainstem and the Hun and Taizi rivers.

Literature Sources and Review Approach

The review uses a narrative approach. Foundational SWAT papers and the existing reference collection were supplemented by web searches of journal publishing platforms and publicly available institutional records. Searches combined "SWAT" with "meteorological forcing", "CMADS", "multivariable calibration", "multi-site calibration", "evapotranspiration", "reservoir operations" and "irrigation". Regional searches included "Liao River", "West Liao River", "Hun River"

and "Taizi River". Chinese- and English-language studies were selected for their relevance to these topics, the clarity of their methods and data, and their usefulness for comparing observational constraints. The resulting collection contains 45 references.

For each quantitative example, the synthesis retains the evaluated variable, timescale and calibration or validation stage. Results are compared qualitatively; effect sizes are not pooled across basins or experimental designs. Where only an abstract was verified, the study is used to establish its scope and approach, without adding unverified performance statistics. Observational analyses and applications of other models provide regional context but are distinguished from tests of SWAT. The selection is not exhaustive, and access to full texts affects the coverage. The conclusions consequently describe the evidence available in this collection rather than the frequency of particular outcomes across all published SWAT studies.

2. SWAT and a Framework for Analysing Multiple Hydrological Components

2.1. From Streamflow at Gauging Locations to Water Partitioning within a Basin

Conventional streamflow modelling focuses primarily on flow volume at the basin outlet and its temporal variability. Simulations can be evaluated directly against observations at the corresponding river cross-section [1] [3]. SWAT also represents runoff generation, evapotranspiration, changes in soil moisture, and channel routing. Its sub-basins and hydrological response units enable comparisons of water partitioning across different land use, soil, and slope conditions. In conventional SWAT applications, hydrological response units generally group areas with similar characteristics and do not necessarily correspond to spatially contiguous land parcels. Consequently, spatially detailed maps of model outputs are not necessarily supported by observations with commensurate spatial resolution and accuracy.

Abbaspour *et al.* [6] demonstrated the use of SWAT for continental-scale water-resource and water-quality assessment in Europe, including calibration and uncertainty analysis. Such applications extend the area that can be examined, but also raise questions about data consistency and parameter transfer. Outlet records constrain total outflow, while internal gauges constrain tributary contributions. Evaluating a mapped component requires observations that represent that component over a comparable area. Increasing the number of sub-basins cannot resolve this difference in observational coverage.

Model configuration is another source of differences among studies. SWAT+ reorganises watershed objects and their connections [7]. The gwflow extension adds a spatially distributed groundwater-flow representation [8]. These are separate developments, and a comparison should identify both the SWAT version and any coupled modules. Results obtained with a groundwater extension cannot be

taken as evidence that conventional SWAT represents groundwater heads or stream-aquifer exchange in the same way.

2.2. Distinguishing Streamflow, Water Yield, and Actual Evapotranspiration

The distinction between streamflow and water yield becomes important when a study extends from gauge records to sub-basin maps. Discharge at a gauge integrates upstream contributions following channel routing and, where applicable, regulation. SWAT water yield represents a sub-basin's contribution to the stream network; the components included in this output should be verified for the model version used. Actual evapotranspiration represents water returned to the atmosphere under prevailing water availability and vegetation conditions [3]. Potential evapotranspiration is a different quantity and cannot substitute for actual evapotranspiration in the water balance. Units also require careful consideration. Comparing discharge, typically reported as volume per unit time, with a land surface flux expressed as water depth requires a common reporting period and a clearly defined contributing area.

Spatial aggregation can influence the interpretation of these outputs. Water yield expressed as depth can be averaged across sub-basins using area weights, whereas summing discharge at nested gauges may count the same upstream water twice. Storage requires a different calculation: soil water storage describes the amount of water held at a given time, whereas the water balance accounts for the change in storage between the beginning and end of the reporting period. The same distinction applies to green water accounting. Water held in the soil is a stock, whereas evapotranspiration is a flux. Adding these quantities without defining the accounting period and purpose would obscure their physical meaning. These distinctions are particularly relevant when comparing studies that report outlet discharge, mapped water yield, or soil water storage under the general heading of basin water resources.

2.3. Linking Inputs to Process Evaluation

Figure 1 links scope and variable definitions, inputs and structure, observational constraints, independent evaluation, and scenario interpretation. Meteorological

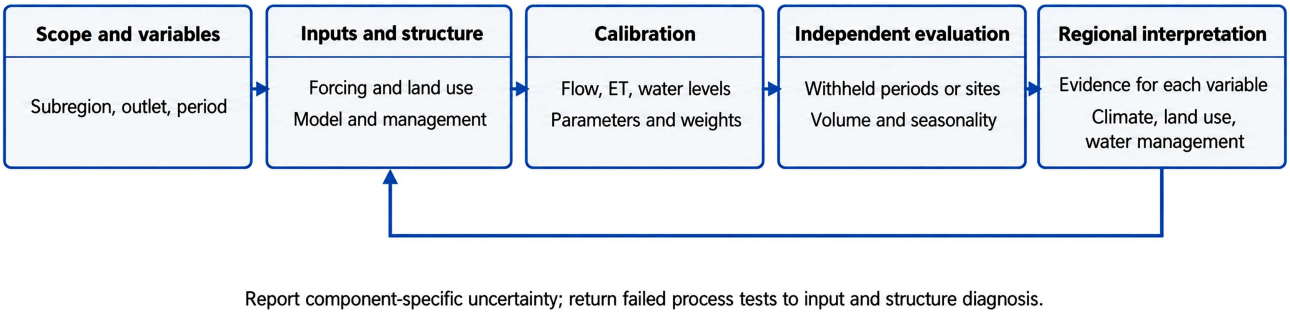

Figure 1. Conceptual framework for reviewing multiple hydrological components and regional applications (developed in this review).

data drive the model; observations constrain parameters; withheld periods or sites test transferability. Regional interpretation requires evaluation matched to each target variable. The framework is proposed here, not a completed simulation of the entire region.

3. Major Advances in Modelling Multiple Hydrological Components

3.1. Increasing Diversity of Meteorological Forcing Data

Meteorological forcing is a practical starting point because errors in rainfall and temperature propagate into several hydrological components. Station interpolation becomes difficult where monitoring is sparse or uneven. CMADS provides meteorological forcing for SWAT by integrating information from multiple sources in a consistent data format [9]. Studies of alternative meteorological products indicate that their suitability varies by region. Data selection should therefore account for basin conditions, product characteristics, and study objectives [10].

Meng *et al.* compared SWAT simulations driven by CMADS, CFSR, and ground-based station data in the Heihe River Basin. The different forcing datasets yielded different streamflow and water balance estimates, with CMADS showing promise in that application [11]. These findings support considering merged products for use in data-sparse regions. However, they do not establish that CMADS outperforms ground-based observations in every tributary of the Liao River. The two regions differ in climate, precipitation-generating conditions, station coverage, and water use. The suitability of these products for the Liao River Basin therefore needs to be evaluated against local data.

The evaluation of meteorological datasets should distinguish between the accuracy of the inputs themselves and the performance of streamflow simulations after parameter calibration. Xiao *et al.* examined the relationship between precipitation inputs and SWAT parameter uncertainty, offering insights into the interaction between input errors and parameter adjustments [12]. Future comparisons could employ two complementary experimental approaches. The first would hold parameters constant to examine how simulations respond to a change in the input dataset. The second would calibrate the model separately for each input dataset and compare both model performance and changes in parameter values. Together, these approaches could help determine whether improvements arise primarily from meteorological information or parameter compensation, although additional observations would still be needed to support this assessment. Precipitation evaluation should also extend beyond annual totals. Seasonal distribution, the duration of dry spells, and extreme events can all influence runoff generation. Similar annual precipitation totals do not necessarily result in similar streamflow dynamics.

In the Hun River Basin, Zhang *et al.* [13] compared monthly streamflow simulations driven by CMADS, CFSR, and ground-based observations. The corresponding validation-period NSE values were 0.95, 0.47, and 0.94 at Beikouqian

Station and 0.54, −0.07, and 0.63 at Shenyang Station, respectively. CMADS outperformed CFSR in this experiment but did not outperform ground-based observations at Shenyang. Results from a single station therefore cannot establish the overall superiority of one dataset. ERA5-Land [14], CMFD [15], and CHIRPS precipitation [16] could also be included in future comparisons. These products differ in the variables they provide, their data integration methods, and their resolution. Comparisons should therefore use clearly specified product versions and a common evaluation period. Their performance in hydrological simulations of the Liao River Basin cannot be inferred solely from reported product accuracy.

3.2. Strengthening Internal Process Evaluation through Multivariable Observations

When calibration relies solely on streamflow, different parameter sets may produce similar simulations at the basin outlet. These results alone cannot establish whether internal hydrological processes are represented realistically. Multivariable studies therefore incorporate evapotranspiration, soil moisture, or vegetation data to evaluate different processes. Koltsida and Kallioras jointly used satellite-based evapotranspiration and streamflow to calibrate SWAT, assessing both water outflow and evapotranspiration losses [17]. Lee *et al.* used multiple remote sensing datasets for spatial calibration and uncertainty analysis, focusing particularly on the model's ability to reproduce spatial variability within a basin [18].

Remotely sensed evapotranspiration can support the evaluation of internal hydrological processes, but it is also subject to error. GLEAM combines remote sensing information with water balance methods and other approaches to estimate land evaporation and root-zone soil moisture [19]. He *et al.* used the coupled water-carbon model PML-V2, calibrated against flux tower observations, to develop daily evapotranspiration and gross primary production products at a spatial resolution of 500 m across China. These products remain model-based estimates rather than direct observations at individual pixels [20]. Agreement between model outputs and remote sensing products provides additional evidence for the plausibility of simulated processes. However, remote sensing products should not be treated as error-free references. If a model and a remote sensing product share meteorological inputs, their errors may also be correlated. The extent to which such comparisons provide an independent evaluation therefore warrants further assessment.

Odusanya *et al.* used satellite-based evapotranspiration for multi-site calibration and validation in a data-sparse basin, demonstrating that spatially distributed evapotranspiration data can contribute to model evaluation [21]. Practical applications nevertheless require careful attention to resampling, valid pixel coverage, temporal aggregation, and quality screening. Monthly means, water depths accumulated over a specified period, and mean daily fluxes represent different quantities, and their calculation methods must be harmonised before comparison. When aggregated to sub-basins, pixel-level estimates should be weighted by the valid area they represent within each sub-basin. Inconsistent processing may

cause differences arising from data scales to be misinterpreted as errors in simulated processes, leading to inappropriate parameter adjustments.

The benefits of multivariable calibration require variable-specific evaluation. Koltsida and Kallioras [17] reported streamflow NSE values during calibration of 0.71 for streamflow-only calibration and 0.70 for joint calibration at Monastiri. Using remotely sensed products as references, Ha *et al.* [22] reported monthly NSE values of 0.65 for evapotranspiration and 0.57 for leaf area index over a five-year validation period in a Vietnamese basin. Franco and Bonumá [23] compared constraints provided by observed streamflow and remotely sensed evapotranspiration, illustrating the relevance of low-flow diagnostics. These studies provide additional evidence for evaluating hydrological processes but do not establish that incorporating additional variables improves every performance metric.

3.3. Combining Multi-Site Calibration with Comprehensive Performance Evaluation

Multi-site calibration incorporates information from river cross-sections within a basin and supports the evaluation of streamflow simulations at multiple locations. Abbas *et al.* applied SWAT+, coupled with the gwflow groundwater module, to four basins in the United States. They incorporated observations from streamflow gauges and groundwater monitoring wells into the calibration objectives and adjusted the weights to balance the influence of individual monitoring sites. This approach provides a framework for integrated multi-site and multivariable evaluation [24]. Incorporating additional monitoring sites also requires attention to overlapping drainage areas at upstream and downstream gauges, differences in data quality, and whether parameters are shared across regions. These choices influence each site's contribution to calibration and the resulting model performance.

The study by Abbas *et al.* [24] provides methodological guidance on defining multi-site and multivariable calibration objectives, balancing their weights, and jointly analysing parameter sensitivity and uncertainty. However, its simulation of groundwater heads and stream-aquifer exchange relies on the gwflow module [8]. Adopting a similar calibration strategy in conventional SWAT therefore does not give the model equivalent capabilities for simulating distributed groundwater flow. When applying these methods to the Liao River Basin, the need for a coupled groundwater module should be assessed against the study requirements for groundwater levels, stream-aquifer exchange, and water abstraction. Observational data and calibration parameters should then be selected accordingly.

Bai's review of calibration strategies indicated that the effectiveness of multi-site, multivariable, and multi-objective approaches depends on basin conditions and study design. Incorporating additional types of observations does not necessarily improve simulations [25]. Abbaspour *et al.* also emphasised that calibration should account for model structure, input data, and study objectives while explicitly addressing uncertainty and the conditions under which the results are applicable [26]. Data selection should be guided by the problem under investigation.

For example, an unrealistic distribution of tributary contributions calls for additional streamflow observations within the basin, whereas implausible evapotranspiration losses require information on land surface processes. Errors in the timing of flow variations downstream of a reservoir may require reservoir operation records. Identifying likely sources of error before selecting additional data can improve the effectiveness of multivariable calibration.

Model evaluation should assess water volumes as well as the timing and amplitude of hydrological variations. Moriasi *et al.* recommended combining statistical metrics with graphical analysis and selecting evaluation criteria appropriate to the simulated variable and temporal scale [27]. By decomposing mean squared error and NSE, Gupta *et al.* showed that different error components may offset one another within an aggregate performance metric [28]. Knoben *et al.* noted that NSE and KGE have different benchmarks and should not be evaluated using identical thresholds [29]. A high correlation coefficient alone therefore does not demonstrate that water volumes are simulated accurately. Likewise, good overall performance does not guarantee reliable simulations during low-flow periods or months characterised by extreme conditions. Studies using models to analyse multiple hydrological components should report performance separately for calibration and validation periods, high-flow and low-flow seasons, and key hydrological components.

Franco *et al.* [30] compared single-site, multi-site, and multivariable strategies. Station-averaged daily streamflow validation KGE ranged from 0.62 to 0.68 and NSE from 0.40 to 0.60. Additional data did not significantly improve internal-station accuracy, although uncertainty constraints changed. **Table 1** compares evidence types rather than ranking models: basins, samples, and references differ, and identical NSE values do not imply equal reliability across variables.

Table 1. Reported quantitative results and evidence limits.

Study and target	Stage and result	Interpretation and limit
Zhang *et al.* [13]; monthly flow	Validation NSE, CMADS/CFSR/stations: Beikouqian 0.95/0.47/0.94; Shenyang 0.54/−0.07/0.63 (original Table 6).	Site-dependent forcing performance; does not validate ET.
Koltsida and Kallioras [17]; Monastiri flow	Calibration NSE: flow-only 0.71; joint flow-ET 0.70 (original Table 3).	A calibration trade-off, not independent validation.
Ha *et al.* [22]; monthly ET and leaf area index	Five-year validation: ET NSE 0.65, KGE 0.80; LAI NSE 0.57, KGE 0.83.	Agreement with remote sensing, not error-free field data.
Franco *et al.* [30]; daily flow	Validation station-mean KGE 0.62 - 0.68; NSE 0.40 - 0.60 across strategies.	Added data need not improve every station.

4. Findings and Differences among Studies of the Liao River Basin

The Liao River region examined in this section includes the West Liao River and

its tributaries, such as the Laoha River, the East Liao River, the Liao River mainstem, and the Hun-Taizi-Daliao river system (Figure 2). This grouping does not imply that all these river systems drain to a single present-day outlet. Outflow boundaries for the Liao River mainstem and the Hun-Taizi-Daliao system should therefore be treated separately. Gauge drainage areas, study periods, and outlets are retained as defined in the original studies. Findings for the Hun and Taizi rivers are not treated as directly equivalent to those for the West Liao River or the region as a whole.

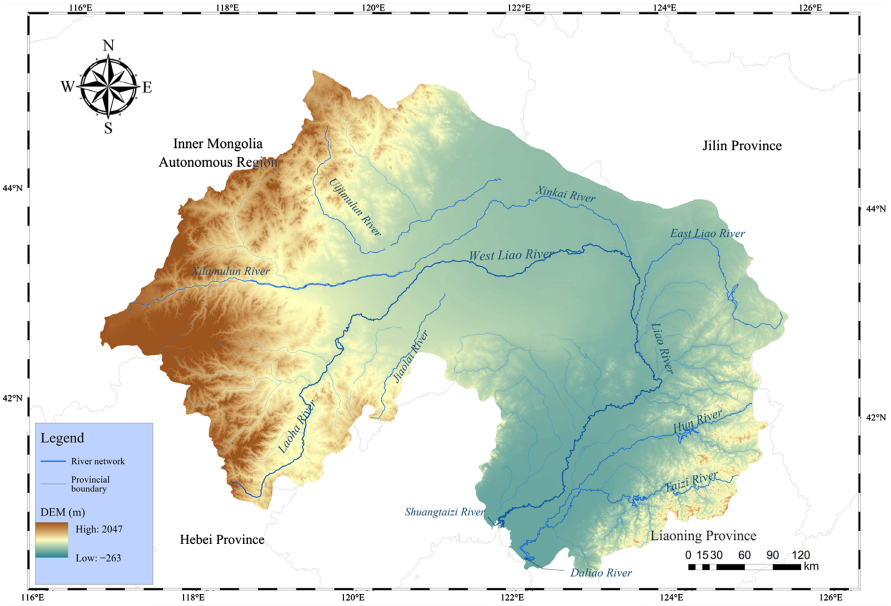

Figure 2. Schematic map of the Liao River region covered by this review. The geographic scope used to organise the literature does not imply that all river systems share a single present-day outflow boundary. Map approval number: GS (2024) 0650.

4.1. Direct Regional Applications and Evidence of Streamflow Change

SWAT has been applied directly within the region, although study objectives and evaluation targets vary. Zong *et al.* [31] examined landscape change, water yield, and nonpoint source pollution in the Hun-Taizi watershed. Monthly streamflow simulations were calibrated for 2003-2010 and validated for 2011-2014, with validation NSE values ranging from 0.64 to 0.98 across nine stations. These results support the model's ability to simulate streamflow at those sites and over those periods but do not independently validate sub-basin evapotranspiration or water storage. Fu *et al.* [32] estimated agricultural nonpoint source pollutant yields in the Huntai Basin; evaluating pollutant yields remains distinct from jointly validating water balance components.

Yu *et al.* [33] combined SWAT, landscape analysis, and a geographical detector to investigate wetlands in the West Liao River region during 1980-2015. Their joint precipitation-evaporation q statistic exceeded 0.70, indicating an explanatory association rather than a causal percentage of streamflow change attributable

to climate. Liu *et al.* [34] estimated mean annual water retention of approximately 2.46 billion m^3 in the middle and upper reaches of the Hun River during 2000-2019. This model-based estimate depends on the definition of the water retention service and does not represent an observed change in total water storage. Hao and Wang [35] coupled SWAT with WEAP to assess water resource vulnerability in the Laoha River Basin, linking hydrological supply with water demand. Table 2 summarises the evidence and its limits.

Table 2. Direct regional SWAT applications.

Regional study	Scope and method	Evidence boundary
Zhang *et al.* [13]	Hun; CMADS/CFSR/station forcing.	Monthly flow evaluation; ET and storage need separate tests.
Zong *et al.* [31]	Hun-Taizi; SWAT and landscape analysis.	Flow calibration 2003-2010, validation 2011-2014; validation NSE 0.64 - 0.98 at nine sites. Water-yield maps remain model estimates.
Yu *et al.* [33]	West Liao wetlands, 1980-2015; SWAT and geographical detector.	The q statistic measures association, not causal contribution or simulation efficiency.
Liu *et al.* [34]	Middle/upper Hun water retention, 2000-2019.	Estimated 2.46 billion m^3/year; not observed total-storage change.
Hao and Wang [35]	Laoha; coupled SWAT-WEAP supply and demand.	Vulnerability depends on demand and management assumptions.
Fu *et al.* [32]	Huntai agricultural nonpoint pollutant yields.	Supports pollution scenarios, not validation of all hydrological components.

Studies of the Liao River Basin have examined streamflow changes across different spatial extents and time periods. Zhang and He analysed monthly streamflow records from 1956-2000 at representative gauging stations on the Liao River mainstem, the Hun River, and the Taizi River. They examined intra-annual distribution and interannual variability, finding that streamflow was unevenly distributed throughout the year, with no significant interannual trend in the analysed series [4]. Jiang and Wang conducted trend and attribution analyses using data from 1953-2011. They identified declines in annual and seasonal mean streamflow and concluded that human activities played an important role in streamflow changes during the study period [5].

Although these findings differ, the differences alone do not establish that either study is incorrect. Gauge drainage areas, record start and end dates, methods for calculating annual and seasonal values, and the division of records into distinct periods may all influence the results. These factors should be examined to determine whether the studies address the same question before their findings are compared. For example, a record ending earlier may exclude subsequent periods of change, while patterns at individual stations may differ from results aggregated over a larger area. Future studies should clearly specify the drainage area and study

period associated with each station and analyse the mainstem and tributaries separately. Areas referred to as the "Liao River Basin" should not be assumed to share identical spatial boundaries across studies.

A study of the Laoha River, a tributary of the West Liao River, used the VIC model and land use scenarios to analyse the effects of land cover change and human water use on streamflow [36]. This study contributes to an understanding of hydrological responses in the Liao River Basin but does not provide direct evidence of SWAT's performance. Different models can offer complementary explanations of hydrological processes. However, quantitative estimates of individual contributions depend on model structure, the baseline period, and scenario design and cannot be directly transferred to other tributaries.

4.2. Drought Indicators and Storage Effects in Streamflow Interpretation

River discharge reflects only part of hydrological change. Gong used precipitation and temperature data from 1961-2018 to examine drought characteristics in the Liao River Basin across different accumulation periods. The results showed that the identification of moisture anomalies depends on the temporal scale [37]. Meteorological drought indices characterise the broader conditions of water supply and demand but are not equivalent to streamflow, actual evapotranspiration, or available water resources. When these indices are used alongside SWAT outputs, their intended role should be clearly specified, whether to characterise meteorological conditions or to assess event timing. If they are used to evaluate a hydrological process directly, the basis for that relationship should also be explained.

From a water balance perspective, reduced precipitation, changes in evapotranspiration demand, and increased water abstraction and use can all influence streamflow. Changes in storage may delay these effects. Analyses of multiple hydrological components should therefore examine both their covariation and physically plausible time lags. For example, a decline in streamflow at a river cross-section in a given month does not imply a corresponding decline in water yield in every sub-basin during that month. Channel storage and routing, together with antecedent water storage, also influence discharge. Correlation analysis can help identify possible explanations, but without process observations and comparative scenarios, it is difficult to establish which factor is primarily responsible.

Satellite-gravity total water-storage anomalies require attention to spatial support, leakage, and temporal coverage; they are not equivalent to groundwater or small-sub-basin soil water. GRACE-REC [38] is a climate-driven reconstruction trained on GRACE observations, not the original satellite record. It cannot independently validate abstraction effects, and shared meteorological inputs may introduce correlated errors.

4.3. Reservoir and Water Use Processes as Key Constraints on Regional Interpretation

Assessing the effects of human activities requires explicit representation of reser-

voir storage, releases, and water use processes in the model water balance. In the Yalong River Basin, Liu *et al.* used SWAT scenarios to examine different reservoir capacities, locations, and relative positions of two reservoirs. They found that these configurations influenced flood peak attenuation and the intra-annual distribution of streamflow [39]. Qiu *et al.* compared different representations of reservoir operations and irrigation in the Yakima River Basin, United States. Incorporating reservoir outflows calculated by RiverWare improved SWAT streamflow simulations. Including irrigation further increased simulated evapotranspiration, bringing it into closer agreement with the reference data [40]. The former study illustrates the effects of reservoir configuration on streamflow dynamics, whereas the latter highlights the combined effects of reservoir operations and irrigation. Both demonstrate the need for appropriate representation of reservoirs and water use, as adjustments to runoff generation and routing parameters alone cannot fully capture these effects.

Applying these methods to the Liao River Basin first requires verifying that observations correspond to the simulated quantities. Reservoir inflow, reservoir outflow, and streamflow at downstream gauges reflect different processes and should not be used interchangeably for calibration. If reservoir storage and releases are poorly represented, adjusting soil and groundwater parameters may improve agreement between simulated and observed monthly streamflow hydrographs while introducing biases in evapotranspiration and water storage within the basin. Water balance records covering agricultural irrigation, industrial and domestic withdrawals, and return flows should also be as complete as possible. Where data are insufficient, studies can examine hydrological responses under explicitly stated assumptions. However, estimates of individual factors' contributions should be interpreted cautiously and should not be used directly to develop detailed operational schedules.

The representation of management practices can draw on SWAT+ decision tables [41], the work of Chawanda *et al.* on mass balance, reservoirs, and irrigation [42], and the storage-inflow-release relationships developed by Yassin *et al.* [43]. The latter provides a transferable parameterisation rather than a regional evaluation specific to SWAT. These methods do not replace local operational records. The SWAT-WEAP application in the Laoha River Basin [35] supports the explicit representation of water abstraction sources, return flows, and irrigation schedules, with consistent meteorological and land use conditions across scenarios.

5. Research Gaps and Future Directions

5.1. Reporting Uncertainty in Individual Hydrological Components

Errors associated with model inputs, parameters, structure, and management data should be discussed separately, and their effects on streamflow, evapotranspiration, and changes in water storage should be reported. Comparing simulations driven by different forcing datasets under fixed parameters with simulations cali-

brated separately for each dataset can reveal evidence of parameter compensation, but cannot fully disentangle the sources of error. The spread among products that share observation stations or algorithms may also underestimate the true uncertainty. Periods or stations excluded from calibration should be reserved for evaluating water balance biases, seasonal dynamics, and water balance closure. Components for which independent observations are unavailable should be explicitly identified as model estimates requiring validation. Model performance in simulating outlet streamflow should not substitute for an assessment of the reliability of all hydrological components.

5.2. Improving Cold-Region Process Representation and Scale Consistency across Data Sources

Research in the Liao River Basin should give greater attention to hydrological processes during the cold season and the transition to spring. Temperature, snow cover, and freeze-thaw data can help assess the timing and variability of spring runoff generation. Model suitability should not be judged solely on warm-season performance or annual statistics. Where performance varies substantially across regions, input data and process representations should be examined before adjusting parameters. This sequence can reduce the risk of mistaking model structural biases for differences in natural conditions. This proposed research direction reflects the conditions of the Liao River Basin, but its effectiveness still needs to be evaluated against local observations.

Data resolution should be appropriate to the research question. Resampling coarse meteorological or evapotranspiration data to a finer grid does not add information to the original observations. Increasing the number of hydrological response units may also complicate parameter specification. Studies could begin at a sub-basin scale supported by the available data and assess whether alternative subdivision schemes alter the main conclusions. Observations, meteorological inputs, and land use data should also be temporally aligned. Dataset versions, temporal coverage, and methods for handling missing values should be documented to avoid mistaking differences arising from changes in data sources for actual hydrological changes.

Ahl *et al.* [44] reported validation NSE values of 0.90 and 0.76 for monthly and daily streamflow, respectively, in a snow-dominated watershed, although late-summer and winter baseflow remained poorly represented. Overall performance metrics can therefore conceal seasonal deficiencies. Snowmelt-module optimisation undertaken for alpine regions of northern China [45] should be evaluated under snow and temperature conditions in the Liao River Basin before being transferred to this region. Observations of snow cover, soil temperature, the onset of spring streamflow, and winter low flows can help distinguish errors associated with snowmelt, freeze-thaw processes, and groundwater.

5.3. Investigating Mechanisms of Change within the Limits of Available Data

In the West Liao and Laoha river basins, priority should be given to combining

streamflow observations, irrigation withdrawal records, groundwater levels, and wetland extent data to examine the relationship between consumptive water use and recharge. Studies of the Hun and Taizi rivers should focus on streamflow upstream and downstream of reservoirs, evapotranspiration, and comparisons among land use scenarios. For the Liao River mainstem and the East Liao River, gauge drainage boundaries, data periods, and tributary connections should be defined consistently. These priorities illustrate the need for research in the Liao River region to address region-specific problems. Specifically, three combinations of data could be evaluated over a common validation period: "streamflow only", "streamflow plus evapotranspiration", and "streamflow plus evapotranspiration and management records". Separate experiments could then compare land use scenarios under fixed meteorological conditions, meteorological scenarios under fixed land use, and management scenarios under fixed natural inputs. Results should identify which variables are simulated more or less accurately, report biases during high-flow and low-flow seasons and changes in parameter values, and explicitly acknowledge any differences that remain unexplained. This design translates the integration of multiple data sources into testable steps and avoids attributing changes definitively to a single cause based solely on correlations or one set of scenarios.

6. Conclusions

SWAT can link streamflow to water partitioning within a basin, and its applications have expanded to encompass integrated analyses of actual evapotranspiration, water storage, and sub-basin water resources. Studies of multiple hydrological components require consistent variable definitions, spatial boundaries, and temporal scales. Each result must also be supported by appropriate evidence to assess whether the model realistically represents internal hydrological processes. Meteorological datasets from multiple sources, streamflow observations from multiple sites, and remotely sensed evapotranspiration provide additional evidence for model evaluation. Their value depends on data quality, correlations among errors, consistency across scales, and parameter settings. Good performance in simulating outlet streamflow may coexist with biases in internal hydrological processes. Evaluation should therefore encompass key seasons, independent validation periods, and individual hydrological components. The reliability of conclusions should also be assessed in light of uncertainties in model inputs, parameters, and structure.

Evidence from SWAT applications within the region is available, but the selected studies do not demonstrate consistent validation of all hydrological components across the region. Comparisons that account for differences in spatial boundaries, evaluation stages, and model versions reveal site-dependent performance of forcing datasets, calibration trade-offs, and the distinction between water retention services and total water storage. Future work should align independent observations and management records with subregional research questions,

employ reproducible controlled experiments, evaluate cold-season processes, and report uncertainty for individual hydrological components. The narrative approach to study selection and the availability of full texts limit the coverage of this review. Its contribution is therefore a set of research priorities and evidence requirements rather than a unified estimate of regional attribution.

Declaration of AI-Assisted Technology Use

During the preparation and revision of this narrative review, the author used OpenAI's Codex to assist with identifying relevant literature, organising and summarising published findings, drafting and revising passages, translating reference entries, improving English expression, and preparing the conceptual framework figure. These activities involved assistance with both content development and presentation. The author reviewed and revised the manuscript and takes full responsibility for its final content, including the accuracy of references, the interpretation of published findings, and the conclusions. The quantitative results discussed in this review are attributed to the cited studies; no new empirical data or hydrological simulations were generated for this manuscript. AI tools are not credited as authors.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R. (1998) Large Area Hydrologic Modeling and Assessment Part I: Model Development. *Journal of the American Water Resources Association*, **34**, 73-89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

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

[3] Arnold, J.G., Moriasi, D.N., Gassman, P.W., *et al.* (2012) SWAT: Model Use, Calibration, and Validation. *Transactions of the ASABE*, **55**, 1491-1508. https://doi.org/10.13031/2013.42256

[4] Zhang, J. and He, J.S. (2011) Analysis of Runoff Series Characteristics in Liaohe Basin. *China Rural Water and Hydropower*, **4**, 10-13. (In Chinese) https://irrigate.whu.edu.cn/CN/Y2011/V0/I4/10

[5] Jiang, C. and Wang, F. (2016) Temporal Changes of Streamflow and Its Causes in the Liao River Basin over the Period of 1953-2011, Northeastern China. *Catena*, **145**, 227-238. https://doi.org/10.1016/j.catena.2016.06.015

[6] Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H. and 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

[7] Bieger, K., Arnold, J.G., Rathjens, H., White, M.J., Bosch, D.D., Allen, P.M., *et al.*

(2017) Introduction to SWAT+, a Completely Restructured Version of the Soil and Water Assessment Tool. *Journal of the American Water Resources Association*, **53**, 115-130. https://doi.org/10.1111/1752-1688.12482

[8] Bailey, R.T., Bieger, K., Arnold, J.G., *et al.* (2020) A New Physically-Based Spatially-Distributed Groundwater Flow Module for SWAT+. *Hydrology*, **7**, Article 75. https://doi.org/10.3390/hydrology7040075

[9] Meng, X., Wang, H., Shi, C., Wu, Y. and Ji, X. (2018) Establishment and Evaluation of the China Meteorological Assimilation Driving Datasets for the SWAT Model (CMADS). *Water*, **10**, Article 1555. https://doi.org/10.3390/w10111555

[10] Tan, M.L., Gassman, P.W., Liang, J. and Haywood, J.M. (2021) A Review of Alternative Climate Products for SWAT Modelling: Sources, Assessment and Future Directions. *Science of the Total Environment*, **795**, Article 148915. https://doi.org/10.1016/j.scitotenv.2021.148915

[11] Meng, X., Zhang, X., Yang, M., Wang, H., Chen, J., Pan, Z., *et al.* (2019) Application and Evaluation of the China Meteorological Assimilation Driving Datasets for the SWAT Model (CMADS) in Poorly Gauged Regions in Western China. *Water*, **11**, Article 2171. https://doi.org/10.3390/w11102171

[12] Xiao, Y., Sun, R.C., Wang, Q. and Duan, Q.Y. (2024) Study on Parameter Uncertainty in SWAT Model Driven by Different Precipitation. *Journal of Hohai University* (*Natural Sciences*), **52**, 43-52. (In Chinese)

[13] Zhang, L., Meng, X., Wang, H., Yang, M. and Cai, S. (2020) Investigate the Applicability of CMADS and CFSR Reanalysis in Northeast China. *Water*, **12**, Article 996. https://doi.org/10.3390/w12040996

[14] Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., *et al.* (2021) ERA5-Land: A State-of-the-Art Global Reanalysis Dataset for Land Applications. *Earth System Science Data*, **13**, 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

[15] He, J., Yang, K., Tang, W., Lu, H., Qin, J., Chen, Y., *et al.* (2020) The First High-Resolution Meteorological Forcing Dataset for Land Process Studies over China. *Scientific Data*, **7**, Article No. 25. https://doi.org/10.1038/s41597-020-0369-y

[16] Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., *et al.* (2015) The Climate Hazards Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes. *Scientific Data*, **2**, Article No. 150066. https://doi.org/10.1038/sdata.2015.66

[17] Koltsida, E. and Kallioras, A. (2022) Multi-Variable SWAT Model Calibration Using Satellite-Based Evapotranspiration Data and Streamflow. *Hydrology*, **9**, Article 112. https://doi.org/10.3390/hydrology9070112

[18] Lee, S., Kim, D., McCarty, G.W., Anderson, M., Gao, F., Lei, F., *et al.* (2024) Spatial Calibration and Uncertainty Reduction of the SWAT Model Using Multiple Remotely Sensed Data. *Heliyon*, **10**, e30923. https://doi.org/10.1016/j.heliyon.2024.e30923

[19] Martens, B., Miralles, D.G., Lievens, H., van der Schalie, R., de Jeu, R.A.M., Fernández-Prieto, D., *et al.* (2017) GLEAM v3: Satellite-Based Land Evaporation and Root-Zone Soil Moisture. *Geoscientific Model Development*, **10**, 1903-1925. https://doi.org/10.5194/gmd-10-1903-2017

[20] He, S., Zhang, Y., Ma, N., Tian, J., Kong, D. and Liu, C. (2022) A Daily and 500 m Coupled Evapotranspiration and Gross Primary Production Product across China during 2000-2020. *Earth System Science Data*, **14**, 5463-5488. https://doi.org/10.5194/essd-14-5463-2022

[21] Odusanya, A.E., Mehdi, B., Schürz, C., Oke, A.O., Awokola, O.S., Awomeso, J.A., *et al.* (2019) Multi-Site Calibration and Validation of SWAT with Satellite-Based Evapotranspiration in a Data-Sparse Catchment in Southwestern Nigeria. *Hydrology and Earth System Sciences*, **23**, 1113-1144. https://doi.org/10.5194/hess-23-1113-2019

[22] Ha, L.T., Bastiaanssen, W.G.M., van Griensven, A., *et al.* (2018) Calibration of Spatially Distributed Hydrological Processes and Model Parameters in SWAT Using Remote Sensing Data and an Auto-Calibration Procedure: A Case Study in a Vietnamese River Basin. *Water*, **10**, Article 212. https://doi.org/10.3390/w10020212

[23] Franco, A.C.L. and Bonumá, N.B. (2017) Multi-Variable SWAT Model Calibration with Remotely Sensed Evapotranspiration and Observed Flow. *RBRH*, **22**, e35. https://doi.org/10.1590/2318-0331.011716090

[24] Abbas, S.A., Bailey, R.T., White, J.T., Arnold, J.G., White, M.J., Čerkasova, N., *et al.* (2024) A Framework for Parameter Estimation, Sensitivity Analysis, and Uncertainty Analysis for Holistic Hydrologic Modeling Using SWAT+. *Hydrology and Earth System Sciences*, **28**, 21-48. https://doi.org/10.5194/hess-28-21-2024

[25] Bai, J.W. (2025) Review on Effects of Multiple Calibration Strategies on Hydrological Model Performance. *Yangtze River*, **56**, 99-105. (In Chinese)

[26] Abbaspour, K.C., Vaghefi, S.A. and Srinivasan, R. (2018) A Guideline for Successful Calibration and Uncertainty Analysis for Soil and Water Assessment: A Review of Papers from the 2016 International SWAT Conference. *Water*, **10**, Article 6. https://doi.org/10.3390/w10010006

[27] Moriasi, D.N., Gitau, M.W., Pai, N. and Daggupati, P. (2015) Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Transactions of the ASABE*, **58**, 1763-1785.

[28] Gupta, H.V., Kling, H., Yilmaz, K.K. and Martinez, G.F. (2009) Decomposition of the Mean Squared Error and NSE Performance Criteria: Implications for Improving Hydrological Modelling. *Journal of Hydrology*, **377**, 80-91. https://doi.org/10.1016/j.jhydrol.2009.08.003

[29] Knoben, W.J.M., Freer, J.E. and Woods, R.A. (2019) Technical Note: Inherent Benchmark or Not? Comparing Nash-Sutcliffe and Kling-Gupta Efficiency Scores. *Hydrology and Earth System Sciences*, **23**, 4323-4331. https://doi.org/10.5194/hess-23-4323-2019

[30] Franco, A.C.L., de Oliveira, D.Y. and Bonumá, N.B. (2020) Comparison of Single-Site, Multi-Site and Multi-Variable SWAT Calibration Strategies. *Hydrological Sciences Journal*, **65**, 2376-2389. https://doi.org/10.1080/02626667.2020.1810252

[31] Zong, M., Hu, Y., Liu, M., Li, C., Wang, C. and Ping, X. (2020) Effects of Landscape Pattern Change on Water Yield and Nonpoint Source Pollution in the Hun-Taizi River Watershed, China. *International Journal of Environmental Research and Public Health*, **17**, Article 3060. https://doi.org/10.3390/ijerph17093060

[32] Fu, Y.C., Zang, W.B., Dong, F., *et al.* (2016) Yield Calculation of Agricultural Non-Point Source Pollutants in Huntai River Basin Based on SWAT Model. *Transactions of the Chinese Society of Agricultural Engineering*, **32**, 1-8. (In Chinese)

[33] Yu, C.L., Wang, Z.C., Liu, D., *et al.* (2020) Evolution Process and Driving Force Analysis of Natural Wetlands in Xiliao River Basin Based on SWAT Model. *Transactions of the Chinese Society of Agricultural Engineering*, **36**, 286-297. (In Chinese)

[34] Liu, J.H., Zheng, X., Fan, J.M. and Zhao, L.L. (2021) Evaluation of the Value of Water Retention Service in the Middle and Upper Reaches of Hunhe River Based on SWAT Model. *Chinese Journal of Applied Ecology*, **32**, 3905-3912. (In Chinese)

[35] Hao, L. and Wang, J.A. (2012) Evaluate to Water Resources Vulnerability Using SWAT-WEAP Model in Tributary of Xiliaohe River. *Journal of Natural Resources*, **27**, 468-479. (In Chinese)

[36] Yang, X., Ren, L., Liu, Y., Jiao, D. and Jiang, S. (2014) Hydrological Response to Land Use and Land Cover Changes in a Sub-Watershed of West Liaohe River Basin, China. *Journal of Arid Land*, **6**, 678-689. https://doi.org/10.1007/s40333-014-0026-4

[37] Gong, Y. (2022) Spatio-Temporal Distribution Characteristics and Influencing Factors of Drought in the Liaohe River Basin, China. *Frontiers in Environmental Science*, **10**, Article 1044837. https://doi.org/10.3389/fenvs.2022.1044837

[38] Humphrey, V. and Gudmundsson, L. (2019) GRACE-REC: A Reconstruction of Climate-Driven Water Storage Changes over the Last Century. *Earth System Science Data*, **11**, 1153-1170. https://doi.org/10.5194/essd-11-1153-2019

[39] Liu, X., Yang, M., Meng, X., Wen, F. and Sun, G. (2019) Assessing the Impact of Reservoir Parameters on Runoff in the Yalong River Basin Using the SWAT Model. *Water*, **11**, Article 643. https://doi.org/10.3390/w11040643

[40] Qiu, J., Yang, Q., Zhang, X., Huang, M., Adam, J.C. and Malek, K. (2019) Implications of Water Management Representations for Watershed Hydrologic Modeling in the Yakima River Basin. *Hydrology and Earth System Sciences*, **23**, 35-49. https://doi.org/10.5194/hess-23-35-2019

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

[42] Chawanda, C.J., Arnold, J., Thiery, W. and van Griensven, A. (2020) Mass Balance Calibration and Reservoir Representations for Large-Scale Hydrological Impact Studies Using SWAT+. *Climatic Change*, **163**, 1307-1327. https://doi.org/10.1007/s10584-020-02924-x

[43] Yassin, F., Razavi, S., Elshamy, M., Davison, B., Sapriza-Azuri, G. and Wheater, H. (2019) Representation and Improved Parameterization of Reservoir Operation in Hydrological and Land-Surface Models. *Hydrology and Earth System Sciences*, **23**, 3735-3764. https://doi.org/10.5194/hess-23-3735-2019

[44] Ahl, R.S., Woods, S.W. and Zuuring, H.R. (2008) Hydrologic Calibration and Validation of SWAT in a Snow-Dominated Rocky Mountain Watershed, Montana, U.S.A. *Journal of the American Water Resources Association*, **44**, 1411-1430. https://doi.org/10.1111/j.1752-1688.2008.00233.x

[45] Liu, Y., Cui, G. and Li, H. (2020) Optimization and Application of Snow Melting Modules in SWAT Model for the Alpine Regions of Northern China. *Water*, **12**, Article 636. https://doi.org/10.3390/w12030636