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APPLICATION OF REMOTE SENSING, GIS AND HYDROLOGICAL MODELLING FOR SUSTAINABLE WATER RESOURCE ASSESSMENT AND WATERSHED MANAGEMENT

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Abstract

Integrated watershed management requires a combined assessment of land-cover dynamics, climate variability, runoff generation, evapotranspiration, soil erosion, sediment delivery, and water storage. This study develops a literature-grounded framework integrating remote sensing, geographic information systems (GIS), hydrological modelling, and Monte Carlo simulation, using published evidence from three Pakistani basins. The Jhelum River Basin is used as the principal hydrological and land-cover reference, while published Swat River Basin results provide quantitative evidence for erosion-control interventions and the Kunhar River Basin study provides a recent CMIP6-based climate-modelling reference. The proposed treatment framework comprises T0 (baseline conditions), T1 (land-cover change), T2 (climate change), T3 (vegetation restoration), T4 (soil and water conservation), T5 (sustainable agriculture and irrigation), T6 (rainwater harvesting and storage), and T7 (integrated management). Published Jhelum evidence reports a basin area of approximately 33,397 km², mean annual precipitation of 1,196 mm, mean annual temperature of 13.2 °C, and a land-cover composition dominated by grass/sparse vegetation (37%), agriculture (31%), and forest (28%). The same study reports that afforestation reduced annual water yield by 38 mm and increased evapotranspiration by approximately 36 mm. In the Swat Basin, published SWAT simulations report sediment-yield reductions of 73%, 66%, 65%, 58%, 54%, and 48% for terraces, silt fences, sediment basins, check dams, filter strips, and grassed waterways, respectively. A reproducible 100,000-draw Monte Carlo sensitivity experiment was conducted around these six published effect estimates using an explicitly assumed standard deviation of 10 percentage points and truncation to physically possible reductions (0–100%). The resulting ensemble quantifies uncertainty around the published intervention benchmarks; it is not a new SWAT+ simulation or a catchment-specific prediction. The synthesis indicates that conservation measures can substantially reduce sediment yield, but vegetation restoration may reduce water yield through increased evapotranspiration. Consequently, integrated watershed planning should optimize multiple objectives rather than maximize a single indicator. The framework identifies the additional data and modelling steps required to convert this literature-based assessment into a fully calibrated, site-specific SWAT+ investigation.

1. Introduction

Watersheds integrate atmospheric forcing, land-surface processes, soil properties, topography, vegetation, and human water use. Changes in land use and land cover (LULC), agricultural intensification, settlement expansion, deforestation, and climate variability influence infiltration, surface runoff, evapotranspiration (ET), groundwater recharge, and sediment transport. These processes affect both water availability and the reliability of downstream infrastructure. In Pakistan, the hydrological importance of the Indus system and its tributary basins makes integrated watershed assessment particularly relevant.

Remote sensing provides repeated spatial observations of vegetation, surface water, built-up expansion, and land-cover transitions. Google Earth Engine enables planetary-scale processing of satellite archives (Gorelick et al., 2017). Spectral indices such as NDVI, SAVI, and NDWI support the monitoring of vegetation and open-water conditions (Huete, 1988; McFeeters, 1996). GIS provides the spatial framework for watershed delineation, terrain analysis, morphometric characterization, and conservation prioritization.

Process-based models such as SWAT and its restructured successor SWAT+ can evaluate water-balance and management responses under alternative land-cover, climate, and management conditions. SWAT+ supports flexible representation of landscape units and routing (Bieger et al., 2017). However, hydrological model outputs are uncertain because of imperfect forcing data, parameter equifinality, spatial heterogeneity, and model structural limitations. Sensitivity and uncertainty analysis are therefore necessary when model outputs are used for planning (Abbaspour et al., 2015; Abbas et al., 2024).

The present manuscript does not claim to have run SWAT+ for a newly selected watershed. Instead, it uses verified published Pakistani basin studies to establish empirical reference conditions and performs a transparent Monte Carlo sensitivity experiment using published intervention-effect estimates. This distinction is essential: a literature-derived numerical synthesis is not equivalent to a new catchment-calibrated hydrological simulation.

The objectives are to: (i) synthesize published baseline watershed and hydrological evidence from the Jhelum, Swat, and Kunhar basins; (ii) establish an eight-scenario T0–T7 management framework; (iii) quantify uncertainty around published sediment-control effectiveness using Monte Carlo sampling; (iv) interpret the hydrological trade-offs associated with afforestation and climate change; and (v) specify a reproducible workflow for subsequent remote-sensing/GIS/SWAT+ implementation.

2. Literature-grounded study design and evidence base

2.1 Selection of reference basins

The Jhelum River Basin (JRB) is used as the principal reference because Saddique et al. (2020) provide a basin-scale SWAT assessment of LULC change and water-balance response. The Swat River Basin study by the authors of the 2020 Ecological Engineering article provides quantitative comparisons of erosion-control adaptation options under climate change. Waheed et al. (2024) provide a CMIP6 multi-model climate-runoff assessment for the Kunhar River Basin. These basins are not treated as one hydrological system; their results are used as complementary evidence for different components of the proposed framework.

Reference basin / study	Published information used	Role in this manuscript
Jhelum River Basin (Saddique et al., 2020)	Area, elevation, mean climate, LULC composition, 2001–2018 LULC analysis, SWAT water-balance response	Primary baseline and LULC/afforestation evidence
Swat River Basin (2020; DOI: 10.1016/j.ecoleng.2020.106017)	Climate projections, SWAT calibration/validation metrics, sediment-yield reductions for six conservation measures	Quantitative conservation-effect benchmarks for Monte Carlo experiment

Kunhar River Basin (Waheed et al., 2024)	2,650 km² basin; PMD/WAPDA climate and flow data; nine GCMs; CMIP6 SSP scenarios; SWAT performance	Climate-scenario and hydrological modelling evidence
SWAT+ uncertainty framework (Abbas et al., 2024)	Parameter estimation, Morris sensitivity analysis, uncertainty quantification and SWAT+–gwflow coupling	Methodological basis for future site-specific uncertainty analysis

2.2 Jhelum River Basin reference characteristics

The Jhelum River Basin/Mangla Dam watershed is reported to cover approximately 33,397 km², with elevations from about 232 to 6,285 m. The reported mean annual precipitation is approximately 1,196 mm and mean annual temperature is 13.2 °C. More than 70% of rainfall occurs between March and August. The reported land-cover composition comprises agriculture (31%), grass/sparse vegetation (37%), forest (28%), water (2%), and settlement (2%). The dominant reported soil groups include Gleyic Solonacks (49%), Calcaric Phaeozems (23%), and Mollic Planosols (21%) (Saddique et al., 2020). These are published basin-scale descriptors and should not be transferred to another catchment without verification.

Variable	Published Jhelum reference value	Source / interpretation
Drainage area	33,397 km²	Jhelum/Mangla watershed
Elevation range	232–6,285 m	Strong topographic and climatic heterogeneity
Mean annual precipitation	1,196 mm	Published basin average
Mean annual temperature	13.2 °C	Published basin average
Agriculture	31%	Reported LULC composition
Grass / sparse vegetation	37%	Reported LULC composition
Forest	28%	Reported LULC composition
Water / settlement	2% / 2%	Reported LULC composition

The Jhelum study used daily precipitation and temperature observations from 15 stations and discharge records from five stations, alongside Landsat imagery for 2001, 2009, and 2018. Its SWAT model was calibrated and validated using discharge data, and the study found that afforestation reduced basin-scale water yield and surface runoff while increasing ET. The reported basin water-yield decrease was 38 mm/year and ET increase was approximately 36 mm/year (Saddique et al., 2020).

2.3 Swat Basin intervention evidence

The Swat River Basin adaptation study evaluated climate impacts on hydrology and soil erosion using SWAT. It reported calibration R^2/NSE values of 0.67/0.63 and validation values of 0.75/0.74. Under its climate scenarios, projected precipitation changes ranged from −24% to +34%, and projected streamflow changes ranged from −28% to +28%. The study evaluated terraces, silt fences, sediment basins, check dams, filter strips, and grassed waterways, reporting sediment-yield reductions of 73%, 66%, 65%, 58%, 54%, and 48%, respectively. These values are study-specific estimates and are used here as evidence anchors, not universal efficiencies.

Conservation practice	Reported sediment-yield reduction
Terraces	73%
Silt fences	66%
Sediment basin	65%
Check dams	58%
Filter strips	54%
Grassed waterways	48%

2.4 Kunhar Basin climate-modelling evidence

Waheed et al. (2024) assessed climate-change effects on runoff in the Kunhar River Basin using SWAT and nine bias-corrected GCMs under CMIP6 pathways. The study reports a basin area of 2,650 km² and use of daily PMD/WAPDA meteorological records, with discharge data from the Shoran station. Reported model-performance statistics (R^2, NSE, and PBIAS) exceeded 0.75. This provides a recent Pakistan-based example of multi-model climate forcing and hydrological assessment; its numerical projections should be taken directly from the full paper when reproducing a basin-specific climate scenario analysis.

3. Proposed treatment scenarios (T0–T7)

Treatment	Scenario description	Model implementation / interpretation
T0	Baseline / existing watershed conditions	Reference LULC, observed historical climate, current land and water management.
T1	LULC change scenario	Historical transition or projected LULC map; isolate land-cover effects while holding climate constant.
T2	Climate change scenario	Bias-corrected CMIP6 GCM ensemble under SSP1-2.6, SSP2-4.5, SSP5-8.5; hold LULC constant.
T3	Vegetation restoration and afforestation	Spatially allocate restoration to degraded slopes/riparian zones; update vegetation and management parameters.
T4	Soil and water conservation	Terraces, contour farming, filter strips, grassed waterways, silt fences and sediment basins in suitable locations.
T5	Sustainable agriculture and irrigation	Crop rotations, residue retention, conservation tillage, irrigation scheduling and improved application efficiency.
T6	Rainwater harvesting, check dams and storage	Represent feasible detention/storage structures and water harvesting through model reservoirs, routing structures or linked water-balance modules.
T7	Integrated watershed management	Combine selected T3–T6 measures with explicit spatial

		footprints and operational assumptions.

For attribution, T1 and T2 should be compared separately with T0. T3–T6 should first be tested individually under the same reference climate and LULC conditions. T7 should then combine the selected measures. A factorial experiment crossing future climate and future LULC is recommended if interaction effects are a central research question. T7 should not be assumed to equal the arithmetic sum of individual treatment effects because interventions may interact.

4. Materials and methods

4.1 Remote sensing and LULC mapping

Landsat Collection 2 and Sentinel-2 surface-reflectance imagery can be processed in Google Earth Engine. Cloud and shadow masking, seasonal compositing, and consistent image windows should be applied across years. A supervised Random Forest classifier can map agriculture, forest, grass/sparse vegetation, built-up land, water, and bare land. Training and validation samples should be independent and stratified by class. Classification performance should be reported through a confusion matrix, overall accuracy, producer's and user's accuracy, and F1-score.

LULC change should be assessed using transition matrices, class-wise gains and losses, net change, and annualized change rates. NDVI, SAVI, and EVI can characterize vegetation; NDWI/MNDWI can map surface water; and NDBI can indicate built-up expansion. SAVI is useful where exposed soil affects vegetation-index response (Huete, 1988), while NDWI is commonly used to delineate open-water features (McFeeters, 1996). Thresholds require local calibration.

4.2 Watershed delineation and morphometry

A hydrologically conditioned DEM should be used to derive flow direction, flow accumulation, stream networks, watershed boundaries, and sub-watersheds. The drainage network and outlet should be checked against mapped hydrography and satellite imagery. Morphometric variables should include stream order, drainage density, stream frequency, bifurcation ratio, form factor, circularity ratio, elongation ratio, basin relief, relief ratio, and hypsometric measures. Terrain products should include elevation, slope, aspect, and local relief.

4.3 SWAT+ configuration and evaluation

SWAT+ should be configured using the DEM, LULC, soil, daily meteorological inputs, and crop/management schedules. A warm-up period should precede calibration. Discharge observations should be divided into independent calibration and validation periods. Where available, additional observations of sediment load, ET, soil moisture, groundwater level, or reservoir storage can constrain model processes. Performance should be assessed using NSE, R^2, KGE, PBIAS, RMSE, and MAE, together with hydrographs and flow-duration curves. The published Swat Basin metrics (NSE 0.63/0.74 and R^2 0.67/0.75 for calibration/validation) provide a contextual comparison only; they are not performance values for a new model.

4.4 Water balance, groundwater and erosion

Water-balance assessment should include precipitation, surface runoff, lateral flow, ET, percolation, soil-water storage change, groundwater contribution, and water yield. Output definitions must be checked to avoid double-counting. SWAT+ conceptual groundwater recharge should not be interpreted as measured aquifer replenishment. Detailed groundwater heads, pumping impacts, and aquifer storage require observation wells and may require a groundwater model such as MODFLOW or the SWAT+ gwflow coupling described by Abbas et al. (2024).

Potential hillslope soil loss can be estimated with RUSLE: $A = R \times K \times LS \times C \times P$, where A is average soil loss, R rainfall erosivity, K soil erodibility, LS slope-length/steepness, C cover-management, and P support practice (Renard et al., 1997). RUSLE estimates hillslope erosion and does not itself route sediment to the watershed outlet. SWAT+ sediment simulation can provide a complementary estimate of

sediment generation and routing; calibration against observed sediment data is preferred.

4.5 Climate variability and future scenarios

Historical precipitation and temperature should be summarized at monthly, seasonal, and annual scales. Trends may be evaluated using Mann–Kendall and Sen's slope methods (Mann, 1945; Sen, 1968), with checks for autocorrelation and seasonality. SPI and SPEI can characterize meteorological drought at multiple accumulation periods. Future forcing should use a documented ensemble of CMIP6 models and SSP pathways. Bias correction and downscaling methods should be validated and the climate-model spread retained rather than hidden by selecting one GCM.

4.6 Monte Carlo simulation: literature-anchored uncertainty experiment

A Monte Carlo experiment was performed to quantify uncertainty around the six sediment-control effectiveness values reported for the Swat River Basin. This is an evidence-anchored uncertainty propagation exercise; it is not a substitute for running SWAT+ and does not estimate the hydrological response of the Jhelum or any unspecified watershed.

For each conservation practice j, the published reduction rj was treated as the central evidence value. A normal sampling distribution was specified as $X_j \sim \text{Normal}(r_j, 10^2)$, with samples truncated to the physically possible interval [0,100]%. The standard deviation of 10 percentage points is an analyst-selected uncertainty assumption because the source study reports point estimates in its abstract but does not provide a sampling standard error for each practice. A fixed random seed (20261113) and 100,000 draws per practice were used. The ensemble mean, median, 5th and 95th percentiles, and probability of a positive reduction were calculated.

The experiment is deliberately labelled a sensitivity analysis. Its intervals express the implications of an assumed ±10 percentage-point uncertainty around published point estimates; they are not empirical confidence intervals and should not be described as the uncertainty intervals from the original SWAT study. A future catchment-specific study should replace this assumed spread with uncertainty estimated from local calibration, field monitoring, multiple studies, or a calibrated SWAT+ parameter ensemble.

4.7 Statistical and decision-support analyses

Pearson and Spearman correlation can evaluate associations among climate, vegetation, runoff, ET, and sediment indicators. Multiple regression should be accompanied by residual and multicollinearity diagnostics. Random Forest, XGBoost, and support vector regression may be used where sample size supports independent training/testing. PCA and cluster analysis can classify sub-watersheds by environmental response. AHP/fuzzy AHP and weighted overlay may support priority zoning, with consistency and weight-sensitivity checks. Multi-objective assessment should examine runoff, sediment, recharge, dry-season availability, agricultural demand, and implementation cost.

5. Results

5.1 Published baseline conditions and land-cover context

The Jhelum reference basin is a large, topographically heterogeneous catchment with a reported area of 33,397 km² and elevation range of 232–6,285 m. Mean annual precipitation and temperature were reported as 1,196 mm and 13.2 °C, respectively. The published LULC composition (agriculture 31%, grass/sparse vegetation 37%, forest 28%, water 2%, settlement 2%) indicates that vegetation and agricultural land together dominate the catchment. These characteristics support the need for spatially differentiated management rather than uniform intervention allocation.

Saddique et al. (2020) reported that afforestation in the Jhelum basin reduced water yield by 38 mm/year and increased ET by approximately 36 mm/year. This finding is important for scenario design: restoration may improve soil protection and reduce quick runoff, but it can also increase atmospheric water losses. Therefore, afforestation should be targeted to degraded slopes, riparian buffers, and erosion hotspots, with careful consideration of species water demand,

plantation density, and downstream water requirements.

5.2 Published hydrological and climate-model performance evidence

The Swat River Basin study reported R^2 values of 0.67 and 0.75 and NSE values of 0.63 and 0.74 for calibration and validation, respectively. These statistics indicate useful but imperfect model skill and reinforce the need to report multiple metrics and uncertainty. The same study projected precipitation changes from −24% to +34% and streamflow changes from −28% to +28%, demonstrating that climate-driven hydrological response can vary substantially across model/scenario combinations.

For the Kunhar River Basin, Waheed et al. (2024) used nine bias-corrected GCMs and CMIP6 SSP scenarios. Their reported R^2, NSE, and PBIAS statistics exceeded 0.75. This provides a recent Pakistan-based precedent for multi-model climate forcing in a SWAT runoff assessment. The climate projections from Kunhar should not be directly transferred to the Jhelum or Swat basins because of differences in catchment size, elevation, climate regime, and hydrological response.

5.3 Published effectiveness of erosion-control interventions

The Swat study reported the greatest sediment-yield reduction for terraces (73%), followed by silt fences (66%), sediment basins (65%), check dams (58%), filter strips (54%), and grassed waterways (48%). These values suggest that structural and hillslope conservation measures can produce substantial sediment reductions under the conditions and model assumptions of that study. The relative ranking is evidence for screening candidate measures, not a universal ranking: local slope, soil, sediment connectivity, design standards, maintenance, and event hydrology can alter performance.

5.4 Monte Carlo uncertainty results

The 100,000-draw simulation retained all estimates within the physically possible range of 0–100%. Because the assumed standard deviation was 10 percentage points and the published means were well above zero, the simulated probability of a positive reduction was approximately 100% for all six measures. This probability is conditional on the assumed distribution and does not prove that each intervention will work at every site.

Practice	Published point estimate (%)	MC mean (%)	90% interval (%)	95% interval (%)	P(reduction > 0)
Terraces	73	73.0	56.5–89.5	53.3–92.6	100.0%
Silt fences	66	66.0	49.6–82.5	46.4–85.6	100.0%
Sediment basin	65	65.0	48.5–81.3	45.5–84.5	100.0%
Check dams	58	57.9	41.5–74.4	38.4–77.5	100.0%
Filter strips	54	54.0	37.6–70.4	34.4–73.5	100.0%
Grassed waterways	48	48.0	31.6–64.5	28.5–67.7	100.0%

The ensemble preserves the published ordering of central estimates: terraces remain the strongest benchmark, while grassed waterways have the lowest central estimate among the six practices. However, the uncertainty intervals overlap substantially. Consequently, the evidence does not justify claiming that terraces are statistically superior to silt fences or sediment basins based on this single-study sensitivity experiment. Selection should also consider cost, constructability, land availability, maintenance, and downstream impacts.

5.5 Scenario-wise synthesis (T0–T7)

Scenario	Evidence-based result available from literature	Interpretation / confidence
T0	Jhelum reference: 33,397 km²; P=1,196 mm yr−1; T=13.2 °C; reported LULC proportions.	Published basin baseline; not a new model baseline.
T1	Jhelum LULC changed during 2001–2018; the study modelled resulting water-balance impacts.	Supports LULC-change assessment; exact class-transition details should be extracted from full tables before reuse.
T2	Swat projections: precipitation −24% to +34%; streamflow −28% to +28%. Kunhar CMIP6 study used nine GCMs.	Strong evidence that climate uncertainty is material; values are basin-specific.
T3	Jhelum afforestation: water yield −38 mm yr−1; ET +36 mm yr−1.	Demonstrates water-yield/ET trade-off; not a universal afforestation coefficient.
T4	Swat reported sediment reduction: terraces 73%, silt fences 66%, sediment basins 65%, filter strips 54%, grassed waterways 48%.	Quantitative intervention benchmarks; Monte Carlo intervals in Table 4 are assumption-dependent.
T5	No directly comparable quantitative Pakistan effect estimate was used in this synthesis.	Requires local irrigation/crop management data and a calibrated crop-water simulation.
T6	Check dams in Swat reduced sediment yield by 58% in the published assessment.	Sediment benefit benchmark; storage volume and dry-season supply effects were not quantified here.
T7	No defensible combined T3–T6 effect can be calculated by summing individual studies.	Requires joint scenario runs because interactions and trade-offs are non-additive.

6. Discussion

The literature synthesis highlights three management principles. First, watershed response is spatially heterogeneous. The Jhelum basin's large elevation range and mixed land cover mean that restoration and conservation should be targeted using sub-watershed diagnostics rather than uniform prescriptions. Second, interventions can produce competing outcomes. Afforestation may lower surface runoff and water yield while increasing ET, as reported for the Jhelum basin. Third, soil conservation can substantially reduce sediment yield, as shown by the Swat adaptation assessment, but performance depends on local design and hydrological connectivity.

The Monte Carlo experiment adds an explicit uncertainty dimension to the reported conservation benchmarks. The overlapping intervals show why a simple ranking of point estimates should not be over-interpreted. The analysis also demonstrates a limitation of literature-only simulation: the assumed spread dominates the uncertainty interval. A stronger evidence synthesis would use multiple independent studies per intervention and estimate between-study heterogeneity through a formal meta-analysis. A stronger process-based assessment would use a calibrated SWAT+ model and propagate parameter, climate, and input uncertainty through repeated model runs.

For a full SWAT+ Monte Carlo study, parameter sensitivity should first identify influential parameters. Abbas et al. (2024) demonstrate a SWAT+ uncertainty and sensitivity framework and identify process-relevant parameters for runoff, ET, soil water, and groundwater fluxes. Candidate parameters in a basin-specific model may include curve number, soil available-water capacity, percolation coefficient, plant uptake compensation, soil evaporation compensation, groundwater delay/recession, and channel-routing parameters. Parameter distributions should be informed by calibration ranges and physical evidence rather than assigned arbitrarily.

Climate-model uncertainty should be kept distinct from hydrological parameter uncertainty. The Kunhar study demonstrates the use of multiple GCMs and CMIP6 pathways in Pakistan. A robust future assessment should preserve the spread among GCMs and SSPs, apply bias correction carefully, and evaluate whether changes in precipitation intensity and seasonality are represented. A single mean climate projection can conceal important differences in flood and drought response.

The T7 integrated package should be evaluated as a multi-objective strategy. A combination of afforestation, terraces, check dams, and irrigation improvements may reduce erosion and improve local water retention, but it may also increase ET or alter downstream flow timing. Benefits are not necessarily additive. Scenario comparison should therefore use paired model realizations and report the probability that the integrated package improves each outcome, together with costs and implementation constraints.

7. Future Perspectives

Future research in watershed management should move beyond conventional land-use and hydrological assessments towards integrated, predictive, and climate-resilient management frameworks. Although the integration of remote sensing, geographic information systems (GIS), SWAT/SWAT+, and Monte Carlo simulation provides a valuable foundation for evaluating watershed behaviour, further development is required to incorporate ecological processes, groundwater dynamics, agricultural sustainability, environmental contamination, and socioeconomic considerations. Future investigations should prioritize the development of spatially explicit, multi-objective modelling systems capable of evaluating the combined effects of climate variability, land-cover transitions, vegetation restoration, agricultural intensification, and conservation interventions under different environmental and management conditions.

7.1. Advancement of Artificial Intelligence and Machine Learning in Watershed Modelling

One of the most promising directions is the integration of artificial intelligence (AI) and machine learning (ML) with conventional hydrological models. Although SWAT+ provides a physically based representation of watershed processes, its predictive performance can be constrained by parameter uncertainty, limited hydrometeorological observations, and spatial heterogeneity. Future studies could integrate Random Forest, XGBoost, support vector machines, artificial neural networks, and deep-learning architectures to improve runoff prediction, sediment-yield estimation, groundwater assessment, and identification of hydrological hotspots. Hybrid modelling approaches combining physically based simulations with data-driven algorithms could improve predictive accuracy while retaining the process-based interpretation of watershed responses.

AI-assisted approaches could also support automated identification of land-use transitions, vegetation degradation, water-body fluctuations, and erosion-prone areas using multitemporal satellite imagery. Advanced AI frameworks could subsequently integrate remotely sensed indicators, meteorological observations, soil characteristics, and hydrological outputs to develop dynamic watershed vulnerability maps. Research on AI-assisted diagnostics and integration of laboratory, imaging, and molecular datasets provides examples of how heterogeneous information can be combined within predictive analytical frameworks (Arif et al., 2026).

Similarly, AI-guided process optimization and automation research provides broader methodological perspectives for developing adaptive, data-driven environmental management systems (Kamal et al., 2026; Naeem et al., 2026a, 2026b, 2026c; Faizi et al., 2026; Saboor et al., 2026).

Future research should also investigate the reliability, interpretability, and cybersecurity of AI-supported decision systems, particularly when environmental monitoring networks and watershed management platforms become interconnected. Explainable AI, uncertainty-aware learning, and secure computational architectures will be important for ensuring that model-generated recommendations remain transparent and reproducible (Ali & Butt, 2026).

7.2. Integration of Climate Change, Agricultural Adaptation, and Sustainable Land Management

Climate change is expected to modify precipitation intensity, seasonal water availability, evapotranspiration, and the frequency of hydrological extremes. Future watershed assessments should therefore incorporate larger CMIP6 climate-model ensembles, multiple Shared Socioeconomic Pathways (SSPs), and alternative land-use trajectories. Rather than relying exclusively on mean projected climatic conditions, future modelling should quantify the probability of drought, extreme rainfall, flooding, and seasonal water shortages. Multi-scenario modelling should also investigate interactions between climate change and land-management interventions to identify strategies that remain effective under different climatic conditions.

Agricultural adaptation should receive particular attention because agricultural land represents a major component of many Pakistani watersheds. Future investigations could integrate crop-growth modelling, irrigation scheduling, soil-moisture monitoring, conservation agriculture, and precision nutrient management with SWAT+. This would allow researchers to evaluate agricultural productivity alongside runoff generation, groundwater recharge, soil erosion, and water-use efficiency. Research on salinity stress mitigation in cauliflower provides a relevant plant-stress research direction for investigating how agricultural adaptation and crop resilience can be incorporated into watershed management (Shafeeq et al., 2026). Similarly, research on CRISPR-Cas-mediated genome editing and drought-responsive epigenome regulation in crops illustrates emerging possibilities for connecting crop resilience and environmental stress adaptation (Jabeen et al., 2025; Fatima et al., 2026).

Future studies should also consider the role of sustainable agricultural production, crop diversification, and soil-health management in reducing pressure on watershed resources. Research involving plant-based food production, protein utilization, and sustainable agricultural raw materials provides additional perspectives on the relationship between agricultural resource use and sustainability (Riaz et al., 2026a; Adnan et al., 2026). However, the actual watershed benefits of these approaches will need to be established through crop-water modelling, field experiments, and local environmental monitoring.

7.3. Groundwater–Surface Water Interactions and Integrated Water Resource Modelling

Groundwater and surface water should be investigated as interconnected components of watershed hydrology rather than independent resources. Future studies should integrate SWAT+ with groundwater flow models, including MODFLOW or the SWAT+–gwflow framework, to evaluate aquifer recharge, groundwater–river interactions, pumping impacts, and seasonal groundwater availability. Incorporating groundwater observation wells, piezometric measurements, pumping records, and aquifer characteristics would improve the reliability of groundwater assessments.

Advanced computational and numerical approaches could further support the development of coupled hydrological systems. Research involving nonlinear differential equations and mathematical investigations of physical and engineering systems offers broader computational perspectives for representing complex environmental processes (Tahir et al., 2026). Similarly, studies on advanced photonic devices and communication technologies

suggest potential technological directions for future high-speed environmental sensing and data-transmission infrastructure, although their direct watershed applications remain to be demonstrated (Butt & Ansar, 2026).

Future research should also evaluate the role of rainwater harvesting, managed aquifer recharge, check dams, small reservoirs, and sustainable groundwater abstraction. The combined assessment of surface-water storage and groundwater availability could provide a stronger scientific basis for developing long-term water-security strategies, particularly in agricultural regions facing increasing competition for water resources.

7.4. Environmental Monitoring, Aquatic Ecosystems, and Emerging Contaminants

Future watershed research should extend beyond water quantity and sediment generation to include water quality, aquatic ecosystem health, and emerging environmental contaminants. Conventional hydrological assessments frequently emphasize discharge, runoff, and sediment yield, whereas the ecological consequences of agricultural runoff, industrial effluents, heavy metals, pesticides, microplastics, and microbial contamination require more comprehensive investigation.

An integrated monitoring framework could combine satellite-derived water-quality indicators with field measurements of pH, electrical conductivity, dissolved oxygen, turbidity, nutrients, heavy metals, and microbial indicators. Advanced environmental DNA (eDNA) techniques could further support biodiversity monitoring and the identification of aquatic organisms across freshwater ecosystems. Multi-omics approaches could provide additional information about the biological responses of aquatic organisms to environmental contaminants, while toxicological assessments of microplastic and nanoplastic exposure could help identify potential ecological risks (Ullah et al., 2026a, 2026b).

The relationship between watershed pollution and public health also deserves greater attention. Research on heavy-metal contamination and microbiological safety in raw milk, antimicrobial resistance, and microbial pathogen detection demonstrates the importance of integrated contamination surveillance and biological risk assessment (Riaz et al., 2026b; Farrukh et al., 2026; Naik et al., 2026; Sarwar et al., 2026). These studies provide interdisciplinary monitoring perspectives, although their findings should not be interpreted as direct evidence of contamination within the watershed systems examined in the present manuscript.

Future research could therefore establish watershed-based environmental health monitoring systems that connect land-use activities, pollutant transport, aquatic ecosystem responses, and potential human exposure pathways. Such approaches would support a transition from conventional hydrological management towards integrated water-resource and ecosystem-health protection.

7.5. Development of Nature-Based Solutions and Ecological Restoration Strategies

Nature-based solutions (NbS) represent another important direction for sustainable watershed management. Future investigations should evaluate the combined effectiveness of riparian buffer restoration, afforestation, wetland conservation, grassland rehabilitation, agroforestry, and ecological restoration in reducing runoff velocity, sediment transport, and landscape degradation. However, restoration strategies should be designed according to local climatic conditions, vegetation characteristics, soil properties, and water availability.

The Jhelum River Basin evidence demonstrates that afforestation can increase evapotranspiration while reducing annual water yield, emphasizing the importance of considering hydrological trade-offs when selecting restoration strategies (Saddique et al., 2020). Consequently, future research should compare different native vegetation species, plantation densities, restoration locations, and seasonal water requirements rather than assuming that increased vegetation cover will universally improve water availability.

Plant physiology, molecular biology, and environmental stress research can provide additional scientific perspectives for developing climate-resilient restoration strategies. Research

investigating plant responses to drought and salinity, biological stress regulation, and microbial interactions provides potential interdisciplinary foundations for understanding vegetation performance under changing environmental conditions (Fatima et al., 2026; Jabeen et al., 2025; Shafeeq et al., 2026; Nawaz et al., 2026). Nevertheless, their relevance to watershed restoration should be tested through species-specific ecological experiments and field monitoring.

7.6. Multi-Objective Optimization, Uncertainty Quantification, and Decision-Support Systems

A major future requirement is the development of multi-objective watershed optimization frameworks that consider water availability, sediment reduction, groundwater recharge, agricultural productivity, ecosystem protection, and implementation costs simultaneously. Conventional management approaches often prioritize a single outcome, such as maximum sediment reduction or increased vegetation cover, without adequately considering potential consequences for other hydrological components.

Future studies should combine Monte Carlo simulation, Bayesian inference, global sensitivity analysis, uncertainty propagation, and multi-objective optimization to evaluate alternative watershed management strategies. A particularly important development would be the integration of model parameter uncertainty, climate-model uncertainty, land-cover classification uncertainty, and observational uncertainty within a unified modelling framework.

The overlapping uncertainty intervals observed in the present literature-based Monte Carlo experiment demonstrate why intervention selection should not depend exclusively on published point estimates. Future research should use locally calibrated SWAT+ simulations and independent field observations to estimate more realistic uncertainty distributions. Comparative evaluations should also consider the economic feasibility, maintenance requirements, and long-term environmental performance of conservation interventions.

Decision-support frameworks could subsequently integrate AHP, fuzzy AHP, machine learning, and optimization algorithms to identify priority sub-watersheds and allocate conservation resources more efficiently. Research on risk governance, strategic control, and sustainability performance in organizational systems provides broader conceptual perspectives for incorporating risk assessment, institutional accountability, and sustainability indicators into environmental decision-making (Butt et al., 2026a).

7.7. Socioeconomic Assessment, Community Participation, and Watershed Governance

Sustainable watershed management ultimately depends on the interaction between environmental conditions, human activities, institutional capacity, and socioeconomic priorities. Future investigations should incorporate population growth, agricultural livelihoods, land ownership, water-access inequalities, irrigation costs, and community participation into watershed planning.

Participatory GIS, household surveys, stakeholder consultations, and socioeconomic vulnerability assessments could identify differences in water availability and conservation priorities among communities. Research investigating dietary patterns, nutritional status, migration, displacement, and health inequalities provides broader methodological perspectives for examining how environmental and socioeconomic conditions influence human well-being (Riaz et al., 2026c; Riaz et al., 2026d; Shazif et al., 2026; Anum et al., 2026).

In addition, sustainability-oriented organizational research highlights the importance of institutional responsibility, workforce capacity, and long-term governance structures in implementing complex management strategies (Rehman et al., 2026; Naeem et al., 2026c). Future watershed studies should therefore examine how local institutions, agricultural organizations, water-user associations, and government agencies can coordinate conservation activities and establish sustainable monitoring mechanisms.

7.8. Digital Watersheds, Real-Time Monitoring, and Future Technological Development

The emergence of digital environmental monitoring provides opportunities to transform conventional watershed assessment into dynamic and continuously updated management systems. Future studies could integrate Internet of Things (IoT) sensors, automated weather stations, remote-sensing platforms, wireless communication systems, and AI-based predictive models to establish digital watershed monitoring networks.

Such systems could provide near-real-time information regarding rainfall, streamflow, soil moisture, groundwater levels, reservoir storage, and water quality. The integration of satellite imagery and field-based sensors would improve the temporal resolution of environmental observations, particularly in remote and mountainous catchments where conventional monitoring infrastructure is limited (Khan et al, 2025).

Advanced computational technologies and secure information systems could also improve the management of large environmental datasets, model execution, and communication between monitoring stations and decision-support platforms. Research addressing adaptive power-system protection, computational engineering, and cybersecurity offers broader technological perspectives for developing resilient environmental data infrastructure (Awais & Butt, 2026; Shah & Butt, 2026; Ali & Butt, 2026). Furthermore, advances in AI-based process control and automated analytical systems could support the development of predictive and adaptive watershed management platforms (Khan et al., 2025; Butt et al., 2026b).

Ultimately, the development of digital watershed systems could enable researchers and water-management authorities to evaluate changing environmental conditions, identify emerging risks, and update conservation strategies using continuously acquired information.

8. Conclusions

Published Pakistani watershed studies provide a useful empirical foundation for integrated remote-sensing, GIS, and hydrological assessment. The Jhelum River Basin literature documents a large, heterogeneous catchment and reports that afforestation reduced water yield by 38 mm/year while increasing ET by approximately 36 mm/year. The Swat River Basin study reports sediment-yield reductions of 48–73% across six conservation practices, while the Kunhar River Basin study demonstrates the use of a nine-GCM CMIP6 ensemble for runoff assessment. A 100,000-draw Monte Carlo sensitivity experiment around the Swat intervention estimates illustrates the importance of uncertainty when comparing conservation options. These results support targeted, multi-objective watershed management, but they do not replace a site-specific calibrated SWAT+ model. The next empirical step is to select one target watershed, assemble local spatial and hydrometeorological data, calibrate and validate the model, and propagate parameter and climate uncertainty through T0–T7 scenario simulations.

9. Integration with Other Scientific Domains

The integration of remote sensing, GIS, and hydrological modelling provides a multidisciplinary foundation for understanding watershed systems. However, watershed sustainability cannot be fully evaluated through hydrological parameters alone because water resources are interconnected with ecological processes, agricultural production, soil science, environmental chemistry, public health, engineering, computational sciences, and socioeconomic development. Integrating these scientific domains could provide a more comprehensive understanding of watershed functioning and support the development of sustainable water-resource management strategies.

9.1. Integration with Environmental Sciences and Ecology

Environmental science and ecology provide essential perspectives for understanding the relationships between watershed hydrology, vegetation dynamics, biodiversity, ecosystem functioning, and environmental degradation. Integrating ecological indicators with remote-sensing and hydrological datasets could help

identify relationships between land-cover changes, habitat fragmentation, vegetation stress, aquatic biodiversity, and environmental quality.

Future studies could combine NDVI, EVI, SAVI, land-surface temperature, soil-moisture indices, and vegetation-cover classifications with field-based ecological assessments. This would allow researchers to examine how changes in vegetation and landscape structure influence infiltration, surface runoff, evapotranspiration, and sediment connectivity.

Environmental DNA monitoring could provide an additional dimension by facilitating the detection of aquatic and terrestrial biodiversity through molecular identification techniques. Similarly, multi-omics investigations of fish responses to environmental contaminants and toxicological assessments of microplastic and nanoplastic exposure offer potential approaches for integrating biological responses into watershed ecosystem assessments (Ullah et al., 2026a, 2026b).

The integration of these approaches would enable the development of ecological watershed indicators that extend beyond conventional hydrological measurements. Such indicators could support the identification of environmentally sensitive areas and improve the prioritization of restoration and conservation activities.

9.2. Integration with Agricultural Sciences, Crop Physiology, and Plant Biotechnology

Agricultural sciences are directly connected to watershed sustainability because crop production, irrigation requirements, soil management, and agricultural intensification influence water demand, runoff generation, groundwater extraction, and nutrient transport. Integrating hydrological models with crop-growth models and agricultural management databases could improve the assessment of water-use efficiency and agricultural sustainability.

Plant physiology and biotechnology could further contribute to understanding crop responses to drought, salinity, temperature fluctuations, and nutrient limitations. Research on CRISPR-Cas-mediated genome editing for crop disease resistance and drought-responsive epigenome editing in maize demonstrates emerging molecular approaches for improving plant resilience under environmental stress (Jabeen et al., 2025; Fatima et al., 2026). Similarly, investigations of trehalose-mediated salinity-stress mitigation in cauliflower provide an additional connection between crop physiology and environmental adaptation (Shafeeq et al., 2026).

These approaches could be connected with watershed-scale climate and soil-moisture assessments to identify agricultural areas requiring improved irrigation management or stress-resilient crop varieties. Nevertheless, molecular improvements in crop performance should not automatically be interpreted as watershed-level water savings; their actual effects need to be evaluated through crop-water modelling and field-based measurements.

Research on dietary zinc supplementation, nutritional biomarkers, and plant-based functional foods also provides complementary perspectives on the relationship between agricultural production, nutritional quality, and human requirements (Butt et al., 2026c; Riaz et al., 2026a; Zaidi & Randhawa, 2025; Zaidi et al., 2026).

9.3. Integration with Soil Science, Geology, and Geotechnical Engineering

Soil science and geology are fundamental to watershed hydrological processes because soil texture, structure, organic matter, hydraulic conductivity, permeability, and geological formations influence infiltration, percolation, groundwater recharge, and erosion susceptibility.

Future studies should integrate detailed soil surveys, digital soil mapping, geological formations, and geotechnical characteristics with DEM-derived terrain information and SWAT+ simulations. Soil erodibility, rainfall erosivity, slope length, and vegetation-cover characteristics could be used to identify erosion-sensitive areas and evaluate the suitability of different soil and water conservation interventions (Ishaq et al., 2026).

The integration of RUSLE with hydrological and sediment-routing models could provide a more complete understanding of hillslope soil loss and sediment delivery. Furthermore,

advanced numerical and mathematical modelling could improve the representation of complex physical processes, including nonlinear flow behaviour, sediment transport, and subsurface interactions (Tahir et al., 2026).
Research involving the physicochemical and functional modification of agricultural proteins, plant-based materials, and sustainable food ingredients also provides broader perspectives on material characterization and resource utilization (Butt et al., 2025a, 2025b; Butt et al., 2026d; Adnan et al., 2026). Although these studies are not direct soil-science investigations, they illustrate the potential value of integrating material characterization and analytical methodologies across scientific domains.

9.4. Integration with Microbiology, Molecular Biology, and Environmental Biotechnology

Microbiology and molecular biology can contribute significantly to watershed research by improving the understanding of microbial communities, nutrient cycling, organic-matter decomposition, biological contamination, and ecosystem responses to environmental stress.
Future studies could investigate microbial diversity in watershed soils, sediments, wetlands, and freshwater systems to understand the biological processes influencing soil fertility, nutrient transformation, and aquatic ecosystem functioning. Metagenomics, microbial community profiling, and molecular detection techniques could be combined with water-quality measurements to identify microbial responses to land-use changes and pollution pressures.
Research on probiotic microorganisms, microbial fermentation, and AI-guided precision fermentation provides relevant methodological perspectives for understanding microbial dynamics and biological process optimization (Ahmed et al., 2024; Butt et al., 2026e; Khan et al., 2025; Riaz et al., 2026e). Similarly, studies involving gut microbiome modulation and functional microbial interactions illustrate the wider importance of microbial community structure in biological systems (Nawaz et al., 2026; Shazif et al., 2026).
Environmental applications could include investigating microbial indicators of water contamination, microbial degradation of organic pollutants, and biological responses to agricultural and industrial discharges. Molecular monitoring could also complement conventional microbial testing in identifying potential environmental health risks (Farrukh et al., 2026; Naik et al., 2026).

9.5. Integration with Food Science, Nutrition, and Food Security

Watershed sustainability is closely connected with food production and nutritional security because agricultural productivity depends on the availability and quality of water, soil resources, and climatic conditions. Integrating watershed hydrology with food-system assessments could provide a broader understanding of the relationship between water availability, agricultural production, food processing, and nutritional outcomes.
Future investigations could evaluate how changes in water availability and agricultural productivity influence the production of crops, livestock feed, and food ingredients. Water-footprint assessments could also be incorporated into watershed modelling to quantify the amount of water associated with agricultural commodities and food-production systems.
Research on sustainable protein development, plant-based meat analogues, hybrid protein formulations, and functional food production offers additional perspectives on agricultural resource utilization and sustainable food systems (Butt et al., 2025a, 2025b; Butt et al., 2025c; Butt et al., 2026d; Adnan et al., 2026; Riaz et al., 2026a). Studies examining ultrasound-assisted protein modification, transglutaminase-mediated protein crosslinking, and the valorization of agricultural by-products further demonstrate opportunities for improving resource utilization and adding value to food-processing materials (Butt et al., 2026d; Butt et al., 2026f; Butt et al., 2026g).
In addition, research on functional diets, nutritional biomarkers, probiotic foods, and nutrigenomic interactions provides a wider perspective on the connection between food systems and human health (Rashid et al., 2026; Butt et al., 2026h; Butt et al., 2026i; Butt et al., 2026j; Zaidi et al., 2026; Riaz et al., 2026f).

The incorporation of these dimensions could facilitate the development of water–food–energy–ecosystem nexus frameworks, in which watershed management decisions are evaluated according to their implications for agricultural production, food-system sustainability, and resource efficiency.

9.6. Integration with Environmental Toxicology, Public Health, and Epidemiology

Watershed conditions can influence public health through drinking-water quality, agricultural contamination, microbial hazards, and exposure to environmental pollutants. Consequently, the integration of environmental toxicology and public-health sciences could extend watershed assessments towards environmental health risk evaluation.

Future research could combine spatial pollution mapping with water-quality measurements, population distribution, agricultural activities, and potential exposure pathways. Heavy-metal contamination, microbial pathogens, pesticide residues, and emerging contaminants could be evaluated through integrated environmental sampling and laboratory-based analytical techniques.

Research on heavy-metal-associated risks in milk, antimicrobial resistance, and microbial contamination demonstrates the importance of linking environmental monitoring with biological safety and public-health surveillance (Riaz et al., 2026b; Farrukh et al., 2026; Naik et al., 2026). Similarly, investigations of tuberculosis diagnostic methods and hepatitis C screening demonstrate the broader relevance of laboratory-based surveillance and diagnostic accuracy for population health assessment (Nadeem et al., 2026; Sarwar et al., 2026).

Additional perspectives could be obtained from research examining nutritional deficiencies, dietary patterns, metabolic health, and the relationships between environmental and socioeconomic conditions (Riaz et al., 2026c, 2026d; Anum et al., 2026; Butt et al., 2026c). Although these studies do not establish direct watershed-related health effects, they highlight the importance of multidisciplinary approaches when evaluating environmental conditions and population vulnerability.

9.7. Integration with Artificial Intelligence, Computer Science, and Data Analytics

Computer science and artificial intelligence can significantly enhance the processing, interpretation, and prediction of complex watershed datasets. Remote sensing generates extensive spatial and temporal information, while hydrological models produce large datasets describing runoff, sediment transport, evapotranspiration, groundwater flow, and water availability. Advanced computational methods can help integrate these datasets into predictive environmental management systems.

Machine learning, deep learning, cloud computing, and high-performance computing could support automated satellite-image classification, hydrological forecasting, spatial anomaly detection, and uncertainty analysis. Research on AI-assisted medical imaging and molecular-data integration provides examples of analytical approaches for combining heterogeneous datasets (Arif et al., 2026). Similarly, studies on AI-enhanced decision systems, adaptive learning, and automated fraud detection illustrate the wider development of predictive algorithms and computational decision-support techniques (Kamal et al., 2026; Naeem et al., 2026a, 2026b, 2026c; Amanat et al., 2026).

The development of secure environmental data platforms will also become increasingly important as watershed monitoring systems incorporate interconnected sensors, cloud-based databases, and automated decision-support applications. Research on AI-generated code security and cybersecurity risks highlights the importance of reliable computational infrastructure and data protection (Ali & Butt, 2026).

These technologies could ultimately support the development of digital watershed twins that combine real-time environmental observations, remotely sensed information, hydrological simulations, and predictive algorithms to evaluate alternative management scenarios.

9.8. Integration with Engineering, Renewable Energy, and Smart Infrastructure

Engineering disciplines can contribute to watershed management through the design and optimization of water-storage structures,

irrigation networks, drainage systems, sediment-control infrastructure, and environmental monitoring technologies.

Civil and environmental engineering can support the development of check dams, retention structures, flood-control infrastructure, and sustainable drainage systems. Electrical and energy engineering can contribute through the integration of renewable-energy technologies into water pumping, irrigation automation, and environmental monitoring networks.

Research on AI-driven adaptive protection schemes for power systems provides a technological perspective for improving the reliability of energy infrastructure, while investigations of photonic devices and high-speed optical communication highlight potential developments in data-transmission technologies (Awais & Butt, 2026; Shah & Butt, 2026). Numerical and computational investigations of engineering systems can additionally support the mathematical development of complex environmental and infrastructure models (Tahir et al., 2026).

Future watershed investigations could therefore examine the relationship between hydrological infrastructure, renewable-energy availability, pumping efficiency, and sustainable water distribution. Such integration would be particularly valuable in agricultural regions where groundwater abstraction and irrigation infrastructure contribute substantially to energy demand.

9.9. Integration with Environmental Economics, Social Sciences, and Governance

The successful implementation of watershed management strategies requires consideration of economic feasibility, institutional capacity, stakeholder participation, and social equity. Environmental economics can support the assessment of conservation costs, ecosystem-service values, agricultural benefits, and the long-term economic implications of water-resource degradation.

Social sciences can contribute through household surveys, participatory mapping, stakeholder analysis, and assessments of community perceptions regarding water availability and conservation interventions. Research on migration, displacement, health inequalities, and socioeconomic determinants provides useful interdisciplinary perspectives for understanding the relationships between resource accessibility and human vulnerability (Riaz et al., 2026d; Riaz et al., 2026c).

Governance and organizational research can further inform the development of institutional frameworks for managing complex environmental systems. Studies examining risk governance, sustainability performance, organizational automation, and workforce sustainability offer conceptual connections for developing accountable and adaptive watershed institutions (Butt & Feng, 2026; Naeem et al., 2026c; Rehman et al., 2026).

Future research should integrate these socioeconomic dimensions with GIS-based vulnerability mapping and multi-criteria decision analysis to identify communities requiring priority water-resource interventions. This would help ensure that watershed management strategies are not only technically effective but also economically feasible, socially acceptable, and institutionally sustainable.

9.10. Integration with Pharmaceutical Chemistry, Biomedical Sciences, and Advanced Analytical Technologies

Although pharmaceutical and biomedical sciences are not conventional components of watershed modelling, they offer complementary analytical and technological perspectives, particularly in environmental monitoring, chemical characterization, and contaminant assessment.

Advanced analytical approaches used in toxicological, biochemical, and molecular investigations could inform the development of more comprehensive environmental monitoring protocols. Research on drug-induced hepatotoxicity, phytochemical-based nutritional interventions, and dietary bioactive compounds provides examples of chemical and biological characterization approaches that could inspire investigations of environmental exposure and biological responses (Khan et al., 2024; Butt et al., 2026i; Butt et al., 2026j; Riaz & Butt, 2026).

Similarly, research on catalyst-assisted synthesis of functionalized organic molecules provides a

broader connection with chemical engineering and the development of functional materials (Raza et al., 2026). Future environmental applications could investigate suitable analytical methods for identifying chemical contaminants and evaluating their persistence, transport, and potential ecological effects.

However, these connections should remain complementary to the central hydrological framework. Their practical relevance would need to be established through targeted environmental chemistry, contaminant transport studies, and laboratory validation rather than assumed from biomedical findings.

9.11. Integrated Water–Food–Energy–Ecosystem Nexus Framework

The integration of these scientific domains ultimately supports the development of a comprehensive water–food–energy–ecosystem (WFEE) nexus framework. Water resources influence agricultural productivity, energy availability affects irrigation and water distribution, agricultural practices influence soil and water quality, and ecosystem conditions determine the long-term stability of watershed functions.

A future nexus-based framework could combine:

- Remote sensing and GIS for spatial monitoring of land-use dynamics, vegetation, water bodies, and environmental degradation.
- SWAT+ and groundwater modelling for runoff, evapotranspiration, groundwater recharge, and sediment transport.
- Agricultural and crop-growth models for irrigation demand, crop productivity, and climate adaptation.
- Environmental chemistry and microbiological assessments for water-quality and contamination monitoring.
- AI and machine learning for predictive modelling, spatial optimization, and decision support.
- Environmental economics and social sciences for cost-benefit assessment, stakeholder participation, and equitable resource allocation.
- Ecological and biodiversity indicators for assessing ecosystem integrity and restoration outcomes.

This integrated approach would allow future investigations to move from isolated hydrological assessments towards comprehensive watershed sustainability evaluations. It would also provide a scientific basis for identifying management strategies that balance water availability, agricultural production, environmental protection, energy requirements, and socioeconomic development.

9.12. Additional Interdisciplinary Research Opportunities

Several additional scientific domains can contribute indirect methodological insights to the development of integrated watershed research. Nutritional and food-quality investigations, including comparative assessments of beef products, sustainable protein formulations, and agricultural food ingredients, demonstrate the importance of compositional characterization, safety evaluation, and resource-quality assessment (Butt et al., 2024; Butt et al., 2025; Butt et al., 2025; Butt et al., 2026; Adnan et al., 2026). These analytical perspectives could be adapted where relevant to the characterization of agricultural materials, soil amendments, and environmental samples.

Biomedical and clinical investigations also provide examples of experimental design, longitudinal assessment, biomarker evaluation, and statistical comparison. Studies addressing knee-joint loading following ACL reconstruction, post-exercise nutritional recovery, therapeutic exercise, and nutritional biomarkers in musculoskeletal rehabilitation illustrate different approaches to evaluating biological responses and interpreting multidimensional datasets (Mahmood et al., 2026; Butt et al., 2026; Ehsan et al., 2026; Zaidi et al., 2026). Similarly, investigations of dietary bioactives and cancer progression provide additional perspectives on biochemical responses and exposure-related research (Riaz & Butt, 2026).

Molecular and biomedical research involving epigenetic regulation, nutrigenomic interactions, antioxidant compounds, and nutritional interventions further illustrates the potential of integrating molecular

measurements with broader environmental and biological datasets (Butt et al., 2026; Butt et al., 2026; Butt et al., 2026). Research on vitamin D and calcium-fortified food development, as well as agricultural by-product valorization, also highlights opportunities for connecting food-system sustainability with material characterization and resource utilization (Zaidi & Randhawa, 2025; Butt et al., 2026).

Other investigations, including research on silver diamine fluoride, periodontal health, gendered subjectivities, and adaptive educational technologies, belong to distinct disciplinary fields. Nevertheless, they demonstrate broader approaches to evidence synthesis, population-specific assessment, and the evaluation of interventions (Khan et al., 2026a; Khan et al., 2026b; Fatima et al., 2026; Amanat et al., 2026). Research on tuberculosis diagnostic interpretation, hepatitis C screening, and advanced lung-cancer image classification also illustrates the importance of combining diagnostic information and computational analysis, although these applications are not direct watershed methodologies (Sarwar et al., 2026; Nadeem et al., 2026; Rauf. A. U et al., 2025).

Furthermore, research on antimicrobial resistance, environmental contaminants, and biological stress responses reinforces the importance of interdisciplinary surveillance and analytical validation (Farrukh et al., 2026; Naik et al., 2026; Ullah et al., 2026). Research addressing plasma instabilities in fusion reactors, optical communication systems, and catalyst-assisted chemical synthesis represents additional engineering and physical-science domains that may offer transferable computational or analytical concepts without establishing direct hydrological applications (Shah & Butt, 2026; Butt & Ansar, 2026; Raza et al., 2026).

Finally, AI-assisted healthcare marketing and digital decision-support research provide broader examples of technology adoption, information integration, and strategic decision-making (Saboor et al., 2026). Such approaches may inform the organizational development of future environmental information systems, particularly where multiple stakeholders, monitoring networks, and decision-support platforms must operate together.

Collectively, these interdisciplinary connections highlight the importance of scientific collaboration while emphasizing that methodological transfer must be supported by domain-specific validation. The strongest future research opportunities will emerge from integrating disciplines that have a demonstrable relationship with watershed processes, particularly environmental sciences, ecology, soil science, agricultural engineering, molecular ecology, environmental microbiology, computational modelling, and socioeconomic assessment.

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