

Article

Projected Future Trends in Runoff and Sediment Transport in Typical Rivers of the Yellow River Basin, China

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Abstract

This study systematically evaluated the response mechanisms of water and sediment processes in the Kuye River Basin to climate change and human activities from 2023 to 2053 by integrating multi-source climate scenarios (CMIP5 models), land-use change projections (based on the Markov chain model), and a distributed hydrological model (SWAT model). The results indicate that under the RCP8.5 high-emission scenario, annual precipitation in the basin shows a non-significant increasing trend but with intensified interannual variability. Spatially, precipitation exhibits a pattern of increasing from northwest to southeast, with a marked decadal transition occurring around 2043. Land-use structure undergoes significant transformation, with construction land projected to account for 30.54% of the total basin area by 2050, while grassland and cropland continue to decline. Water and sediment processes display distinct phased characteristics: a fluctuating adjustment phase (2023–2033), a relatively stable phase (2034–2043), and a sharp growth phase (2044–2053). Parameter sensitivity analysis identifies the curve number (CN2) and soil bulk density (SOL_BD) as key regulatory parameters, revealing the synergistic mechanism by which land-use changes amplify climatic effects through alterations in surface properties. Based on the findings, an adaptive watershed management framework is proposed, encompassing dynamic water resource regulation, spatial zoning, targeted erosion control, and iterative scientific management. Particular emphasis is placed on addressing hydrological transition risks around 2043 and promoting low-impact development practices in high-erosion areas. This study provides a scientific basis for the integrated management of water and soil resources in the context of ecological conservation and high-quality development in the Yellow River Basin. The methodology developed herein offers a valuable reference for predicting water and sediment processes and implementing adaptive management in similar semi-arid basins.



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Keywords: climate change; land use change; water–sediment processes; SWAT; the Loess Plateau; predictions

1. Introduction

Under the dual pressures of global climate change and intensive human activities, watershed hydrological and sediment processes are undergoing profound transformations [1]. These changes directly impact water resource sustainability, flood control security, and ecological health, posing significant challenges to regional sustainable development. The

Loess Plateau, one of the world's most severe soil erosion regions, has drawn considerable scientific attention regarding its fluvial water-sediment dynamics [2]. The Kuye River Basin, located in the transitional zone between the Loess Plateau and the Mu Us Desert, represents a critical area within the Middle Yellow River's coarse sediment-producing region [3]. Its unique geographical setting, climatic sensitivity, and vulnerable underlying surface conditions make it an ideal natural laboratory for studying the coupled effects of climate change and anthropogenic activities. In recent years, under global warming, the basin has experienced increased frequency of extreme precipitation events, rapid urbanization, and energy base development, leading to dramatic land use/cover changes [4]. Understanding how these natural and anthropogenic drivers synergistically influence future runoff and sediment yield processes is not only a scientific frontier in semi-arid hydrological response mechanisms but also an urgent requirement for supporting the national strategy of ecological conservation and high-quality development in the Yellow River Basin.

Foundational research on hydrology and sediment transport in the Loess Plateau has accumulated a profound body of knowledge, laying a solid theoretical framework for subsequent related studies. As early as the 1950s, Chinese scholars initiated systematic explorations into soil erosion mechanisms on the Loess Plateau. Among these studies, the research by the team led by Academician Xiong Yi on the correlation between the physical and chemical properties of loess and erosion is the most representative, clarifying the dominant role of loess particle composition and pore structure in slope erosion [5]. Since the 1980s, the work "Fluvial Process in the Lower Yellow River" by Academician Qian Ning has become a classic in this field, systematically elaborating on the laws of water-sediment transport and riverbed adjustment mechanisms in the Yellow River Basin. It was the first to quantify the contribution of sediment yield from the Loess Plateau to downstream silting and proposed the core viewpoint that "water-sediment matching" affects fluvial geomorphological evolution [6]. In subsequent studies, scholars have further revealed the long-term trends of water-sediment changes in the Loess Plateau through long-term in-situ observations and watershed-scale reviews. For instance, based on hydrological observation data from 1950 to 2010, Wang et al. [7] found a significant decreasing trend in sediment transport in major basins of the Loess Plateau, with vegetation restoration and engineering measures such as terraces and check dams contributing over 60%. From a climatic perspective, Li et al. [8] demonstrated the regulatory effect of East Asian Summer Monsoon fluctuations on the spatiotemporal distribution of precipitation in the Loess Plateau, providing key insights into the climatic driving basis of watershed water-sediment changes. These classic studies and long-term observation results have established a three-dimensional analytical framework of "climate-underlying surface-human activities" for water-sediment processes in the Loess Plateau, serving as an important theoretical basis for current water-sediment trend prediction research.

From 2018 to 2024, research on water-sediment simulation in semi-arid basins has achieved multiple breakthroughs in technical methods, with core progress focusing on three areas, climate scenario application, land use prediction, and hydrological model optimization, providing more accurate technical support for watershed-scale water-sediment prediction. In terms of climate scenario application, CMIP6 models have been gradually popularized. Compared with CMIP5 models, they show significantly improved simulation accuracy of extreme climate events, laying a more reliable data foundation for future climate projections in semi-arid basins. For example, Peng et al. [9] compared the multi-model ensemble results of CMIP5 and CMIP6, finding that CMIP6 reduced the simulation error of precipitation intensity in the East Asian semi-arid region by 15–20%, particularly demonstrating advantages in the spatiotemporal characterization of extreme precipitation events. Based on the SSP-RCP combined scenarios of CMIP6, Liu et al. [10] predicted

that precipitation in semi-arid basins from 2020 to 2060 would show a trend of “slight increase in total amount and intensified extremeness,” providing refined climatic inputs for water–sediment risk assessment. In land use prediction, the Markov chain model has been widely applied and continuously optimized in semi-arid basins due to its simplicity and applicability. Researchers have improved prediction rationality by coupling spatial constraints; for instance, Sun et al. [11] integrated spatial factors such as topographic slope and distance to urban areas into the Markov chain model to predict the 2030 land use pattern of the Yanchi Basin in Ningxia, achieving an accuracy improvement of approximately 12% compared to traditional models. Meanwhile, some studies have combined it with Cellular Automaton (CA) models to construct CA-Markov composite models, further enhancing the ability to simulate the spatial pattern of land use [12]. In terms of SWAT model optimization, targeting the high heterogeneity of underlying surfaces and high parameter sensitivity in semi-arid basins, scholars have improved simulation accuracy through local calibration and process modification. Chen et al. [13] used the SUFI-2 algorithm to locally optimize the soil erosion parameters of the SWAT model, increasing the NSE coefficient for sediment transport simulation in semi-arid basins from 0.68 to 0.82. Chen et al. [14] modified the calculation method of the evapotranspiration module in the model to adapt to the characteristics of large diurnal temperature differences and complex evapotranspiration processes in semi-arid basins, effectively reducing runoff simulation errors). These latest research results have established a technical methodology for long-term water–sediment prediction in semi-arid basins and provided direct references for model construction and parameter calibration in this study.

Specialized research on the Kuye River Basin has gradually expanded from single historical process attribution to a comprehensive research direction of “change characteristics–effect assessment–management optimization” in recent years. In terms of climate change impact analysis, existing studies focus on the direct driving effects of precipitation and temperature changes on water–sediment processes. Based on observation data from 1960 to 2020, Lan et al. [15] found that the annual precipitation in the Kuye River Basin showed a slight decreasing trend, while the number of heavy rainfall days increased by 23%, significantly enhancing the sensitivity of basin sediment transport to precipitation. Through quantitative analysis using statistical models, Liu et al. [16] concluded that climate change contributed approximately 35% to the runoff reduction in the Kuye River Basin from 1990 to 2020, providing key data for distinguishing the relative roles of climate and human activities. In the assessment of land use transition effects, studies mostly focus on construction land expansion and vegetation cover changes caused by energy development and urbanization. Zhang et al. [17] pointed out that the construction land area in the Kuye River Basin increased by 1.8 times from 2000 to 2020, mainly due to energy base construction, which directly led to an increase in the impervious surface ratio and a rise in the surface runoff coefficient by approximately 0.15. Through comparative analysis, Yang et al. [18] found that ecological restoration projects such as the Grain for Green Program increased the basin’s vegetation coverage by 10–15%, effectively reducing slope erosion while altering the watershed runoff generation and convergence paths. In terms of water resource management practice, existing achievements focus on exploring adaptive measures. Luo et al. [19] proposed a reservoir operation scheme based on “storing clear water and releasing muddy flow” to address the uneven intra-annual distribution of water and sediment in the Kuye River Basin. Chen et al. [20] constructed an integrated management model combining watershed soil and water conservation projects with ecological restoration, providing a practical path for reducing coarse sediment input into the Yellow River.

However, existing research often treats climatic forcing and land use change as independent drivers, lacking sufficient quantitative analysis of their synergistic effects and

nonlinear interactions within an integrated framework. Particularly, the coupled mechanisms between internal climate variability and cumulative human impacts at decadal scales remain underexplored. Furthermore, although some studies have conducted future water–sediment trend predictions (including those up to 2050 and beyond), most are limited to single-scenario or single-driver analysis, lacking systematic assessment of water–sediment dynamic responses under multi-scenario combinations, abrupt characteristics during critical periods, and full-chain uncertainties, which hinders the formulation of proactive adaptation strategies.

To address these gaps, this study establishes a comprehensive assessment framework for the Kuye River Basin by integrating multi-source climate scenarios, land use change projections, and a distributed hydrological model. By coupling CMIP5 climate model data, Markov chain-based land use simulations, and a rigorously calibrated SWAT (Soil and Water Assessment Tool) hydrological model, we systematically evaluate basin-scale water and sediment responses to climate change and land use transitions from 2023 to 2053. The research focuses on identifying phased characteristics of water–sediment changes across different periods, distinguishing the dominant roles and synergistic amplification mechanisms of climate variability and underlying surface alterations, and ultimately proposing climate-adaptive integrated watershed management insights. This work aims to advance the mechanistic understanding of water–sediment dynamics in semi-arid transitional zones, while its methodology and findings offer scientific references for water–soil resource management and ecological security in similar regions.

2. Materials and Methods

2.1. Study Area

The Kuye River Basin is situated in northwestern China, spanning Shaanxi Province and the Inner Mongolia Autonomous Region, within the central region of the Loess Plateau. The basin covers an area of approximately 3471 square kilometers. Flowing from south to north into the Yellow River, it serves as one of its key tributaries. Human activities in the basin are frequent, with extensive agricultural practices and water resource development exerting significant impacts on the local environment (Figure 1).

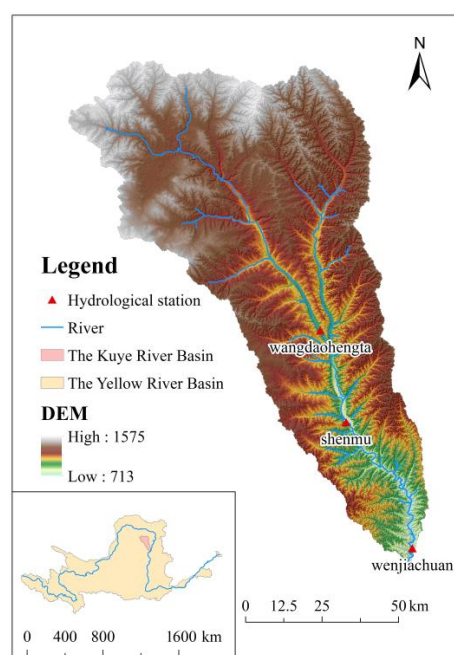


Figure 1. Geographic location of the Kuye River Basin [3].

The basin experiences a temperate continental climate, characterized by distinct seasons. The average annual precipitation ranges from 400 to 500 mm, with the majority occurring during the summer months, often in the form of intense rainstorms that exacerbate soil erosion issues. The mean annual temperature is between 9 °C and 11 °C, with cold winters and hot summers. The region exhibits high evaporation rates and low water resource utilization efficiency. The annual streamflow in the basin is strongly seasonal, with peak discharges in summer and significantly reduced flows during winter, reflecting pronounced seasonal variability.

Located in the heart of the Loess Plateau, the Kuye River Basin is characterized by complex topography dominated by loess hills and gullies. The terrain features numerous ravines and steep slopes, with elevations gradually decreasing from north to south. The loess deposits are deep and highly erodible, with loose soil structures prone to external forces. High gully density and fragmented landforms create favorable conditions for severe soil erosion throughout the basin.

Soils within the basin primarily consist of loess-derived soils, exhibiting moderate fertility but weak resistance to erosion due to their loose structure. The vegetation is representative of a transitional zone between temperate grasslands and desert steppe, with low overall coverage. The dominant plant types include shrubs and herbaceous species. In recent years, reforestation policies, such as the Grain for Green Program, have promoted partial vegetation recovery in some areas. However, the overall vegetative cover remains insufficient to fully mitigate soil erosion.

The Kuye River Basin is among the most severely eroded regions within the Loess Plateau, with water erosion being the primary form, accompanied by wind erosion in certain areas. The steep topography, combined with concentrated and intense rainfall, has led to the development of well-defined erosion gullies. Both sheet erosion and gully erosion are widespread, with occurrences of landslides further exacerbating the problem. These processes result in substantial soil and nutrient loss. Despite the implementation of various soil and water conservation measures, such as the construction of check dams, the basin continues to face significant erosion challenges.

2.2. Data Sources

Rainfall data were sourced from the China Meteorological Science Data Sharing Service (<https://data.cma.cn/> accessed on 15 September 2025), comprising a monthly dataset covering over 30 years from 108 national meteorological stations located in and around the Loess Plateau.

Daily runoff and sediment transport data from the Wangdaohengta, Shenmu, and Wenjiachuan hydrological stations were collected for the period from 1960 to 2019, as sourced from the Hydrological Yearbook of the Yellow River Basin.

The Digital Elevation Model (DEM) for the Kuye River Basin, with a spatial resolution of 30 × 30 m, was downloaded and clipped from the “GDEM V2 30m” dataset available on the Geospatial Data Cloud website (<http://www.gscloud.cn/> accessed on 15 September 2023). Slope data for the basin were then computed using ArcGIS Pro(3.4.3).

Soil type data for the Kuye River Basin, with a spatial resolution of 30 × 30 m, were downloaded and clipped from the Harmonized World Soil Database (HWSD).

Vegetation type data for the Kuye River Basin, with a spatial resolution of 1 × 1 km, were downloaded and clipped from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn/> accessed on 15 September 2023).

The land use data were derived from China’s 1:100,000 Land Use Database. These data were acquired through human–computer interactive interpretation, based on Landsat

TM and China Environment Satellite 1 (HJ-1) imagery. The coordinate system used was WGS_1984_UTM_Zone_49N, with a spatial resolution of 30 m × 30 m.

2.3. Methodology for Calculating Ecological Building Potential

(1) Future Trends of Precipitation Change

In this study, future precipitation data from four CMIP5 climate models—HadGEM3-RA, YSU-RSM, SNU-MM5, and RegCM—are utilized. Each model is associated with two Representative Concentration Pathways (RCPs): RCP4.5 (moderate emissions) and RCP8.5 (high emissions), resulting in eight future climate scenarios. Given the varying relevance of these models to the Kuye River Basin's climate, models that best reflect the actual conditions of the basin must be selected. To more accurately represent future precipitation in the basin, the inverse distance weighting method is employed to interpolate the data from the eight scenarios, with basin-averaged precipitation for 2006–2019 being calculated. The interpolated values are then compared with observed multi-year average precipitation. The selection of climate models and scenarios is determined based on absolute errors and percentage biases.

As shown in Table 1, the smallest error is found when comparing the measured multi-year average precipitation in the Kuye River Basin with that simulated by the HadGEM3-RA model under the RCP8.5 scenario. Therefore, future precipitation projections using the HadGEM3-RA model and the RCP8.5 scenario are chosen for forecasting precipitation in the Kuye River Basin.

Table 1. Comparison of Multi-Year Average Precipitation in the Kuye River Basin (2006–2019) Under Various Scenarios [3].

Climate Model	Emission Scenario	Multi-Year Average Precipitation/mm	Absolute Error /mm	Percentage Bias/%
HadGEM3-RA	RCP4.5	513.10	6.73	1.33%
	RCP8.5	511.65	5.28	1.04%
YSU-RSM	RCP4.5	468.40	37.97	7.50%
	RCP8.5	437.01	69.36	13.70%
SNU-MM5	RCP4.5	346.40	159.97	31.59%
	RCP8.5	256.21	250.15	49.40%
RegCM	RCP4.5	487.96	18.41	3.64%
	RCP8.5	442.01	64.36	12.71%
Observed Value	/	506.37	/	/

(2) Future Trends of Land Use Change

Markov chains are applied in stochastic simulations to predict quantitative changes in land use due to their inherent stability and independence from future states [5]. Therefore, the model can be used to project the future trajectory of land use in the basin. The corresponding modeling equations are as follows:

$$S_{(t+1)} = P_{ij}S_{(t)} \quad (1)$$

In this equation, $S_{(t+1)}$ represents the land use state of the raster data at time $t + 1$, $S_{(t)}$ denotes the land use state of the raster data at the current time t , and P_{ij} is the land use transfer matrix for the region. The land use transfer matrix, derived through Markov chain calculations, provides an effective description of the land use change process in the study area, as well as the quantitative transitions between different land use types.

(3) Establishment of the SWAT Model Database

The data required for the SWAT model is primarily divided into spatial data and hydrometeorological data. Spatial data mainly includes DEM data, soil data, and land use data, while hydrometeorological data encompasses runoff, sediment transport, precipitation, and temperature. The data utilized for establishing the SWAT model in this study are presented in Table 2.

Table 2. Basic Data Table for the SWAT Model.

Data Type	Resolution and Scale	Period	Data Source
DEM	30 m × 30 m	2009	Geospatial Data Cloud
Land Use	30 m × 30 m	2010	Resources and Environmental Science Data Center, Chinese Academy of Sciences
Soil	1 km × 1 km	2000	Food and Agriculture Organization (FAO)
Meteorological	Daily Scale	2008–2018	SWAT Model China Atmospheric Assimilation Driving Dataset
Hydrological	Daily Scale	2008–2018	Hydrological Data of the Yellow River Basin

This study utilizes the China Atmospheric Assimilation Driving Dataset (CMADS) for the SWAT model, extracting data from meteorological stations located within the basin area. The required meteorological data were organized and processed to establish a meteorological database.

When inputting land use data, land use was reclassified into six categories, cropland (AGRL), forestland (FRSD), grassland (PAST), water bodies (WATR), urban residential land (URBN), and unused land (SWRN), as shown in Figure 2a. The parameter values for land use were selected from the default database of the SWAT model.

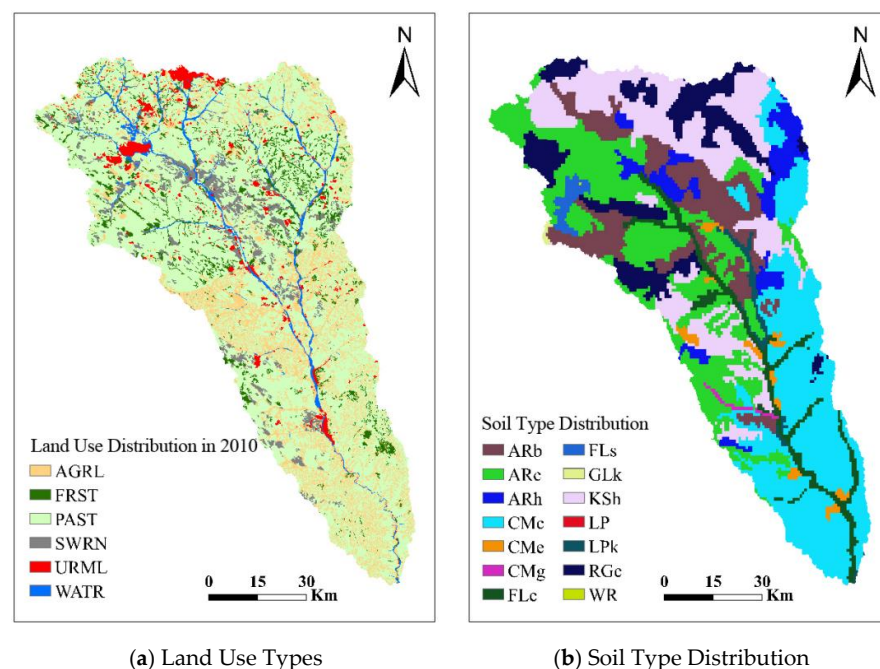


Figure 2. Land Use Types and Soil Type Distribution in the Kuye River Basin within the SWAT Model.

The soil data were clipped and reclassified to produce a spatial distribution map of 14 soil types in the Kuye River Basin, as depicted in Figure 2b. Since the soil data in the SWAT default database are not applicable to the basins in China, the soil type parameters for the Kuye River Basin were recalculated to construct a new soil database. The calculations were performed using SPAW (6.02.70) software.

Slope affects runoff and concentration time in the basin; therefore, the slopes within the basin were classified into three categories: 0–5%, 5–15%, and 15–99.99%.

In this study, when defining Hydrologic Response Units (HRUs), land use, soil type, and slope thresholds were all set to 10%. As a result, the Kuye River Basin was divided into 47 sub-basins and 2694 HRUs. After inputting the processed meteorological data into the model and saving it in the database, the model could be run.

(4) Model Parameter Sensitivity Analysis

The LH-OAT method within the SWAT-CUP(5.2) software was employed for parameter sensitivity analysis in this study. This approach allows for the assessment of parameter sensitivity with a reduced number of model runs. The *p*-value and t-Stat values were utilized as indicators to evaluate the degree of parameter sensitivity, with smaller *p*-values and larger absolute t-Stat values indicating greater sensitivity.

The parameter sensitivity analysis of the SWAT model for the Kuye River Basin is presented in Table 3. Through the sensitivity analysis, 24 parameters that significantly influence runoff and sediment transport in the basin were selected. The parameter with the highest sensitivity is CN2, which primarily affects the magnitude of surface runoff in the basin. The second most sensitive parameter is soil bulk density (SOL_BD), which mainly influences the infiltration process of runoff in the basin.

Table 3. Ranking of Parameter Sensitivity for Runoff and Sediment Transport in the SWAT Model of the Kuye River Basin.

Parameter Name	Parameter Definition	Sensitivity Ranking
CN2	SCS Curve Number	1
SOL_BD	Soil Bulk Density	2
ALPHA_BNK	Main Channel Retention Coefficient	3
HRU_SLP	Average Slope Length	4
SLSUBBSN	Slope Length	5
SOL_K(1)	Soil Saturated Hydraulic Conductivity	6
SOL_AWC(1)	Effective Moisture Content of Surface Soil	7
GW_DELAY	Groundwater Delay Coefficient	8
SPCON	Maximum Sediment Transport Index Coefficient	9
SFTMP	Snowfall Temperature	10
SPEXP	Exponent for Calculating Additional Maximum Sediment in the Channel	11
GWQMN	Shallow Groundwater Runoff Coefficient	12
CH_N2	Main Channel Manning Coefficient	13
USLE_P	Support Parameter for the Universal Soil Loss Equation (USLE)	14
SMTMP	Minimum Snowmelt Temperature	15
GW_REVAP	Groundwater Revaporation Coefficient	16
CH_K2	Hydraulic Conductivity of Main Channel	17
ALPHA_BF	Baseflow Recession Coefficient	18
CANMX	Maximum Canopy Water Capacity	19
ESCO	Soil Evaporation Compensation Coefficient	20
EPCO	Plant Transpiration Compensation Coefficient	21
USLE_C	Minimum Value of C Factor in the Universal Soil Loss Equation (USLE)	22
BIOMIX	Biological Mixing Efficiency	23
REVAPMN	Groundwater Revaporation Depth	24

(5) Model Calibration and Validation

The Wengjiacun Hydrological Station at the Kouye River Basin was selected as the reference station. The observed runoff and sediment data from this station for the years 2008 to 2018 were utilized. The years 2008 and 2009 were designated as the model warm-up period, while 2010 to 2015 were allocated for model calibration, and 2016 to 2018 served as

the model validation period. To ensure the applicability of the model in the study area and the authenticity of the simulation results, an evaluation system based on the correlation coefficient R^2 and the Nash–Sutcliffe efficiency coefficient (NS) was established to assess the model's simulation results. The calculation formulas are as follows:

$$R^2 = \left(\frac{\sum_{i=1}^T (O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^T (O_i - \bar{O})^2 \sum_{i=1}^T (S_i - \bar{S})^2}} \right)^2 \quad (2)$$

$$NS = 1 - \frac{\sum_{i=1}^T (O_i - S_i)^2}{\sum_{i=1}^T (O_i - \bar{O})^2} \quad (3)$$

In the equations, O_i represents the observed value in the i -th year of the observed series. $\bar{O}$ denotes the mean value of the observed series. S_i indicates the simulated value in the i -th year of the simulated series. $\bar{S}$ represents the mean value of the simulated series.

In this study, the SUFI-2 algorithm from SWAT-CUP was employed for the calibration and validation of the selected model parameters. During the calibration process, a parameter range was specified, and the software iteratively varied the parameters within this range to compute runoff and sediment simulation values. This procedure was repeated to identify the best set of runoff and sediment simulation values within the range of simulations, while calculating the corresponding (R^2) and Nash–Sutcliffe efficiency coefficient (NS) for each iteration. After the calibration and validation of the model using SWAT-CUP software, the optimal values for various parameters of the SWAT model in the Kuye River Basin were determined based on practical considerations, as shown in Table 4.

Table 4. Calibration Results of SWAT Model Parameters for the Kuye River Basin.

Parameter Name	Parameter Range	Calibration Method	Optimal Value
ALPHA_BF	0–1	V	0.78
CN2	−0.2–0.2	R	−0.16
GW_DELAY	30–150	V	131.39
GW_REVAP	0–0.2	V	0.06
ALPHA_BNK.	0–1	V	0.06
SOL_K	−0.8–0.8	R	−0.06
SOL_BD	−0.5–0.6	R	−0.13
SOL_AWC	−0.2–0.4	R	0.13
CH_N2	0–0.3	V	0.23
CH_K2	5–130	V	5.49
REVAPMN	0–500	V	232.06
ESCO	0.1–0.9	V	0.30
EPCO	0.1–0.9	V	0.18
SLSUBBSN	−0.5–0.5	R	−0.04
SMTMP	−10–5	V	1.65
SFTMP	−10–5	V	−5.20
CANMX.	−0.5–0.5	R	−0.18
GWQMN.	0–5000	V	286.59
USLE_P	0–1	V	0.43
HRU_SLP	−0.5–0.5	R	0.47
USLE_C	−0.5–0.5	R	0.21
SPEXP.	1–1.5	V	1.04
SPCON	0–1	V	0.33
BIOMIX	0–1	V	0.11

3. Results and Analyses

3.1. Future Trends of Precipitation Change

The annual precipitation for the Kuye River Basin from 2023 to 2052 was calculated based on the HadGEM3-RA climate model under the RCP8.5 high-emissions scenario. The interannual variation curve of annual precipitation during this period is illustrated in Figure 3. The multi-year average precipitation over the next 30 years is projected to be 524.69 mm, with a maximum of 868.83 mm occurring in 2048 and a minimum of 292.61 mm in 2030. The coefficient of variation (Cv) is 0.24, indicating relatively small interannual variability. An analysis of the linear trend line and five-year moving average curve suggests that the overall trend in precipitation for the basin from 2023 to 2052 is upward. A Mann–Kendall (M-K) trend test conducted on the future precipitation series yielded a Z-value of 1.2846 and a *p*-value of 0.1989, indicating that the annual precipitation over the next 30 years exhibits a non-significant increasing trend.

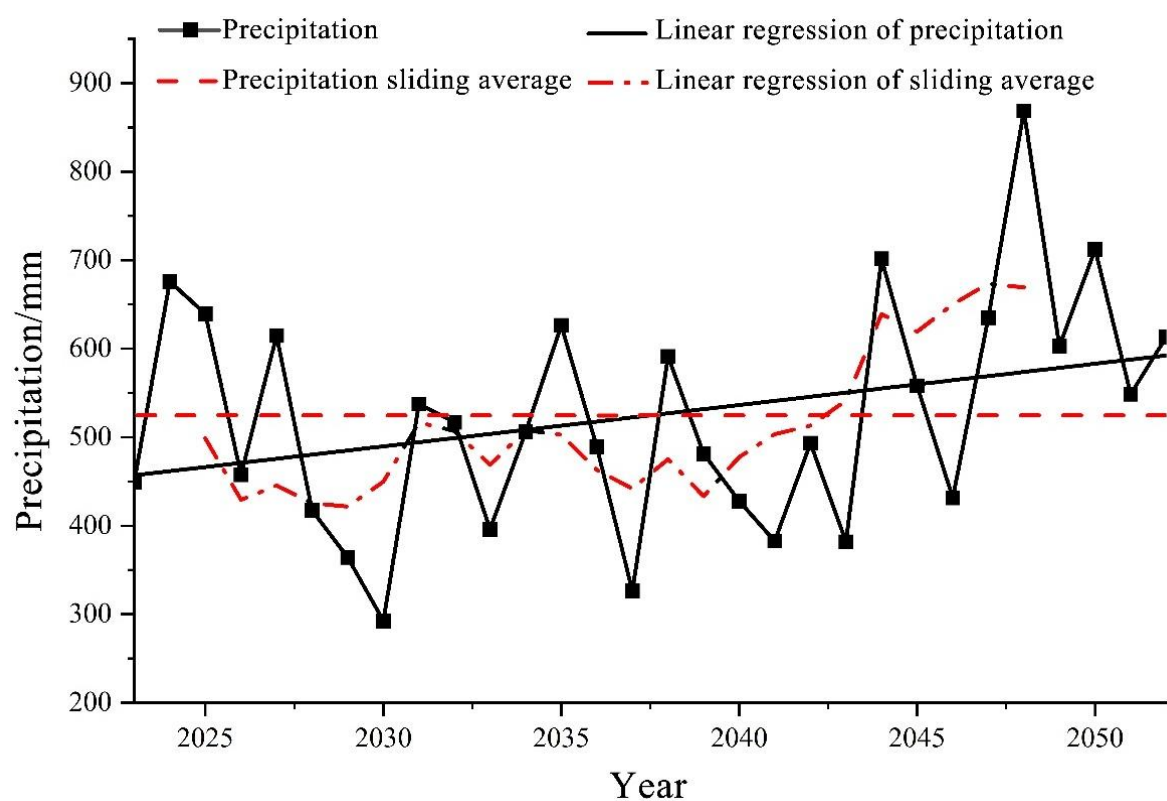


Figure 3. Variation Process Line of Annual Precipitation in the Kuye River Basin from 2023 to 2052 [3].

Figure 4 presents the annual precipitation anomaly process for the Kuye River Basin over the next 30 years. From the annual precipitation anomaly chart, it can be observed that there are 14 years with precipitation above the multi-year average and 16 years below the average, showing no clear positive or negative pattern. The cumulative anomaly curve indicates that precipitation can be divided into two phases: a decreasing phase from 2023 to 2043, with a minimum peak occurring in 2043 when the cumulative anomaly reaches its lowest point. From 2044 to 2052, the cumulative anomaly curve shows an upward trend. This indicates a significant shift in the annual precipitation trend for the Kuye River Basin around the year 2043 [3].

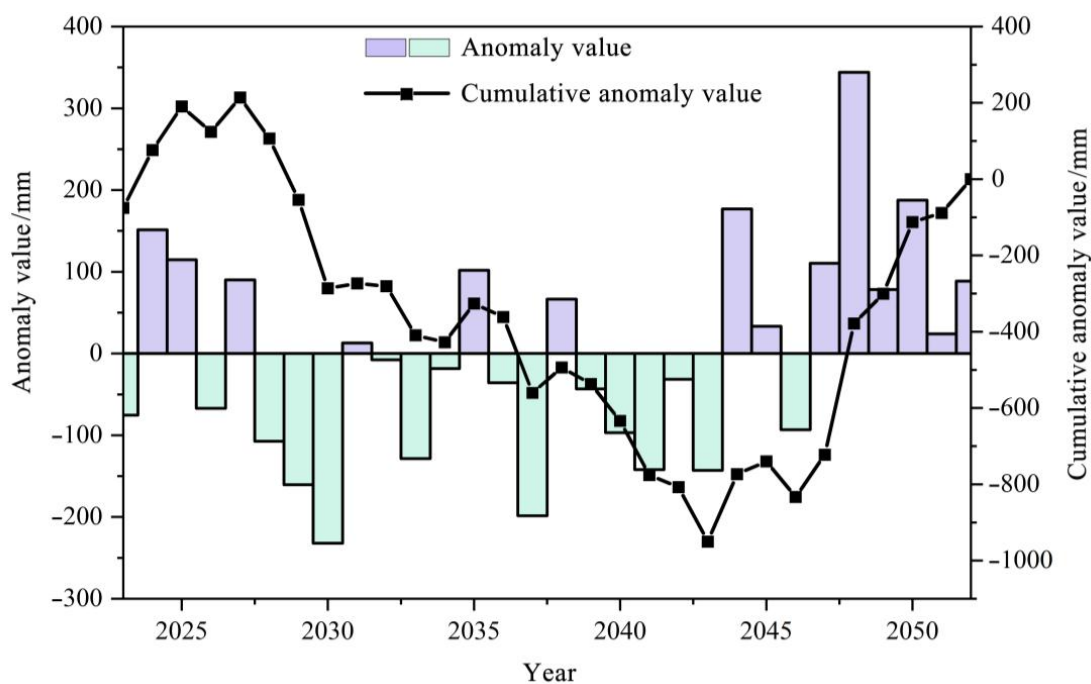


Figure 4. Process Line of Annual Precipitation Anomalies in the Kuye River Basin from 2023 to 2052 [3].

According to the spatial distribution data of the multi-year average precipitation for the Kuye River Basin from 2023 to 2052 (Figure 5), the precipitation over the next 30 years will be unevenly distributed spatially. Precipitation levels increase from the northwest to the southeast. The area with the lowest precipitation is primarily concentrated in the northwestern part of the basin, specifically in the sandy region, with a multi-year average precipitation of approximately 458 mm. Conversely, the area with the highest precipitation is mainly located near the southern part of Wenjiacang, where the multi-year average precipitation reaches around 570 mm.

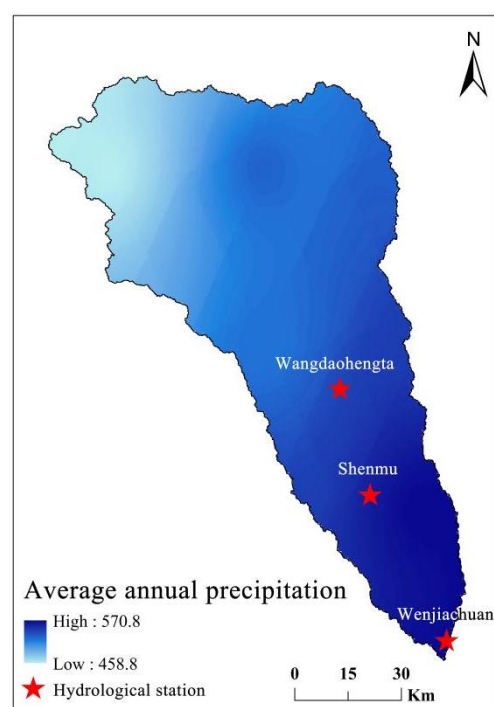


Figure 5. Spatial Distribution of Multi-Year Average Precipitation in the Kuye River Basin [3].

3.2. Future Trends of Land Use Change

Based on the land use data for the Kuye River Basin from 2010 and 2015, predictions were made for land use in the years 2030, 2040, and 2050. The results are illustrated in Figure 6.

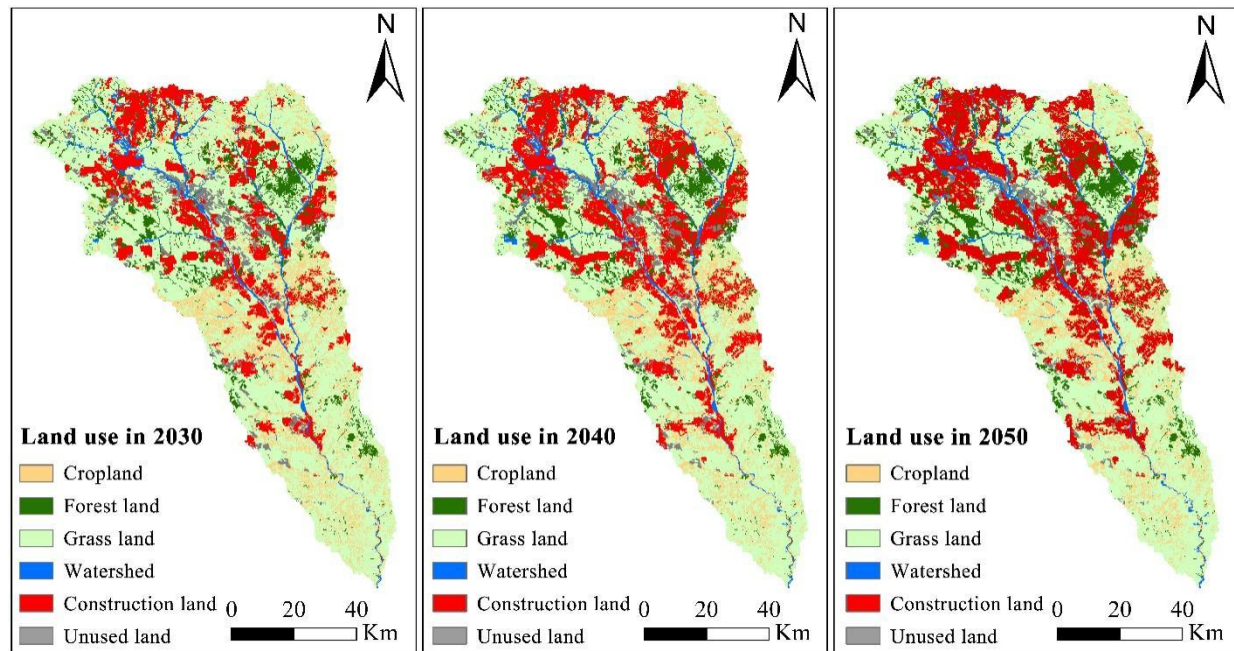


Figure 6. Spatial Distribution of Land Use in the Kuye River Basin for 2030, 2040, and 2050.

According to Figure 6 and Table 5, grassland will remain the dominant land type in the Kuye River Basin for the next 30 years, despite a continued decrease in its area. The share of built-up land is expected to rise significantly, potentially reaching 30.54% of the total land use by 2050. On the other hand, arable land is projected to decline, making up only 13.46% of the total land use by 2050, which will place it as the third largest land use type in the basin.

Table 5. Land Use Types in the Kuye River Basin for the Years 2030, 2040 and 2050.

Land Use Type	2030		2040		2050	
	Area/km ²	Ratio/%	Area/km ²	Ratio/%	Area/km ²	Ratio/%
Cropland	1328.80	15.26%	1246.49	14.31%	1172.04	13.46%
Forest land	420.81	4.83%	389.45	4.47%	362.15	4.16%
Grass land	4750.97	54.55%	4367.27	50.14%	4033.84	46.31%
Watershed	163.70	1.88%	140.89	1.62%	123.22	1.41%
Construction land	1631.56	18.73%	2181.02	25.04%	2659.72	30.54%
Unused land	414.07	4.75%	384.80	4.42%	358.95	4.12%

3.3. Model Calibration and Validation Results

The final calibrated parameter values were incorporated into the SWAT model, and the model was run again. The monthly average runoff and sediment transport processes simulated at the Wanjiachuan station during the calibration and validation periods were compared with the observed values. The results are presented in Figures 7 and 8.

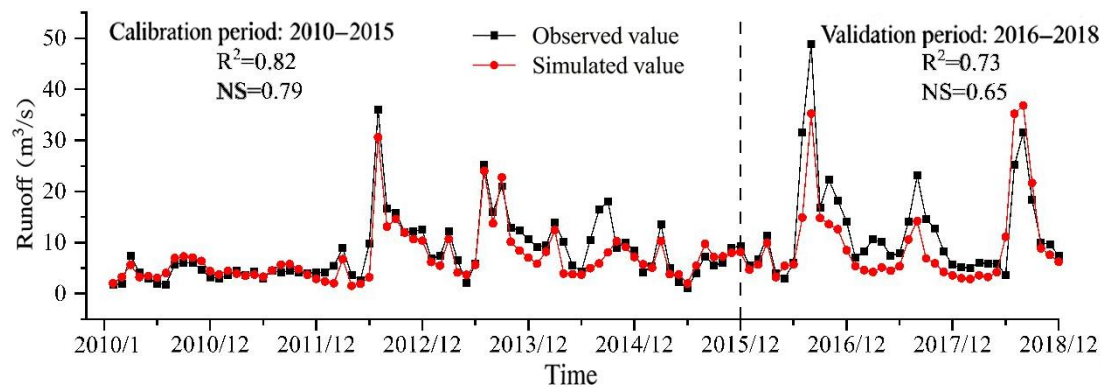


Figure 7. Comparison of Measured and Simulated Runoff at the Wenjia River Station During the Calibration and Validation Periods.

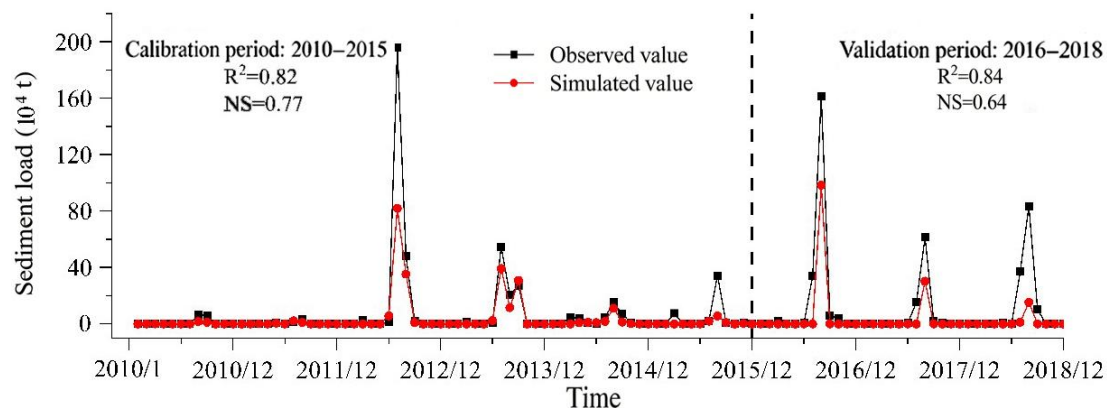


Figure 8. Comparison of Measured and Simulated Sediment Transport at the Wenjia River Station During the Calibration and Validation Periods.

As shown in Figures 7 and 8, the monthly average runoff and sediment transport values during the calibration and validation periods at the Wanjiachuan station closely match the observed values, indicating a good level of simulation accuracy. The simulation results for runoff during the calibration period (2010–2015) yielded an R^2 value of 0.82 and a Nash–Sutcliffe efficiency (NS) of 0.79. For the validation period (2016–2018), the R^2 value was 0.73, and the NS was 0.65. Similarly, for sediment transport, the calibration period results (2010–2015) had an R^2 of 0.82 and an NS of 0.77, while the validation period results (2016–2018) yielded an R^2 of 0.84 and an NS of 0.64. Overall, the calculations and analyses indicate that the SWAT model demonstrates a high accuracy in simulating the runoff and sediment processes in the Kuye River Basin, confirming its good applicability.

3.4. Water and Sediment Change Prediction Results

The SWAT model for the Kuye River Basin was established using future precipitation data from 2023 to 2033 and land use predictions for 2030 as input data to predict the water and sediment processes from 2023 to 2033. Similarly, SWAT models for the periods of 2033 to 2043 and 2043 to 2053 were developed to forecast water and sediment processes in the basin for the years 2033 to 2053.

Based on the established SWAT model for future water and sediment predictions in the Kuye River Basin, runoff and sediment data for the basin's outlet from 2023 to 2053 were extracted from the main river channel field (Rch table) of the model output.

The analysis of Figure 9 and Table 6 indicates that the annual runoff in the Kuye River Basin is projected to show an overall increasing trend in the future, which aligns with the changes in future precipitation. During the period from 2023 to 2033, the annual runoff

displays a slight downward trend, with the extreme value ratio and coefficient of variation being the highest among the future prediction periods, at 7.66 and 0.60, respectively. This suggests that the annual runoff during this period is subject to significant fluctuations. In the subsequent period from 2034 to 2043, a clear downward trend in annual runoff at the basin outlet is observed, with the lowest extreme value ratio and coefficient of variation, indicating a relatively stable state of annual runoff during this time. Conversely, from 2044 to 2053, the annual runoff exhibits a pronounced upward trend, characterized by a large coefficient of variation, signifying a rapid increase in annual runoff during this period.

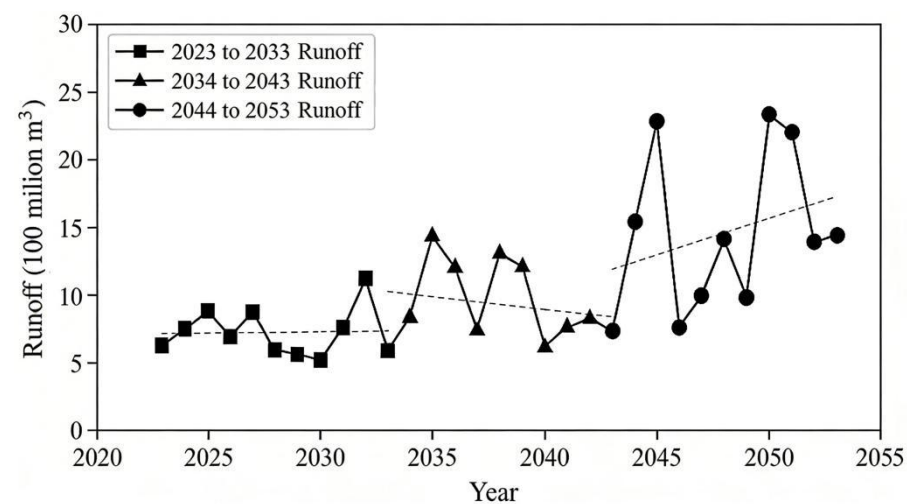


Figure 9. Trend of Future Annual Runoff Changes in the Kuye River Basin.

Table 6. Annual Runoff Interannual Variation Characteristics in the Kuye River Basin.

Research Period	Data Source	Maximum Value /100 Million m ³	Minimum Value /100 Million m ³	Multi-Year Average/100 Million m ³	Extremum Ratio	Coefficient of Variation
1956~2019	Measured Values	14.32	1.25	5.01	10.49	0.57
2023–2033	Predicted Values	7.79	0.90	3.28	7.66	0.60
2034–2043	Predicted Values	11.34	2.00	6.00	4.67	0.52
2044–2053	Predicted Values	21.27	3.58	12.25	4.93	0.50

According to Figure 10 and Table 7, the overall trend of future sediment yield in the Kuye River Basin is rising, which is consistent with the trends observed in future precipitation and runoff. During the period of 2023 to 2033, the annual sediment yield shows a slight upward trend, with the highest extreme value ratio during this period, indicating a considerable variation in annual sediment yield. In the 2034 to 2043 period, the annual sediment yield exhibits a subtle downward trend, with both the extreme value ratio and variance coefficient at their lowest levels, reflecting a relatively stable situation similar to that of the annual runoff in the same period. In the 2044 to 2053 period, there is a noticeable upward trend in annual sediment yield, accompanied by a high variance coefficient, suggesting significant fluctuations in sediment yield during this period, analogous to the changes in annual runoff.

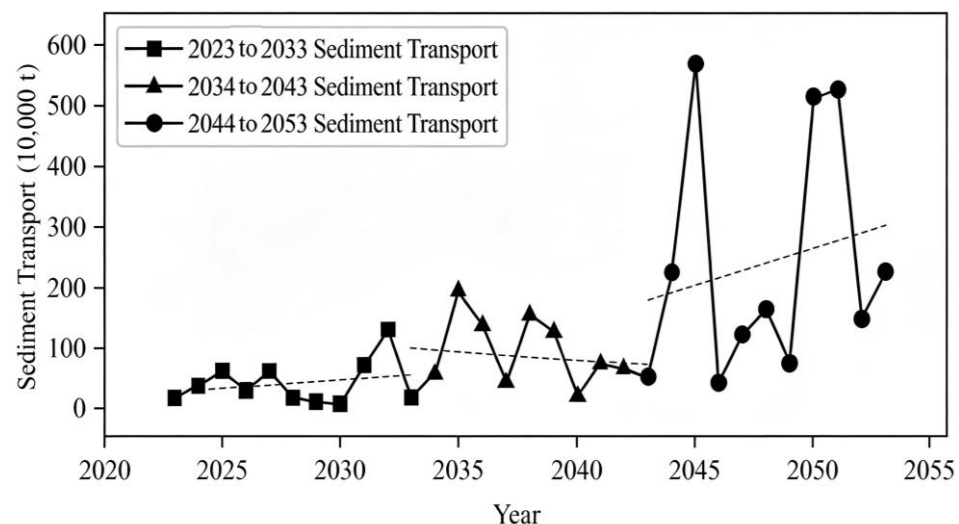


Figure 10. Trend of Future Annual Sediment Yield in the Kuye River Basin.

Table 7. Interannual Variation Characteristics of Future Sediment Yield in the Kuye River Basin.

Research Period	Data Source	Maximum Value /10,000 Tons	Minimum Value /10,000 Tons	Multi-Year Average/10,000 Tons	Extremum Ratio	Coefficient of Variation
1956~2019	Measured Values	33,482.22	3.18	7032.62	10,531.33	1.18
2023–2033	Predicted Values	130.13	6.42	41.48	19.28	0.85
2034–2043	Predicted Values	195.32	20.58	93.26	8.49	1.81
2044–2053	Predicted Values	571.03	41.83	261.98	12.65	7.01

4. Discussion

4.1. Driving Mechanisms of Precipitation and Land-Use Change

The future trend in precipitation change is a specific manifestation of regional climate response under global warming. Under the RCP8.5 high-emission scenario, simulations from the HadGEM3-RA model indicate an overall non-significant increasing trend in basin precipitation, a result generally consistent with most climate model projections for precipitation changes in the East Asian monsoon region [21]. This finding aligns with Zhao et al. [10], who projected precipitation trends in the semi-arid Loess Plateau based on CMIP6 multi-model ensembles and also identified a non-significant upward trend in annual precipitation, though their results emphasized stronger seasonal differentiation with enhanced summer precipitation. The consistency confirms the reliability of our precipitation trend simulation, while the seasonal discrepancy reflects uncertainties arising from model structure differences and scenario settings—an inherent challenge in regional climate projections.

Increased atmospheric water-holding capacity due to rising temperatures provides a thermodynamic basis for enhanced precipitation. However, the spatiotemporal distribution of precipitation is constrained by multiple dynamic processes, including adjustments in atmospheric circulation and changes in land–sea thermal contrasts, leading to considerable uncertainty in regional projections [22]. This conclusion is corroborated by Li et al. [9], who noted that semi-arid precipitation variability is co-dominated by thermodynamic (temperature-driven water-holding capacity) and dynamic (circulation-driven moisture transport) processes, with dynamic processes being the primary source of simulation uncer-

tainty. Our study further specifies that land–sea thermal contrast adjustments exacerbate this uncertainty, supplementing their mechanistic analysis.

The spatial pattern of precipitation—higher in the southeast and lower in the northwest—is closely related to the forced uplift effect of topography on monsoon moisture. The pronounced topographic uplift in the southeastern mountainous area facilitates orographic rainfall, while the flat sandy region in the northwest experiences weakened moisture transport, resulting in relatively lower precipitation. This spatial pattern is consistent with Zhang et al. [15], who analyzed 60-year (1960–2020) observational data and confirmed that topography is a stable controlling factor for the basin’s precipitation spatial heterogeneity. Notably, our future projection suggests this topographic constraint will persist, extending their historical findings to future scenarios and verifying the stability of topographic effects on precipitation patterns.

Notably, a significant inflection point in the cumulative anomaly curve around 2043 suggests decadal-scale fluctuations potentially linked to phase transitions of the Pacific Decadal Oscillation (PDO). The PDO modulates the intensity of the East Asian summer monsoon circulation, influencing moisture transport pathways and intensity, thereby inducing periodic fluctuations in regional precipitation [23]. Shi et al. [8] previously demonstrated that PDO-regulated East Asian summer monsoon variability drives decadal precipitation fluctuations on the Loess Plateau, but our study advances this by pinpointing a specific inflection point around 2043. This temporal refinement fills a gap in decadal-scale precipitation prediction for the basin and highlights the need to incorporate circulation-driven abrupt changes into water resource management frameworks.

The dramatic transformation of land-use structure results from the combined effects of natural conditions and human activities [24]. The substantial expansion of construction land (reaching 30.54% by 2050) directly reflects accelerated regional urbanization and land demand for energy base development. The Kuye River Basin is located in Northern Shaanxi, a crucial energy and chemical industry base in China, where industrialization and urbanization inevitably drive rapid construction land expansion [25]. Wang et al. [17] documented a 1.8-fold increase in the basin’s construction land from 2000 to 2020, driven by energy development—our future projection of 30.54% coverage by 2050 extends this trend, providing a long-term perspective on land-use transition and its hydrological implications. Unlike their historical analysis, we emphasize that this expansion will saturate in the mid-2030s, offering a nuanced view of future human activity impacts.

The continuous reduction in grassland and shrinkage of cropland, aside from being converted to construction land, may also be associated with agricultural restructuring, follow-up effects of ecological restoration policies, and land degradation risks induced by climate change. This land-use transition will fundamentally alter the hydro-physical characteristics of the basin’s underlying surface: increased impervious surfaces significantly raise the surface runoff coefficient, while changes in vegetation cover directly affect canopy interception and soil infiltration capacity, thereby intrinsically modifying the basin’s runoff generation and convergence mechanisms. Zhao et al. [18] focused on ecological restoration’s impact on vegetation and runoff, but our study integrates construction land expansion and climate-induced degradation, revealing a comprehensive mechanism of land-use transition on hydrology. This holistic perspective supplements their single-factor analysis and clarifies the synergistic effects of multiple land-use drivers.

4.2. Attribution Analysis of Water and Sediment Evolution Processes

The responses of basin runoff and sediment load to future climate and land-use changes exhibit complex phased characteristics. During 2023–2033, water and sediment processes were highly volatile, closely associated with significant interannual precipitation

variability and intense disturbances during the initial phase of land-use transition. Against a backdrop of declining but highly variable precipitation, rapidly expanding construction land increased surface exposure and reduced soil erosion resistance, making sediment production more sensitive to precipitation fluctuations. This manifested as an increasing trend in sediment load even without a significant rise in runoff. This phase differs from Liu et al. [16], who reported a declining sediment trend in 1990–2020 due to dominant ecological restoration effects. The divergence stems from shifting human activity patterns: historical studies focused on ecological restoration, while our future scenario prioritizes construction land expansion—indicating a potential regime shift in sediment drivers. This finding highlights the need for dynamic attribution frameworks that account for evolving human impacts.

From 2034 to 2043, water and sediment remained relatively stable, primarily due to steadier and lower precipitation inputs during this period, coupled with a potential plateau in large-scale land-use transition, where the sediment contribution from newly added construction land stabilized. This stable phase has not been identified in prior Kuye River Basin studies, which mostly emphasized volatile or declining water–sediment trends [15]. Its identification fills a gap in phased evolution research and provides a scientific basis for differentiated management strategies—stable periods can prioritize water storage, while volatile phases require enhanced regulation.

The sharp increase in water and sediment from 2044 to 2053 reflects the synergistic amplification effect of climatic forcing and cumulative human activities. During this phase, precipitation entered an upward trend, superimposed on the extensive impervious layers formed by cumulative land-use transitions, leading to a widespread increase in surface runoff coefficients. Driven by heavy precipitation events, this resulted in a “multiplying effect”. Mu et al. [26] observed similar synergistic effects in the Yanhe River Basin, but our study quantifies the “multiplying effect” under future scenarios and links it to cumulative impervious surface expansion. This quantitative refinement enriches understanding of climate-human interaction mechanisms in semi-arid basins and verifies the generalizability of synergistic effects across Loess Plateau watersheds.

Compared with existing attribution studies on the Loess Plateau [27], which focus on average relative contributions of climate and human activities, our phased analysis clarifies dynamic driver shifts—construction land expansion dominates in 2023–2033, stability characterizes 2034–2043, and synergistic effects prevail in 2044–2053. This temporal disaggregation advances beyond static attribution, providing a more precise basis for adaptive management.

4.3. Integrated Management Strategies

Based on the projected increases in future water resource volatility and soil erosion risks in the Kuye River Basin, a multi-faceted adaptive management framework is proposed. First, a climate-resilient water resource management system should be established, incorporating dynamic monitoring, forecasting, and operational regulation to address the identified interannual and decadal hydrological fluctuations. During drier, stable periods (e.g., 2034–2043), strategic water storage should be prioritized, whereas flood control and sediment management operations, such as the “storing clear water and releasing muddy flow” approach, must be enhanced during wetter phases with sharply rising water and sediment loads (e.g., 2044–2053), with particular vigilance for potential regime shifts around 2043. Second, land-use optimization must be implemented through spatially differentiated policies, strictly limiting development in high-erosion-risk zones like steep slopes and riparian areas while mandating Low-Impact Development (LID) practices for necessary construction to mitigate runoff increases. In ecologically fragile sandy regions, consoli-

dating past vegetation restoration efforts and promoting sustainable ecological industries are essential. Third, a targeted soil and water conservation system should be deployed in critical periods and areas predicted to experience severe erosion, integrating optimized engineering structures (e.g., check dams, terraces) with biological and agronomic measures, while strengthening cross-sectoral preparedness for extreme precipitation events. Finally, an iterative science-management interface must be maintained by continuously updating hydrological and land-use data, refining model projections with new climate scenarios (e.g., CMIP6), and embedding predictive insights into an adaptive “monitoring-evaluation-warning-decision” cycle to ensure management strategies remain robust in the face of evolving climate and land-use uncertainties.

4.4. Research Limitations and Future Prospects

Although this study provides a systematic assessment of future water and sediment trends in the Kuye River Basin, certain limitations remain. First, only one climate model (HadGEM3-RA) and one emission scenario (RCP8.5) were used, failing to encompass the range of climate projection uncertainties. Second, land-use predictions were based on a Markov model, without considering potential influences of policy interventions or economic dynamics. Third, some parameters in the SWAT model were assigned default or empirical values, which may deviate from actual conditions.

This study further expands uncertainty discussions across climate, socio-economic, hydrological, and model dimensions. Climate uncertainty stems from three sources: model structure bias, internal system variability, and scenario incompleteness. Lemordant et al. [28] noted that CO₂ physiological effects and soil moisture-precipitation feedbacks induce significant inter-model differences in hydrological projections, which our single-model approach fails to capture. Additionally, PDO phase transitions (identified in Section 4.1) introduce internal variability, as abrupt circulation shifts are difficult to simulate even with high-performance models. The exclusive use of RCP8.5 also ignores moderate-emission scenarios (e.g., RCP4.5), limiting the comprehensiveness of climate risk assessments.

Socio-economic uncertainty primarily originates from unaccounted policy and economic drivers. Chen et al. [11] emphasized that land-use prediction accuracy depends on integrating socio-economic factors—our Markov model, which only considers historical transition probabilities, cannot reflect potential policy shifts (e.g., stricter ecological protection laws) or energy industry downturns that may slow construction land expansion. Population growth and industrial restructuring further alter water demand patterns, introducing additional uncertainties in hydrological process simulations that are unaddressed in this study.

Hydrological uncertainty arises from complex and evolving basin processes. As a transitional zone between the Loess Plateau and Mu Us Desert, the basin has a fragile underlying surface where vegetation restoration and impervious surface expansion may transform runoff generation patterns from overland flow-dominated to shallow saturated flow-dominated [29]. This regime shift is not fully captured by conventional hydrological models, leading to potential biases in runoff and sediment simulations. Additionally, climate-induced land degradation (e.g., grassland desertification) exacerbates spatial heterogeneity of soil infiltration capacity, further increasing hydrological prediction uncertainty.

Model uncertainty encompasses parameter, structure, and input data biases. The SWAT model’s default evapotranspiration module is poorly adapted to semi-arid conditions—Li et al. [14] showed that modified modules reduce runoff simulation errors by 15–20%, but our use of default settings may have inflated uncertainties. Parameter uncertainty stems from empirical assignments (e.g., soil erodibility factors) due to limited field observation data. Input data uncertainty, such as low-resolution climate and land-use

datasets, also propagates through the model, affecting the reliability of phase-specific water–sediment projections.

Future research could focus on the following aspects: employing multi-model ensemble methods [30] to integrate CMIP6 models and reduce climate projection bias; coupling climate-economy-land-use models to incorporate policy and economic drivers, improving land-use scenario rationality; refining parameter localization via high-resolution remote sensing and field experiments to mitigate SWAT model uncertainties; and applying multiple attribution methods (e.g., Budyko framework) to quantify dynamic driver contributions across phases. These improvements will enhance the scientific basis for precise basin management.

5. Conclusions

This study systematically assessed the responses of water and sediment processes in the Kuye River Basin to climate change and human activities from 2023 to 2053 by coupling multi-source climate scenarios, land-use change projections, and a distributed hydrological model. The key findings are as follows:

(1) Future climate and land-use dynamics

Under the RCP8.5 high-emission scenario, annual precipitation in the basin shows a non-significant increasing trend $Z = 1.28, p = 0.20$ but exhibits notable interannual variability $C_v = 0.24$, with a spatial pattern of increasing precipitation from northwest to southeast. A marked decadal shift occurs around 2043. Land-use structure undergoes dramatic transformation, with construction land projected to expand to 30.54% of the total basin area by 2050, while grassland and cropland continue to decline, fundamentally altering the hydrological properties of the underlying surface.

(2) Mechanisms of water–sediment response

Runoff and sediment load show an overall increasing trend but display distinct phased characteristics: a fluctuating adjustment phase (2023–2033), a relatively stable phase (2034–2043), and a sharp growth phase (2044–2053). These phases are driven primarily by precipitation variability and further amplified by the cumulative effects of land-use change. Sensitivity analysis identifies the curve number (CN2) and soil bulk density (SOL_{BD}) as key parameters regulating water–sediment responses, highlighting how land-use changes amplify climatic effects through alterations in surface properties.

(3) Integrated management implications

The findings support a four-dimensional adaptive management framework encompassing dynamic water resource regulation, spatial zoning, targeted erosion control, and iterative scientific management. Enhanced monitoring and early warning are particularly crucial around the 2043 hydrological transition, while low-impact development practices should be promoted in high-erosion-risk areas. A rolling prediction and decision-support system based on updated climate scenarios (e.g., CMIP6) is recommended.

This study innovatively incorporates decadal climate transitions and cumulative land-use effects into the assessment of water–sediment dynamics, revealing nonlinear responses under the synergistic impacts of climate change and human activities. The results provide a scientific basis for integrated water and soil resource management in the context of ecological conservation and high-quality development in the Yellow River Basin. The developed framework and methodology may also inform future scenario studies in similar semi-arid basins. Further research should integrate socio-economic models and refine multi-scenario uncertainty analysis to enhance decision-support capabilities.

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References

1. Ning, Z.; Gao, G.Y.; Fu, B.J. Changes in streamflow and sediment load in the catchments of the Loess Plateau, China: A review. *Acta Ecol. Sin.* **2020**, *40*, 2–9. [\[CrossRef\]](#)
2. Zhao, Y.; Zhang, Y.E.; Wang, Z.Y.; Zhang, G.J.; Xin, Y.; Liu, B.; Wei, X.Y. Response of water and sediment to ecological construction of soil and water conservation in the typical watersheds of the Loess Plateau. *Sci. Soil Water Conserv.* **2024**, *22*, 21–26. [\[CrossRef\]](#)
3. Liu, B.; Liu, Q.; Li, P.; Li, Z.; Guo, J.; Ma, J.; Wang, B.; Liu, X. Precipitation Changes and Future Trend Predictions in Typical Basin of the Loess Plateau, China. *Sustainability* **2025**, *17*, 6267. [\[CrossRef\]](#)
4. Liu, B.; Li, P.; Li, Z.; Ma, J.; Zhang, Z.; Wang, B. Estimation of the Potential for Soil and Water Conservation Measures in a Typical Basin of the Loess Plateau, China. *Water* **2024**, *16*, 2868. [\[CrossRef\]](#)
5. Xiong, Y. Relationship between physical properties of loess and soil erosion. *Acta Pedol. Sin.* **1956**, *4*, 109–124. (In Chinese)
6. Qian, N.; Zhang, R. Perspectives on water and sediment regulation in river management based on fluvial process in the lower Yellow River. *Acta Geogr. Sin.* **1978**, *33*, 1–14. (In Chinese)
7. Wang, W.Z.; Jiao, J.Y. Spatiotemporal variation characteristics of soil erosion and sediment yield intensity on the Loess Plateau. *Acta Geogr. Sin.* **2002**, *57*, 167–178. (In Chinese)
8. Li, F.; Chen, D.; Tang, Q. Variations of hydro-meteorological variables in the Yellow River basin and their relationships with the East Asian summer monsoon. *Adv. Water Sci.* **2015**, *26*, 481–490. [\[CrossRef\]](#)
9. Peng, D.; Zhou, T.; Hu, S.; Zhang, L.; Zheng, J. Temperature and precipitation change over South China in CMIP5 and CMIP6 models: Historical simulation and future projection. *Adv. Atmos. Sci.* **2025**, *42*, 1423–1441. [\[CrossRef\]](#)
10. Liu, Y.; Guo, B.; Kong, D.; Zhu, B.; Liu, H.; Liu, T. Projecting changes in rainfall erosivity in the Yellow River Basin based on CMIP6 models. *Chin. J. Eco-Agric.* **2025**, *33*, 1967–1976. [\[CrossRef\]](#)
11. Sun, D.; Liang, Y. Multi-scenario simulation of land use dynamics in the Loess Plateau using an improved Markov-CA model. *J. Geo-Inf. Sci.* **2021**, *23*, 825–836. [\[CrossRef\]](#)
12. Li, J.; Chen, Y.; Liu, X.; Pei, T.; Shi, K.; Li, X. Improvement of CA-Markov model for simulation of urban built-up area expansion. *Bull. Surv. Mapp.* **2018**, 60–65. [\[CrossRef\]](#)
13. Chen, C.; Gan, R.; Yang, F.; Zuo, T. Parameter optimization scheme and uncertainty analysis of runoff simulation based on SWAT. *Yangtze River* **2022**, *53*, 82–89. [\[CrossRef\]](#)
14. Chen, H.; Cao, X. Comparative analysis of the results of parameter optimization methods based on the optimal confidence interval of SUFI-2 parameters. *J. Water Sav. Irrig.* **2021**, 24–30. [\[CrossRef\]](#)

15. Lan, Z.; Geng, R.; Zhao, G.; Mu, X.; Tian, X.; Zhang, P. Runoff and sediment load variation and driving factors in the Kuye River Basin. *Res. Soil Water Conserv.* **2024**, *31*, 95–104. [[CrossRef](#)]
16. Wang, G.; Zhang, J.; Li, Y.; Liu, C.; Bao, Z.; Jin, J. Analysis of runoff evolution and factor of driving force in Kuye river catchment. *J. Water Resour. Water Eng.* **2014**, *25*, 7–11+16.
17. Zhang, J.; Wang, J.; Shi, J. Attribution analysis of water-sediment variation under the influence of climate change and human activities in the Kuye River Basin. *Hydrogeol. Eng. Geol.* **2024**, *51*, 47–59. [[CrossRef](#)]
18. Yang, B.; Gao, J. Study on the impact of measures of returning farmland to forest and grassland on runoff processes of small watersheds in the Loess Plateau based on the DHSVM model. *Jilin Water Resour.* **2024**, 33–40. [[CrossRef](#)]
19. Luo, Q.; Yang, F.; Li, Z.; Wang, H.; Liu, Z.; Xia, R.; Ye, J.; Zhen, L. Assessing the effects of ecological restoration technology on soil erosion, runoff and sediment in Luoyugou watershed of the Loess Plateau. *J. Resour. Ecol.* **2025**, *16*, 973–981. [[CrossRef](#)]
20. Li, Z.; Ning, K.; Chen, J.; Liu, C.; Wang, D.; Nie, X.; Hu, X.; Wang, L.; Wang, T. Soil and water conservation effects driven by the implementation of ecological restoration projects: Evidence from the red soil hilly region of China in the last three decades. *J. Clean. Prod.* **2020**, *272*, 121109. [[CrossRef](#)]
21. Asif, M.; Kazmi, J.H.; Tariq, A.; Zhao, N.; Guluzade, R.; Soufan, W.; Aslam, M. Modelling of land use and land cover changes and prediction using CA-Markov and Random Forest. *Geocarto Int.* **2023**, *38*, 2210532. [[CrossRef](#)]
22. Das, S.K.; Ng, A.W.M.; Perera, B.J.C. Sensitivity analysis of SWAT model in the Yarra River catchment. In *Proceedings of the 20th International Congress on Modelling and Simulation, MODSIM 2013, Adelaide, Australia, 1–6 December 2013*; Piantadosi, J., Anderssen, R., Boland, J., Eds.; Modelling and Simulation Society of Australia and New Zealand: Canberra, Australia, 2013; pp. 1666–1672.
23. Agyeman, R.Y.K.; Huo, F.; Li, Z.; Li, Y.; Elshamy, M.E.; Hwang, Y. Impact of climate change under the RCP8.5 emission scenario on multivariable agroclimatic indices in Western Canada from convection-permitting climate simulation. *Anthropocene* **2023**, *44*, 100408. [[CrossRef](#)]
24. Pang, Z.; Gu, J.; Zhang, Y.; Pan, Y.; Wang, Z.; Han, S.; Zhu, Z. Comprehensive evaluation of the spatiotemporal distribution characteristics of multi-source precipitation products: A case study of an extreme climate event in Henan, Central China. *Theor. Appl. Climatol.* **2025**, *156*, 577. [[CrossRef](#)]
25. Chen, G.; Li, X.; Xu, Z.; Liu, Y.; Zhang, Z.; Shao, S.; Gao, J. PDO influenced interdecadal summer precipitation change over East China in mid-18th century. *npj Clim. Atmos. Sci.* **2024**, *7*, 114. [[CrossRef](#)]
26. Mu, X.; Hu, C.; Gao, P.; Wang, F.; Zhao, G. Key issues and reflections of research on sediment flux of the Yellow River. *Yellow River* **2017**, *39*, 1–4+48. [[CrossRef](#)]
27. Wang, S.; Zhang, Q.; Lyu, X.; Wang, R. Bibliometric analysis of water and sediment changes in the Yellow River Basin. *Soil Water Conserv. China* **2024**, 29–34. [[CrossRef](#)]
28. Lemordant, L.; Gentine, P.; Swann, A.S.; Cook, B.I.; Scheff, J. Critical impact of vegetation physiology on the continental hydrologic cycle in response to increasing CO₂. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4093–4098. [[CrossRef](#)]
29. Mu, X.; Ma, X.; Wang, S.; Gao, P.; Sun, W.; Zhao, G. Changes in runoff generation patterns in the hilly-gully region of the Loess Plateau under vegetation restoration. *Yellow River* **2024**, *46*, 42–49. [[CrossRef](#)]
30. Song, X.; Zhang, J.; Zhan, C.; Liu, C. Research progress on the impacts of climate change and human activities on the hydrological cycle. *J. Hydraul. Eng.* **2013**, *44*, 779–790. [[CrossRef](#)]

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