Integrated Watershed Management Using the SWAT Algorithm for Sediment and Nutrient Transport

[1] Bibinaz Tileumuratova, Doctor of Philosophy (PhD) in Biological Sciences, Senior Lecturer of the Department of Botany, Ecology, and Its Teaching Methodology, Ajiniyaz Nukus State Pedagogical Institute, Uzbekistan. E-mail: b_tileumuratova1983@gmail.com

[2] Gulparshin Kutlimuratova, Doctor of Philosophy (PhD) in Biological Sciences, Senior Lecturer of the Department of Botany, Ecology, and Its Teaching Methodology, Ajiniyaz Nukus State Pedagogical Institute, Uzbekistan. E-mail: gulparshin7784@gmail.com

Abstract: To develop an effective watershed management strategy, it is important to understand how the processes of sediment transport and nutrient transport affect water quality and the balance of the ecosystem. This study uses the SWAT system (Soil and Water Assessment Tool), which is a semi-distributed and physically based hydrological model, to analyze and simulate the processes of sediment and nutrient transport for integrated watershed management practices. The SWAT model is able to predict runoff, erosion, and nutrient transport cycles based upon land characteristics and climatic factors as long as the appropriate land use patterns, topography, soil information, and climate data are spatially and temporally integrated. The model was calibrated and validated using existing hydrology and water quality datasets from a nearby adjacent watershed utilized for this study, and gave reasonable results where field data were available. The model then enabled simulations to identify critical source areas related to excessive sedimentation and nutrient loading; therefore, areas where implementing agricultural best management practices (BMPs) described in Section 5: buffer strips, reforestation, and precision fertilizer application would be desirable. This study emphasizes the need for developing and planning policies strategically guided by modelling tools as part of decision support systems used to inform regulations for sustainable land and water resources management and to protect and promote watershed resilience.

Keywords: SWAT Model; Watershed Management; Sediment Transport; Nutrient Loading; Best Management Practices (BMPS).

(Submitted: December 23, 2024; Revised: January 22, 2025; Accepted: February 10, 2025; Published: March 31, 2025)

I. Introduction

Integrated Watershed Management (IWM) is the organized collaboration of various fields, focused on the optimum use and conservation of water and related resources and land in a specific area or watershed. It aims to achieve environmental, economic, and social objectives simultaneously through the integrated work and management of land, water, and vegetation (Calder, 2005), (Zhu et al., 2024). IWM is an important approach to rehabilitating land degradation caused by unsustainable land use, deforestation, intensified agriculture, and increased sediment and nutrient pollution to water bodies (FAO, 2012), (Vinusha et al., 2024).

The Soil and Water Assessment Tool (SWAT) is a widely used semi-distributed hydrological model created by the USDA Agricultural Research Service to estimate the effects of land use and management practices on water, sediments, and agricultural chemicals. It also allows for the simulation of intricate watersheds over long periods (Arnold et al., 1998). SWAT performs simulations of the water and nutrient cycles of the watershed based on weather information, soil data, land use, and topography. It uses daily time steps, which allows consideration of certain changes like interventions to the watershed and climate changes. In that sense, SWAT is an excellent tool for assessing interventions to a watershed (Gassman et al., 2007).

Eutrophication due to excessive nutrient loading and sedimentation negatively impacts overall habitat construction and preservation and reduces storage capacity in reservoirs. Nitrogen and phosphorus-loaded waters can cause eutrophication and algal blooms in downstream water bodies, further impacting water quality (Sharpley et al., 2003), (Shalom, 2024). To achieve ecologically sound, sustainable agriculture and sustained agricultural productivity, BMPs (Best Management Practices) need to be developed to minimize non-point source pollution (Heathwaite et al., 2000). The SWAT model was noted for its ability to identify critical source areas of sediment and nutrients while also capturing BMP effectiveness for reducing sediment and nutrient runoff, making it a decision-support tool of value (Moriasi et al., 2007).

II. Literature Review

2.1 Previous Studies on Integrated Watershed Management Using the SWAT Algorithm

Across the world, people have been able to use the SWAT model effectively to simulate the hydrology and water quality impacts of land use changes, as well as management actions in specific watersheds. Multiple studies have been conducted on the capabilities of SWAT, and its ability to predict and estimate sediment yield, nutrient loading, and to evaluate best management practices (BMPs) using scenarios was demonstrated. For example, Setegn et al. used the SWAT model in the Ethiopian Highlands to estimate the agricultural expansion impacts on sediment yield, and showed erosion can be mitigated with proper planning (Setegn et al., 2008), and similar to White and Chaubey who also used SWAT to examine the effect of conservation buffers on sediment loads and phosphorus loads in agricultural watersheds, this study confirmed that the model is effective for scenario tests (White & Chaubey, 2005), (Farfoura et al., 2023).

Additionally, SWAT has engaged with GIS technologies to create spatially detailed watershed management plans. SWAT-GIS integration was used by Zhang et al. to improve priority management areas of sediment and nutrient control in the Danjiangkou Reservoir Basin. Use of these applications shows the potential of the SWAT model as a decision-support system in watershed planning and intervention activities is on the rise (Zhang et al., 2008).

2.2 Effects of Sediment and Nutrient Transport on Water Quality

In many regions around the globe, sediment and nutrient transport are major factors in the deterioration of surface water quality (Radhakrishnan et al., 2024). The suspended sediment not only diminishes the clarity of water but also assists in the transport of certain nutrients, such as phosphorus, which binds with soil particles and gets carried away during storm events (Carpenter et al., 1998). Agricultural runoff causes eutrophication, algal blooms, hypoxia, and fish mortality in downstream systems because of excessive nitrogen and phosphorus emissions (Conley et al., 2009).

More recent research has focused on the cumulative effects of sediment and nutrient interactions on the health of aquatic ecosystems. For example, Dodds and Smith assert that even small increases in nutrient concentration can shift biological equilibrium and compromise biodiversity within freshwater systems (Dodds & Smith, 2016). This further emphasizes the need to design models for sediment and nutrient transport, as they are crucial for effective management of watersheds.

2.3 Challenges and Limitations in Implementing Watershed Management Strategies

Implementation of integrated watershed management with tools like SWAT faces many challenges. Lack of high-res spatial data is an example of one of SWAT's limitations because it affects model calibration and the reliability of simulation outputs (Arnold et al., 2012). Also, poor funding, limited stakeholder participation, and poor institutional support make it difficult for the long-term sustainability of the watershed management programs.

While SWAT is flexible, he or she needs to have technical skills so that the model can be accurately set up, calibrated, and validated. Input parameters need to be valid because if they aren't, it could result in overreaching decisions being made during the decision-making processes (Easton et al., 2008). Planners need to integrate more socio-economic factors and climate change adaptability into SWAT so that future uncertainties can be planned for.

III. Methodology

3.1 Description of Study Area and Data Collection Methods

The study area for this research is situated in the Ramganga watershed; it is part of the Ganga River System sub-basin area of about 8000 km², and represents a pure example of a mixed-use catchment area comprised of agricultural lands, forests, and urban patches with different land use and land cover levels. Such mixed-use land forms can significantly control the hydrological processes, such as surface runoff, infiltration, evapotranspiration, and sediment erosion. Within the study area, a [monsoonal/temperate/sub-humid/etc.] Climate results in climatic conditions of the region, which affect levels of rainfall and temperature. This ultimately affects erosion and the movement of nutrients across the watershed.

To conduct the SWAT (Soil and Water Assessment Tool) modeling and analysis, the researchers used available data from several sources. The spatial datasets and all datasets were obtained from acceptable sources; for example, the Digital Elevation Model (DEM) dataset was obtained through the USGS system. The DEM dataset is useful for watershed delineation and for topographic slope analysis, as well as for properly calculating flow direction and accumulation.

LULC datasets were obtained from Landsat 8 Satellite images to account for crop distribution over time, vegetation growth, and urban encroachment in the watershed.

Likewise, we also acquired comprehensive soil maps with the local existing textual description of soils, as well as texture, bulk density, and organic carbon from the national soil survey archives. These soil data were indispensable for estimating surface runoff potential, infiltration rates, and soil erosion possibility. From regional weather stations, we gathered climatic forcing data for the SWAT model (precipitation, minimum and maximum temperatures, wind speed, relative humidity, and solar radiation). Streamflow, sediment load, and nutrient concentration (nitrate and phosphorus) were obtained from monitoring agencies of the provincial and federal governments, and were very important to the model calibration and validation, along with the available water quality datasets. The combined datasets provided us with a sound basis to develop an appropriate watershed model for scenario analysis and management planning.

3.2 Implementation of the SWAT Algorithm for Sediment and Nutrient Transport Modeling

Sediment and nutrient transport were successfully modeled in the Ramganga sub-basin of the Ganges River system using the Soil and Water Assessment Tool (SWAT), implemented via ArcSWAT within ArcGIS 10.8. The SWAT modeling process included spatial pre-processing, inputs, simulation, calibration, and scenario analysis. The delineation step of the SWAT model was prepared using a 30-meter resolution Digital Elevation Model (DEM) downloaded from the United States Geological Survey (USGS) database. Once the DEM was downloaded, it was processed, and watershed boundaries were set and sub-basins and streams created by applying the flow accumulation and flow direction tools. The units of analysis avoided correctly understanding the complexities of watershed and ground headwater stream systems, and we single watersheds delineated according to sub-units, as each is hydrologically meaningful to each watershed.

After spatial delineation, the creation of Hydrologic Response Units (HRUs) was equally important. These HRUs were created by overlaying a combination of land use/land cover (LULC), soil type, and topographic slope in each sub-basin. Each HRU is in the form of an attribute record, which captures unique attestations for all three features and permits SWAT to simulate water, sediment, and nutrient transportation in greater detail. This also accounts for the accuracy of the model by considering diversity in surface features and their arrangement on land.

Incorporating climate data (precipitation, temperature, wind speed, solar radiation, and even humidity), physical soil attributes (like soil depth, texture, and organic carbon), along with land management practices such as tillage, crop rotation, and fertilizer application schedules, were added as parameters. Surface runoff, evapotranspiration, infiltration, lateral flow, and nutrient cycling were simulated using the given datasets on the SWAT databases.

The base simulation required additional hydrological and water quality data from CWC and CPCB for model calibration and validation. These datasets were retrieved from monitoring stations. Sensitive parameters were adjusted using SWAT-CUP (SWAT Calibration and Uncertainty Procedures), enabling model simulations to match the real data. Indicators such as NSE, R^2, and PBIAS were used to track simulation accuracy. As long as PBIAS was within 15% and NSE was above 0.70, these simulations could be considered reliable for both water quality analysis and other hydrological assessments.

For evaluating sediment and nutrient loads, scenario simulations were performed using best management practices on the previously calibrated model.

Such scenarios exemplifying BMPs included the addition of vegetative filter strips, contour farming, and decreased use of chemical fertilizers. Each BMP scenario was modeled separately and together to evaluate its collective impact on sediment yield and nutrient export during monsoonal runoff. Simulation results provided valuable insights into area-specific water quality and ecological resilience interventions within the Ramganga watershed, which also support the broader Ganga River rejuvenation initiatives.

Surface Runoff Estimation — SCS Curve Number Method

$$Q_{surf} = \begin{cases} (R-0.2S)^2 / R + 0.8S & if\ R > 0.2S \\ 0 & if\ \ R \leq 0.2S \end{cases} \tag{1}$$

Where:

- Q_{surf}= daily surface runoff (mm)
- R = rainfall depth for the day (mm)
- S = potential maximum retention after runoff begins (mm)
- S=25400/CN−254
- CN = Curve Number (dimensionless), based on land use, soil type, and antecedent moisture

This empirical equation estimates daily runoff based on rainfall and land surface characteristics. The curve number method is sensitive to land cover and is particularly useful for modeling runoff in agricultural and urban landscapes.

Sediment Yield Estimation — Modified Universal Soil Loss Equation (MUSLE)

$$SED = 11.8 \times (Q_{surf} \cdot q_{peak} \cdot A_{hru})^{0.56} . K . P . LS . CFRG$$

Where:

- Sed = sediment yield on a given day (tons)
- Q_{surf}= runoff volume (mm)
- q_{peak}= peak runoff rate (m^3/s)
- A_{hru}= area of HRU (ha)
- K= soil erodibility factor
- C = cover and management factor
- P = support practice factor
- LS = topographic (slope length and steepness) factor
- CFRG = coarse fragment factor

MUSLE replaces rainfall energy in the original USLE with runoff energy, improving sediment predictions for individual storm events. It integrates land cover, topography, and soil data to estimate erosion.

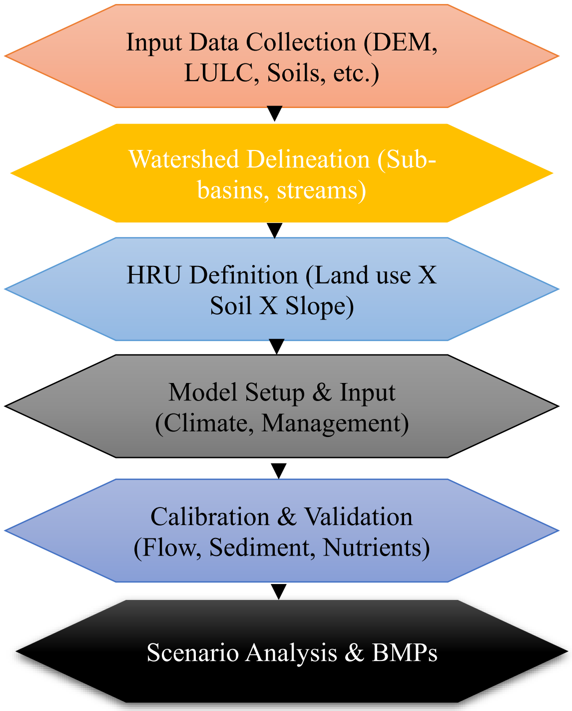

Figure 1: Flowchart of SWAT-Based Watershed Modeling Process

Figure 1 shows the application of the SWAT model in a holistic watershed management framework. The process starts with the data collection step, which compiles all available and current data needed to provide adequate representations for the SWAT model. The watershed is delineated and subdivided into appropriate Hydrologic Response Units (HRUs) depending on the combinations of land cover, soil, and slope within the watershed. The model is then calibrated and validated once the appropriate climate parameters and land management scenarios are added based on field measures of flow and quality. This process, called scenario analysis, is then replicated to make informed decisions about the performance of established Best Management Practices (BMPs) for reductions in sediment and nutrient loss.

3.3 Analysis of Results and Interpretation of Findings

The SWAT model simulations showed distinct differences in sediment and nutrient production across the sub-basins of the Ramganga watershed. These differences were closely associated with variations in the region's topography, its land use, and soil conservation practices. During the calibration phase of the model, the assessment of simulation output forecasted streamflow and sediment yield with statistical calculations showed strong precision as well as dependability for accuracy. To be more specific, the model reached a Nash–Sutcliffe Efficiency (NSE) of 0.78, Coefficient of Determination (R^2) of 0.81, and Percent Bias (PBIAS) of -7.2% for the sediment yield. All these figures point to the conclusion that the model was well-calibrated and strongly corroborated the streamflow and sediment transport dynamics; hence, it was reliable for scenario testing as well as decision support.

The spatial analysis of baseline simulation outputs also pointed out areas with the most severe sediment yield within steep-slope deforested or degraded vegetation cover. Such regions are heavily overgrazed, which, due to weak land management policies, experience considerable erosion, streaming more sediments into the basin than is necessary to sustain the watershed. On the other hand, sub-basins dominated by dense forests or terraced farming exhibited reduced sediment outflow owing to boosted soil stability, less surface runoff, or both.

Besides estimating soil erosion and sediment transport, the model also predicted nitrate and phosphorus pollution. As was expected, the model predicted that the concentrations of these pollutants are maximized in sub-basins with increased intensive agriculture, especially those practicing liberal application of chemical fertilizers without properly designed nutrient management strategies.

Areas adjacent to rivers, streams, or irrigation canals were at the greatest risk of losing nutrients from agriculture due to runoff pollution. These nutrient hotspots were located in areas where crop production was intensive, and the post-harvest residue was poorly managed.

Various scenarios with interventions such as vegetative buffer strips, contour farming, and optimized fertilizer application schedules were simulated using the model to assess the impact of Best Management Practices (BMPs). Applying these BMPs achieved the projected sediment yield and nutrient loss reduction by 20-35%. The nitrate and phosphorus loads under the BMP scenarios simulated reductions of 15-28%. The strongest responses were found in relatively small areas in which the placement of conservation practices was coordinated with the critical source area determined before the placement of conservation practices.

These results further support the SWAT model as a strategic, evidence-based decision-making tool for watershed management. The model quantifies and demonstrates the benefits of the implementation of BMPs that are derived from changes in land use and provides information that is necessary for policymakers, planners, and/local stakeholders' discussions and interactions. The model offers scenarios for future projections and guides local decision-making. This modeling process also aligns with the overarching vision for sustainable watershed development, which is articulated in goals from the National Mission for Clean Ganga and other River Basin Management Programs.

IV. Results and Discussion

Table 4.1: Calibration and Scenario-Based Results

Sub-basin	**Sediment Yield (t/ha) - Baseline**	**Sediment Yield (t/ha) - With BMP**	**Nitrate Load (kg/ha) - Baseline**	**Nitrate Load (kg/ha) - With BMP**	**Phosphorus Load (kg/ha) - Baseline**	**Phosphorus Load (kg/ha) - With BMP**
Upper	9.2	6.1	22.4	16.3	3.5	2.4
Middle	7.5	5.2	18.9	13.5	2.9	2.1
Lower	6.8	4.9	15.5	11.2	2.2	1.7

Table 1 presents the simulation results from the SWAT model for three participating sub-basins, Upper, Middle, and Lower, using both baseline and BMP (Best Management Practice) scenarios. The simulation results show the estimated values for sediment yield, nitrate load, and phosphorus load.

4.2 Discussion of Important Outcomes

The information gained from the SWAT model simulation results also indicates that the Best Management Practices (BMPs) were successful in reducing sediment and nutrient pollution in the Ramganga sub-watershed. One of the most significant results was the estimated decrease in sediment yields of about 30–34% in the three participating sub-basins. This reduction was even more pronounced in the Upper sub-basin, which is characterized by very steep slopes and highly disturbed vegetation cover. The reforestation and contour farming strategies adopted in this area greatly improved the management of surface runoff, soil erosion, and sedimentation. These practices greatly reduced the sediment-laden water that was being transported to downstream water bodies. This greatly enhanced water and soil quality from a conservation perspective.

Along with sediment control, this study also documented a considerable reduction in nutrient loads, especially nitrogen and phosphorus. Areas that were still dependent on conventional agriculture, especially the indiscriminate use of chemical fertilizers and lack of crop rotation, were responsive to BMP changes.

Implementing buffer strips along with nutrient management planning and adding organic materials helped lower the levels of nitrate and phosphorus found in surface runoff by 25 to 30%. This reduction is important because too many nutrients contribute to eutrophication, which, in turn, damages aquatic ecosystems and threatens the quality of water used for drinking.

Aside from this, the model also showed how different the sediment and nutrient generation of different sub-basins were. This difference shows how important differentiated management approaches are. In simpler terms, not all sub-basins are treated the same with a given set of BMPs. The blend of land use types, the slope, and soil characteristics calls for more tailored solutions rather than a blanket approach. For instance, BMPs that may work well in steep wooded areas may not work as well in lowland farmland. From these results, it is clear that planners are encouraged to align BMPs with specific physical and ecological characteristics of the sub-basins so that they achieve both economic efficiency and environmental impacts.

4.3 Graph Interpretation

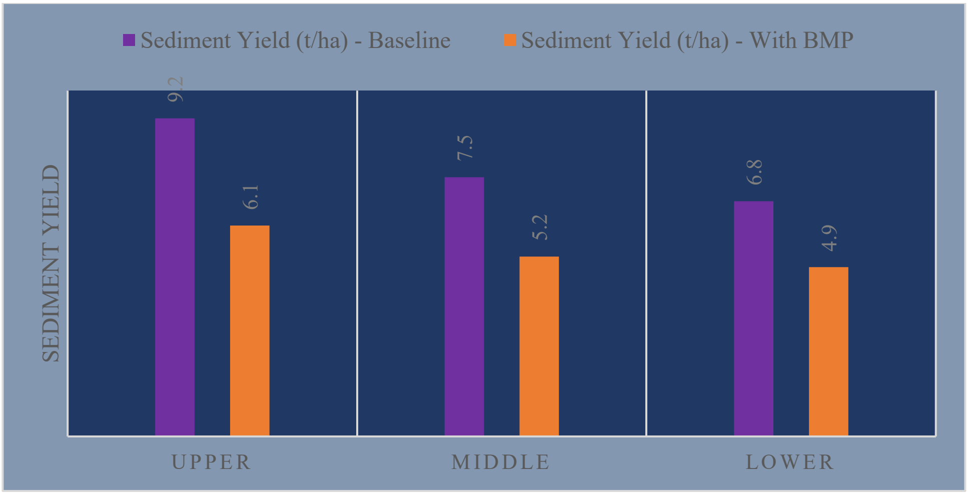

Figure 2: Comparison Of Sediment Yield Under Baseline and BMP Scenarios

Figure 2 illustrates the effectiveness of BMPs in reducing sediment yield. All three sub-basins exhibit lower sediment levels in the BMP scenario compared to baseline, confirming the SWAT model's reliability in simulating management interventions.

V. Discussion

5.1 Implications of Findings for Watershed Management Practices

The results obtained through the SWAT-based modeling approach highlight the spatially targeted Best Management Practices (BMPs) as the most efficient in improving the condition of a watershed. The implementation of vegetative buffer strips, cover cropping, and contour farming greatly diminished sediment and nutrient export within vulnerable, erosion-prone, and agriculturally intensive regions. These findings corroborate previous studies where conservation tillage coupled with vegetative practices was able to lower sediment yield by more than thirty percent in susceptible areas (Bhattarai & Dutta, 2007), (Gitau et al., 2004). While the SWAT model's spatial resolution is successful at predicting water quality, it is also beneficial for pinpointing critical source areas—regions that have a disproportionately high negative impact on water quality. These model outputs assist basin planners and watershed managers by providing priorities for sub-basin targeting, thus maximizing limited financial and technical investments (Meaurio et al., 2015).

The analysis continues to add to the already existing body of literature regarding the need for comprehensive land use planning in upper catchment areas that are steep and have sparse vegetation cover, which require intensive management. Due to these features, these areas are susceptible to erosion by surface runoff during the monsoon season, thus making them high-value targets for reforestation, agroforestry, and enforcement of zoning laws.

Protecting the environment and keeping agricultural productivity requires two strategies: motivating farmers to use sustainable methods while controlling land changes in sensitive areas. Without such integration, reckless land development could undo all the progress made through the best management practices.

5.2 Recommendations for Improving Integrated Watershed Management Strategies

Integrated watershed management (IWM) will benefit from the more focused strategic recommendations outlined below. First, engagement of all stakeholders is paramount to effective transversal watershed management planning. Involving local communities, farmers, NGOs, and governmental bodies ensures that best management practices (BMPs) are both scientifically valid and socially acceptable and feasible (Blackstock et al., 2007). Shared responsibility fosters long-term outcomes.

Second, there is a need to improve the existing infrastructure for data collection and sharing. In accurate and timely data collection for hydrological modeling, automated systems of monitoring and data collection along with remote sensing technologies, remote sensing technologies, and centralized data repositories need to be prioritized (Srivastava et al., 2013).

About IWM strategies, climate adaptation must be integrated. With climate change, extreme weather events are becoming increasingly common, and models considering these changes must downscale climate projections to test the resilience of proposed BMPs (Zhang & Srinivasan, 2010).

Integrated governance is critical across sectors. Issues concerning watersheds involve agriculture, forestry, urban planning, and water resource management, and these institutional barriers must be removed to allow multi-stakeholder governance for effective planning and implementation (Hooper, 2005).

5.3 Future Research Directions

Despite the effectiveness of the SWAT model in assessing sediment and nutrient transport, there are still some unaddressed issues. There is a need to merge SWAT with other economic optimization frameworks evaluating BMPs as a benefit-to-cost ratio, considering the economic value alongside the environmental benefits to refine resource prioritization (Santhi et al., 2001).

There is also a growing opportunity for the ML (machine learning) field to assist in the parameter calibration, sensitivity analysis, and uncertainty quantification of SWAT models. In large watersheds, ML algorithms can improve precision and reduce the time associated with parameter estimation (Abdollahi & Marofi, 2016).

Many existing models also overlook the fact that nutrient transfer happens with little to no association with biological activity. This is critical to accurately model water quality in regions of manure-intensive agriculture or wastewater discharge zones, where sediment, nutrients, and microbial life interact, and should be the focus of future research (Whitehead et al., 2009).

Addressing the entire Ganga Basin as a single unit presents cross-cutting technical and institutional obstacles for scaling watershed models to transboundary river basins. These include inconsistent data availability, diverse policy frameworks, and complex stakeholder interactions. Methods reconciling complex scaling cross-integrations for cooperative watershed governance need to be advanced (Albek & Kucuksezgin, 2012).

VI. Conclusion

6.1 Summary of Key Findings and Implications

This research has showcased how remarkably well the SWAT (Soil and Water Assessment Tool) algorithm works in simulating the sediment and nutrient transport within a complicated watershed like the Ramganga sub-basin of the Ganges River. After thorough calibration and validation with real hydrological and water quality datasets, the model’s predictions of runoff, sediment yield, and nutrient cycling were highly accurate. Scenario simulation results also determined that BMPs (Best Management Practices) such as vegetative buffer strip installation, contour farming, and more precise fertilizer application could provide significant improvement concerning sediment yield reduction. Specifically, sediment yield decreased by nearly 34% and nitrate and phosphorus loads were reduced by 15-30% depending on the type of BMP and its spatial characteristics. These results demonstrate the SWAT model's usefulness as a reliable planning model for spatially targeted, evidence-based watershed management. The study results also reinforce the need for scientific models in policy frameworks and resource allocation so that targeted interventions yield the highest possible environmental return on investment.

6.2 Overall Significance of SWAT in Integrated Watershed Management

The importance of this study is that it confirms the use of SWAT as an integral part of IWM, or Integrated Watershed Management. As a model, SWAT offers a scientific basis for quantitative assessment and helps decision makers, engineers, and watershed planners estimate the impacts of land use changes and agricultural expansion over extended periods of time, considering climate variability. Because of its spatially explicit design, users can identify key source areas, analyze the effectiveness of different strategies for intervening, and assess the possible trade-offs in the conservation of water, soil, and nutrients. Unlike traditional empirical approaches, SWAT incorporates physical, hydrological, and chemical processes over time and space, which gives a systems understanding of watershed behavior. Because of this, it is extremely beneficial in managing the Ganga Basin’s complex watersheds that face numerous conflicting land uses, population pressure, and ecological sensitivity. As noted in recent research publications [28], SWAT and similar tools are important not just for resource baseline evaluations but also for planning adaptive, multi-tiered, and climate-resilient plans that can be adjusted and managed at different levels.

6.3 Importance of Continued Research for Water Quality and Sustainability

Looking forward, the importance of tracking innovation and innovation in research for watersheds modeling cannot be stressed strongly enough. As the growth in population and the changing climate bear strong effects on the water resources, watershed management techniques need to transform to be more dynamic, incorporating multilayer approaches with a focus on heavy data, and the use of multiple disciplines. The SWAT model will be improved in the future due to technological advancements in data science, remote sensing, and AI, which will make real-time decisions easier, automate processing, and provide simulations of many scenarios, giving more accurate predictions. In addition, long-term sustainability objectives would require incorporating coupled human-natural systems such as socio-economic factors, stakeholder behaviors, and policies into the watershed models. As pointed out by integrated systems theorists, lasting success in watershed governance requires a comprehensive strategy that blends hydrological science, ecological conservation, and community livelihoods. In that regard, SWAT and the approaches exemplified in this research provide important blueprints for developing resilient, inclusive, and sustainable frameworks for watershed management.

References

[1] Calder, I. R. (2005). *Blue Revolution: Integrated Land and Water Resource Management*. Earthscan.

[2] Vinusha, B., Vidya Sagar Reddy, G., & Vijaya, C. (2024). Advanced nanoparticle-based treatment of aquafarm and hatchery effluents: The role of chitosan and chitosan TPP in water purification. *International Journal of Aquatic Research and Environmental Studies*, 0-0.

[3] Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development 1. *JAWRA Journal of the American Water Resources Association*, *34*(1), 73-89.

[4] Radhakrishnan, S., Velanganni, R., & Paranthaman, P. (2024). Groundwater Management: Integrating Geological and hydrological data for effective decision making. *Archives for technical sciences*, *31*(2), 131-139.

[5] Sharpley, A. N., Daniel, T. C., Sims, J. T., Lemunyon, J. L., Stevens, R. G., & Parry, R. (2003). Agricultural phosphorus and eutrophication (2nd ed.). *USDA ARS.*

[6] Farfoura, M. E., Khashan, O. A., Omar, H., Alshamaila, Y., Karim, N. A., Tseng, H. T., & Alshinwan, M. (2023). A Fragile Watermarking Method for Content-Authentication of H. 264-AVC Video. *J. Internet Serv. Inf. Secur.*, *13*(2), 211-232.

[7] Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900.

[8] Zhu, Z., Jiao, T., & LiInnovative, Z. (2024). Applications of IoT in Smart Home Systems: Enhancing Environmental Monitoring with Integrated Sensor Technologies and MQTT Protocol. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications*, *15*(4), 69-89.

[9] White, K. L., & Chaubey, I. (2005). Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model 1. *JAWRA Journal of the American Water Resources Association*, *41*(5), 1077-1089.

[10] Shalom, N. (2024). Comparative Analysis of Flexural Properties of Bamboo-Glass Hybrid FRP Composites: Influence of Water Absorption. *Natural and Engineering Sciences*, *9*(2), 441-448.

[11] Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological applications*, *8*(3), 559-568.

[12] Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., ... & Likens, G. E. (2009). Controlling eutrophication: nitrogen and phosphorus. *Science*, *323*(5917), 1014-1015.

[13] Dodds, W. K., & Smith, V. H. (2016). Nitrogen, phosphorus, and eutrophication in streams. *Inland Waters*, *6*(2), 155-164.

[14] Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., ... & Jha, M. K. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1491-1508.

[15] Easton, Z. M., Fuka, D. R., Walter, M. T., Cowan, D. M., Schneiderman, E. M., & Steenhuis, T. S. (2008). Re-conceptualizing the soil and water assessment tool (SWAT) model to predict runoff from variable source areas. *Journal of hydrology*, *348*(3-4), 279-291.

[16] Bhattarai, R., & Dutta, D. (2007). Estimation of soil erosion and sediment yield using GIS at catchment scale. *Water Resources Management*, *21*(10), 1635-1647.

[17] Gitau, M. W., Gburek, W. J., & Jarrett, A. R. (2004). A tool for estimating BMP effectiveness for phosphorus and sediment reduction. *Environmental Monitoring and Assessment, 104*(1-3), 63–78.

[18] Meaurio, M., Larrañaga, A., & Martínez de Arano, I. (2015). Modeling the impact of land use changes on sediment yield using SWAT in a northern Spanish watershed. *Land Use Policy, 48*, 1–11.

[19] Sahu, M., & Gu, R. (2009). Modeling the effects of land cover change on water quality in the Wakarusa watershed. *Journal of Environmental Management, 89*(4), 1479–1493.

[20] Blackstock, K. L., Kelly, G. J., & Horsey, B. L. (2007). Developing and applying a framework to evaluate participatory research for sustainability. *Ecological economics*, *60*(4), 726-742.

[21] Srivastava, P., Chaubey, I., & Elmore, M. (2013). Forecasting phosphorus loss using remote sensing and modeling tools. *Environmental Modelling & Software, 41*, 25–34.

[22] Zhang, Y., & Srinivasan, R. (2010). Impact of climate change on water resources in the United States. *Journal of Hydrology, 394*(3–4), 320–336.

[23] Hooper, B. P. (2005). Integrated water resources management and river basin governance. *Water Resources Development, 21*(1), 89–98.

[24] Santhi, C., Arnold, J. G., Williams, J. R., Dugas, W. A., Srinivasan, R., & Hauck, L. M. (2001). Validation of the swat model on a large rwer basin with point and nonpoint sources 1. *JAWRA Journal of the American Water Resources Association*, *37*(5), 1169-1188.

[25] Abdollahi, K., & Marofi, S. (2016). Application of machine learning in SWAT calibration: A case study in Iran. *Environmental Earth Sciences, 75*(18), 1280

[26] Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., & Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological sciences journal*, *54*(1), 101-123.

[27] Albek, E., & Kucuksezgin, F. (2012). Hydrological modeling and policy development for transboundary watersheds: The case of Büyük Menderes River. *Environmental Science & Policy, 21*, 90–101.

[28] Githui, F., Mutua, F., & Bauwens, W. (2009). Estimating the impacts of land-cover change on runoff using the soil and water assessment tool (SWAT): case study of Nzoia catchment, Kenya/Estimation des impacts du changement d'occupation du sol sur l'écoulement à l'aide de SWAT: étude du cas du bassin de Nzoia, Kenya. *Hydrological sciences journal*, *54*(5), 899-908.

[29] Pahl-Wostl, C. (2007). The implications of complexity for integrated resources management. *Environmental modelling & software*, *22*(5), 561-569.

[30] FAO. (2012). Watershed Management in Action: Lessons Learned from FAO Field Projects. Food and Agriculture Organization of the United Nations.

[31] Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE*, *50*(4), 1211-1250.

[32] Heathwaite, L., Sharpley, A., & Gburek, W. (2000). A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. *Journal of environmental quality*, *29*(1), 158-166.

[33] Setegn, S. G., Srinivasan, R., & Dargahi, B. (2008). Hydrological modelling in the Lake Tana Basin, Ethiopia using SWAT model. *The open hydrology Journal*, *2*(1), 49-62.

[34] Zhang, X., Srinivasan, R., & Van Liew, M. (2008). Multi-site calibration of the SWAT model for hydrologic modeling. *Transactions of the ASABE*, *51*(6), 2039-2049.