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Research article

Does coal mining exert a greater influence than vegetation restoration on streamflow variation? Evidence from the Loess Plateau, China

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ABSTRACT

The streamflow change within the Loess Plateau is of great importance, given its complex driving mechanisms and diverse human activities. While it is widely recognized that human activities play a crucial role in impacting streamflow in this region, the specific contributions of each sort of human activity remain poorly understood. This is especially true for the coal mining since this process is particularly difficult to quantify, and thus, it remains unknown whether it is more important than another widely studied process—vegetation restoration—in streamflow changes. Here, we further improved our newly-developed model (SIMHYD-PML) by incorporating the groundwater seepage, thereby allowing it to explicitly depict the impacts of coal mining and vegetation restoration on streamflow changes. Using two typical basins in the Loess Plateau as examples, three modeling scenarios—vegetation change and coal mining, vegetation change without coal mining, and a non-impact scenario—were implemented to assess whether coal mining contributes more to streamflow changes than vegetation change. Our results show that increased groundwater seepage due to coal mining and enhanced evapotranspiration due to vegetation restoration are indeed two key factors contributing to the streamflow reduction in both basins. Specifically, from 2000 to 2020, coal mining accounted for 58.6 %–63 % (6.3–12.3 mm yr^{-1}), and vegetation restoration accounted for 37.0 %–41.4 % (4.5–7.2 mm yr^{-1}) of the total streamflow reduction. This suggests that coal mining has a greater impact on streamflow processes than vegetation restoration, making it the primary driver of streamflow changes in both catchments. This study enhances our understanding of the impacts of coal mining on streamflow, offering valuable guidelines for water resource management in regions heavily dependent on coal resources.

1. Introduction

Coal, a crucial disposable energy source in China, holds a dominant position in the country's energy structure. Due to limited presence of hydrocarbon reservoirs and reserves, China's dependence on abundant coal reserves is evident and will continue to serve as the primary energy source for a considerable period (Jie et al., 2021; Shi et al., 2021; Yuan et al., 2016). It is projected that coal will account for 50 % of the total primary energy consumption by 2030 and will remain the primary energy source in China at least until 2050 (Chinese Academy of Engineering, 2011). The extraction of coal resources has made significant historical contributions to the sustainable and stable development of the national economy.

However, extensive coal mining results in several ecological and environmental concerns, notably issues related to water (Karan et al., 2019; Qiao et al., 2017; Shang et al., 2017). This degradation manifests in various ways, such as declining groundwater levels, sharp reductions and depletion of spring water flow, diminished river water volume, and alarming increase of water pollution (Cornwall, 2017; Feng et al., 2019; Karan et al., 2019; Tang et al., 2021). Among these challenges, the issue of reduced or interrupted river flow is of primary concern, as it profoundly impacts the economic development of mining areas and the livelihoods of local communities (Wang et al., 2016a,b). Furthermore, it exacerbates the tense water supply-demand imbalance in the region,

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posing additional constraints on ecological, environment conservation and the sustainable development of the economy.

Coal mining can trigger ground subsidence and deformation, resulting in the formation of extensional fractures when the deformation surpasses a certain threshold. Water from the aquifer follows these fractures and infiltrates into the pit, causing a shift in groundwater flow from horizontal drainage to vertical percolation. As a consequence, the groundwater table experiences a rapid decline, leading to a significant reduction in the rive base flow and the spring discharges (Gasparotto et al., 2018; Gredilla et al., 2019). Furthermore, water-conducting fractures and land subsidence accelerate the infiltration rate of surface runoff, thereby influencing the efficiency of surface water and groundwater interchange. This alteration disrupts the connection between surface water and groundwater, leading to the disruption of the hydrological cycle and regional water imbalance (Qiao et al., 2017). Therefore, quantitative assessment of the influence of coal mining on catchment scale streamflow processes and evaluation of the hydrological consequences of coal mining activities are of crucial importance.

Currently, the assessment of coal mining's impact on streamflow primarily focuses on representative coal mining areas or small catchments where the mining operations are active. Experimental analysis and model simulations are employed to examine the effects of coal mining on both surface and subsurface runoff (Ma et al., 2020). Since coal mining predominantly occurs underground, there is a great emphasis on studying the subsurface runoff and its related hydrological processes. The study of the impact of coal mining on basin streamflow is similar to the method of streamflow change attribution analysis, which primarily encompasses statistical analysis methods (including multivariate linear regression) and hydrological modeling approaches (Luan et al., 2021). The statistical analysis method involves comparing multi-year streamflow data with coal mining production data to establish a correlation between the reduction in river streamflow and coal production. The hydrological modeling approach involves calibrating the model with data from a reference period, and subsequently using input data from the period affected by coal mining to estimate the watershed streamflow process during this period. This estimation is then compared with the measured streamflow to analyze the impact of coal mining on the watershed streamflow process. For example, Li et al. (2016) utilized SWAT hydrological model to analyze the causes of the reduction of streamflow in the Kuye River basin, and revealed that from 1997 to 2009, coal mining activities accounted for a reduction of 21.15 mm yr^{-1} in streamflow, which represented approximately 56 % of the total reduction. Guo et al. (2019) quantitatively analyzed the effects of coal mining, climate change, soil and water conservation measures on river streamflow using the monthly water balance model (MWBM) and statistical regression, and found that coal mining was the main reason for the decrease in streamflow after 1997. Song et al. (2021) quantified the extent of human impacts on the streamflow in two representative coal mining catchments, showing that the contribution of human activities accounted for 91 % and 42 % of the runoff change in the two basins in Loess Plateau. Luan et al. (2020) found that the coal mining has reduced streamflow by 49.4 % during 1998–2017 in the Loess Plateau. The incomplete parameterization of coal mining processes and the inadequacies in quantitatively describing and characterizing the impact of coal mining on hydrological processes (the vertical seepage of groundwater along the fractures created during coal mining operations) in basin hydrological models, compounded by the simultaneous influence of other human activities during the period of coal mining impacts, have led to a lack of clear differentiation between the effects of coal mining and those of other human activities in previous studies. Therefore, further investigations remain needed to quantitatively depict the impact of coal mining on the catchment-wide hydrological processes.

Among various human activities, vegetation restoration has garnered the most attention (Chen et al., 2018; Ma et al., 2023; Shi et al., 2022; Yang et al., 2024; Yu et al., 2019). Since 1998, China has implemented the world's most extensive vegetation restoration programs, such as the "Natural Forest Conservation Program" and the "Grain for Green Program". These ecological restoration projects have significantly improved the vegetation condition and ecosystem of the Loess Plateau, resulting in a substantial increase in vegetation coverage and drawing significant attention to ecological restoration efforts (Chen et al., 2019; Feng et al., 2016; Piao et al., 2015; Wang et al., 2019). These large-scale vegetation restoration efforts have caused notable impacts on the hydrological processes in the Loess Plateau (Guo et al., 2024; Ma et al., 2023; Tan et al., 2024; Xu et al., 2018; Yang et al., 2024).

The SIMulation of HYDrology (SIMHYD) model is a conceptual rainfall-runoff model that has been widely applied in hydrological studies due to its relatively simple structure and reliable performance across diverse climatic and land use conditions (Li and Zhang, 2017; Zhang et al., 2016). Its robustness, computational efficiency, and relatively low data requirements make it well-suited for long-term hydrological simulations (Chiew and McMahon, 1994). SIMHYD has been widely adopted in studies involving flood forecasting, catchment response analysis, and the evaluation of land use and climate change impacts on water availability (Bai et al., 2021; Zhang et al., 2010). In parallel, the Penman–Monteith–Leuning (PML) model provides a physically based approach for simulating evapotranspiration by integrating atmospheric conditions with plant physiological processes, including stomatal conductance (Zhang et al., 2019). It has been demonstrated to accurately capture evapotranspiration variability across vegetation types and climate regimes, offering improved realism in water balance modeling (He et al., 2022; Ma and Zhang, 2022; Luo et al., 2025). The integration of SIMHYD for runoff estimation and PML for evapotranspiration simulation provides a comprehensive framework to assess hydrological processes in coal mining regions, where both surface runoff and evapotranspiration can be significantly influenced by land disturbance and vegetation change.

While our previous studies have separated the impacts of coal mining on the streamflow process from vegetation change in a typical catchment in the Loess Plateau (Luan et al., 2020), the groundwater leakage was fully neglected and the hydrological processes associated with coal mining were not considered. To address this knowledge gap, this study focuses on the two typical basins (Huangfuchuan and Gushanchuan) heavily affected by coal mining and vegetation restoration in the Loess Plateau. An additional parameter for groundwater leakage were introduced to the SIMulation of HYDrology Penman-Monteith-Leuning (SIMHYD-PML) hydrological model, previously developed by the current authors, to accurately simulate the impact of coal mining on watershed streamflow processes. This approach enables us to distinguish the effects of coal mining and vegetation changes on catchment streamflow processes. The specific objectives in this study include: (i) improving the SIMHYD-PML model by incorporating the groundwater leakage process; (ii) quantifying the impacts of coal mining and vegetation restoration on the basin-scale streamflow change in the typical basins in the Loess Plateau.

2. Materials and methods

2.1. Study region

The Huangfuchuan and Gushanchuan catchments are located in the northern part of the Loess Plateau in China (Fig. 1), which belong to the middle reach of the Yellow River Basin (YRB), a region known for the inexorable soil erosion (Li et al., 2021a,b). They belong to the north temperate zone and have arid and semiarid continental climate characterized by scarce precipitation and high potential evapotranspiration. Based on the observed data from 1956 to 2020, the annual average runoff depth in the Huangfuchuan catchment is 34.2 mm, with an annual average precipitation of 390.3 mm and an annual average temperature of 7.5 °C. The Huangfuchuan has a main channel length of 137 km and a catchment area of 3246 km^2, primarily located in Jungar Banner, Ordos City, Inner Mongolia Autonomous Region. The

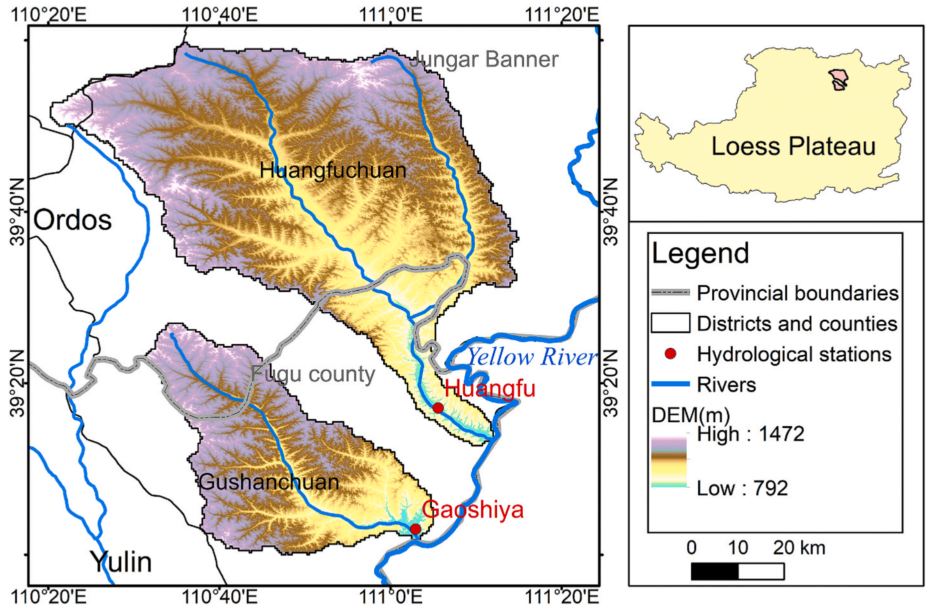

Fig. 1. Geographical locations of two studied catchments (Huangfuchuan and Gushanchuan) in the Loess Plateau.

Gushanchuan has a main channel length of 79.4 km and covers an area of 1272 km^2, primarily located in Fugu County, Yulin City, Shaanxi Province.

The Shendong Mining Area, located at the border of Ordos and Yulin in China, is the largest coal mining base in the northwest region, and the coal mining in the region primarily involves underground mining operations. There has been a significant increase in raw coal production over the years from the annual statistical data on raw coal production in Ordos and Yulin, sourced from the Statistical Yearbooks of Ordos and Yulin, with the average annual production in the 1990s being less than 0.5×10^8 t, rising to over 7×10^8 t in 2020 and surpassed 5×10^8 t, respectively.

2.2. Data

The observed monthly streamflow data from two hydrological stations (Huangfu and Gaoshiya) for the period of 1956–2020 are from the Hydrological Yearbook of the People's Republic of China. The daily precipitation data are from the rainfall stations in the Hydrological Yearbook of the People's Republic of China. There are 13 rainfall stations in the Huangfuchuan catchment and four rainfall stations in the Gushanchuan catchment. The daily maximum and minimum temperatures, sunshine hours, relative humidity, and wind speed from 1998 to 2020 are obtained from the National Meteorological Information Center of China.

In addition to meteorological and hydrological data, the SIMHYD-PML model incorporating groundwater leakage, requires remote sensing data on Leaf Area Index (LAI), land cover, and albedo to calculate actual evapotranspiration. The land use/land cover (LULC) data (30-m resolution) for the 2000s are extracted from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn). The LAI data for the period 2000–2020 are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD15A2H dataset, with a temporal resolution of eight days and a spatial resolution of 500 m, and the Global LAnd Surface Satellite (GLASS) Advanced Very High Resolution Radiometer (AVHRR) LAI product with a spatial resolution of 0.05° and a temporal resolution of 8 days from 1982 to 1999. The albedo data required for net radiation calculation is from the MODIS MCD43B Bidirectional Reflectance Distribution Function product with a resolution of 1 km. Since both the LAI and albedo data are input of the model at a daily scale, the Savitzky and Golay filtering algorithm (Savitzky and Golay, 1964) is applied to smooth the 8-day temporal scale data of LAI and albedo, generating daily data. The digital elevation model (DEM) with 30 m resolution is downloaded from the NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM).

2.3. Methods

2.3.1. Double mass curve method

The Double Mass Curve (DMC) method is a commonly used technique for assessing the consistency and variation of interrelation of two variables. The principle behind this method is that the two variables gradually accumulate over the same time length (Gao et al., 2017; Kohler, 1949; Yue et al., 2003). The calculation of the annual cumulative time series X_i and Y_i is as follows:

$$X_i = \sum_{i=1}^{N} x_i \tag{1}$$

$$Y_i = \sum_{i=1}^{N} y_i \tag{2}$$

where x_i (the reference or baseline variable, representing precipitation in this study) and y_i (the tested variable, representing streamflow in this study) are observed values over N years, with $i = 1, 2, 3, \ldots N$).

2.3.2. The SIMHYD-PML model incorporating groundwater infiltration

The SIMulation of HYDrology (SIMHYD) model is a conceptual lumped rainfall-runoff model proposed in the 1970s (Chiew and McMahon, 1994; Zhang and Chiew, 2009). This model incorporates processes such as rainfall interception, surface runoff, interflow/subsurface flow, groundwater flow, and routing, while considering both infiltration excess and saturation excess mechanisms for surface runoff generation. The model has been successfully applied in various arid and humid regions, including Australia, United States, and China (Li et al., 2013, 2014; Li and Zhang, 2017; Zhang et al., 2014, 2016).

The Penman-Monteith-Leuning (PML) model is based on the Penman-Monteith equation, coupling vegetation transpiration and photosynthetic rates using stomatal conductance (Zhang et al., 2008, 2019). The model utilizes grid-based remote sensing dynamic vegetation information (LAI) as input, extending the estimation of evapotranspiration from field-scale to regional scale (He et al., 2022; Ma and Zhang, 2022).

Coupling the SIMHYD model with PML involves replacing the evapotranspiration process in the SIMHYD model with the PML model and incorporating remote sensing dynamic vegetation data as model input. This integration results in the development of the SIMHYD-PML model, which considers the impact of dynamic vegetation changes on watershed hydrological processes (Li and Zhang, 2017; Zhang and Chiew, 2009; Zhou et al., 2013). Expanding upon the SIMHYD-PML model, the impacts of coal mining on the runoff processes are incorporated into the model. Specifically, for the groundwater storage component, a vertical leakage term (variable) and a leakage coefficient (parameter) are introduced. This parameter represents the rate at which groundwater contributes to drains from the groundwater store, thereby modulating baseflow and overall catchment water balance. Specifically, the parameter was implemented as an additional loss term in the groundwater module of SIMHYD-PML, expressed as a function of groundwater storage and a calibrated seepage coefficient (K2) (Fig. 2). These are related to the annual coal production per unit area, assuming a linear relationship between them. Fig. 2 illustrates the structure and model parameters of the SIMHYD-PML model incorporating vertical

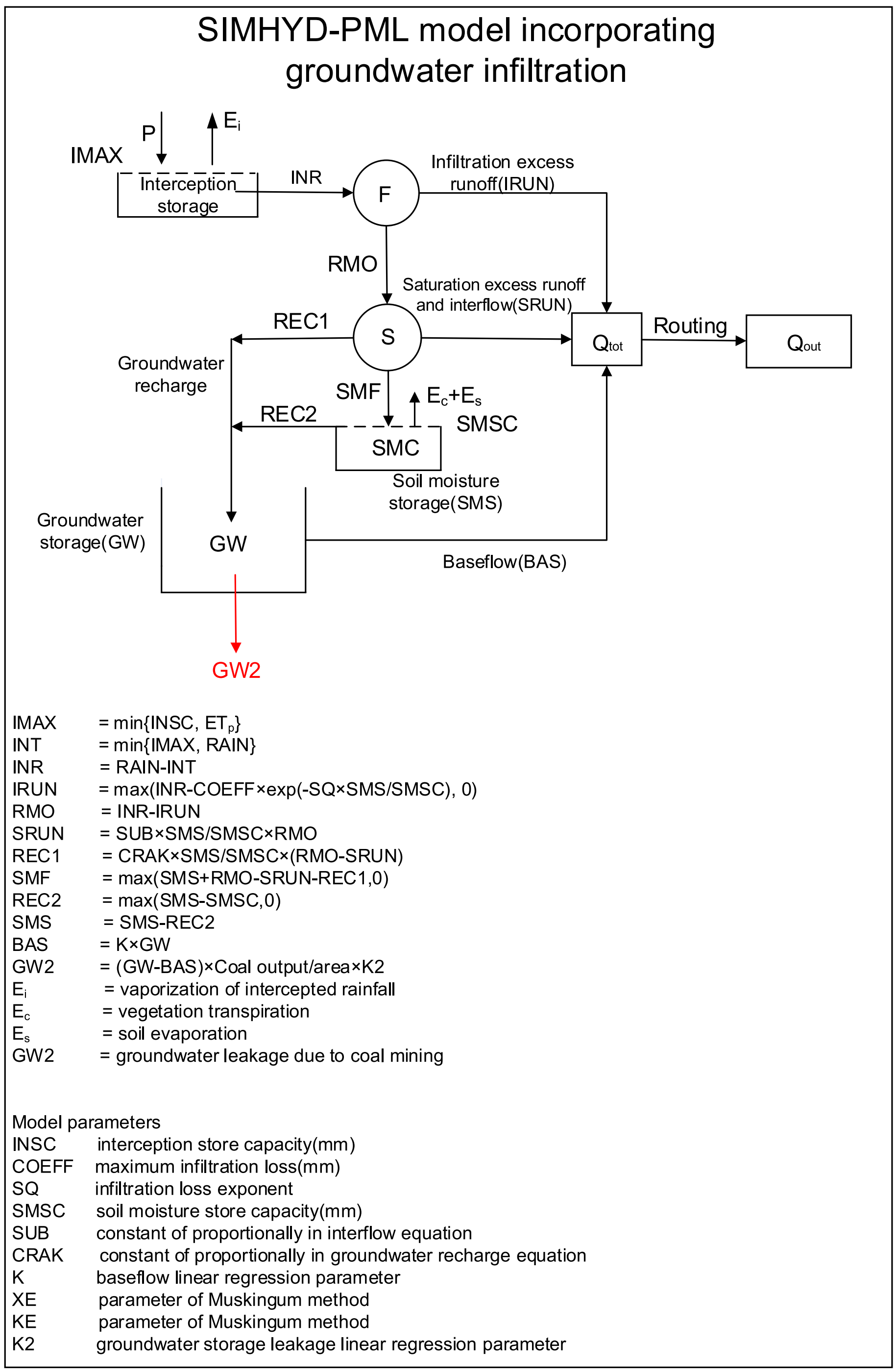

Fig. 2. The structure and parameter of the SIMHYD-PML model incorporating groundwater infiltration.

groundwater percolation.

2.4. Simulation scenario settings

The SIMHYD-PML model including groundwater leakage was calibrated and validated in the study period 2000–2020, when large-scale vegetation restoration and coal mining jointly affected hydrological processes. The period from 1998 to 1999 was designated as the model warm-up phase to eliminate the influence of initial conditions. After the model was fully calibrated, three simulation scenarios together with observations were set up to classify the effects of coal mining and vegetation restoration on the runoff process in the catchment (Table 1). All the scenarios used the same meteorological forcing from 2000 to 2020 to eliminate the effects of climate, while the differences are LAI inputs and coal mining scenarios. The first scenario (S1) was driven by the remote sensing observed daily LAI for 2000–2020 and considered coal mining (vegetation change and coal mining), which is also the scenario of model parameter calibration. The second scenario (S2) was driven by the observed daily LAI for 2000–2020 without considering the influence of coal mining (only vegetation change), where the parameter K2 related to groundwater leakage was set to 0, while the other parameters were the same as the simulated streamflow process in the S1 scenario. The last scenario (S3) was set to represent the conditions before the “Grain for Green” policy and AVHRR LAI data were available. S3 scenario was driven by the average daily LAI during 1982–1997 without including coal mining (no-impact scenario).

Since we used the same meteorological data for 2000–2020, the differences among the simulations were not from climate factors. Thus, the impacts of vegetation change and coal mining on streamflow can be finally calculated according to the following formula:

$$\Delta Q_{ve} = Q_{S2} - Q_{S3} \tag{3}$$

$$\Delta Q_{coal} = Q_{S1} - Q_{S2} \tag{4}$$

where ΔQ_{ve} and ΔQ_{coal} are the impacts of vegetation greening and coal mining on streamflow process, respectively. Q_{S1}, Q_{S2}, and Q_{S3} are the simulated streamflow from 2000 to 2020 by the coupled SIMHYD-PML and groundwater infiltration under S1, S2, and S3, respectively.

2.5. Calibration of SIMHYD-PML model incorporating groundwater infiltration

Particle swarm optimization (PSO), a global optimum solver toolbox in MATLAB, was used to optimize the parameters of the SIMHYD-PML model by incorporating groundwater storage infiltration. In this study, a population size of 300 and the maximum generation of 100 were used to search the optimum solution by the genetic algorithm in the PSO toolbox. The objective function used for calibrating and validating the model in this study is as follows:

$$F = (1 - NSE) + 5|\ln(1 + Bias)|^{2.5} \tag{5}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{N}\left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \tag{6}$$

Table 1
Three simulation scenarios.

Scenarios	Period for meteorological forcings	LAI data	Coal mining
S1	2000–2020	2000–2020	Consider
S2	2000–2020	2000–2020	not consider
S3	2000–2020	1982–1997	not consider

$$Bias = \frac{\sum_{i=1}^{N} Q_{obs,i} - \sum_{i=1}^{N} Q_{sim,i}}{\sum_{i=1}^{N} Q_{obs,i}} \tag{7}$$

where Q_{sim} and Q_{obs} are the simulated and observed monthly streamflow, respectively, and Q_{sim} is Q_{S2} in this study; $\overline{Q_{obs}}$ is the mean value of the observed monthly streamflow, i is the ith month, and N is the total number of months in the calibration period. The goal of calibration is to minimize the F value.

In this study, the warm-up period was set from 1998 to 1999, the calibration period spanned from 2000 to 2013, and the validation period covered the years 2014–2020. The calibration and validation results are shown in Fig. 3. NSE and R^2 values in two catchments both in calibration and validation periods are greater than 0.5, and absolute values of $Bias$ are less than 0.05. This ensures the effectiveness of the developed hydrological model to isolate the impacts of coal mining and vegetation change on streamflow.

3. Results

3.1. Abrupt change detection of annual streamflow

The Mann-Kendall abrupt change analysis method (Burn and Hag Elnur, 2002; Hamed and Ramachandra Rao, 1998; Mann, 1945) was used to investigate annual streamflow data in two study catchments revealed that the abrupt change points in both catchments occurred in 1979 and 1997. The precipitation-streamflow double mass curve was applied to further verify and characterize the abrupt change points of streamflow series (Fig. 4), and it was found reasonable to set the abrupt change points of streamflow series in two study catchments as 1979 and 1997. For Huangfuchuan catchment, the cumulative slope was 0.13 during 1956–1979, decreased to 0.09 during 1980–1997, and further decreased to 0.025 during 1998–2020. In the Gushanchuan catchment, the cumulative slope was 0.195 during 1956–1979, decreased to 0.122

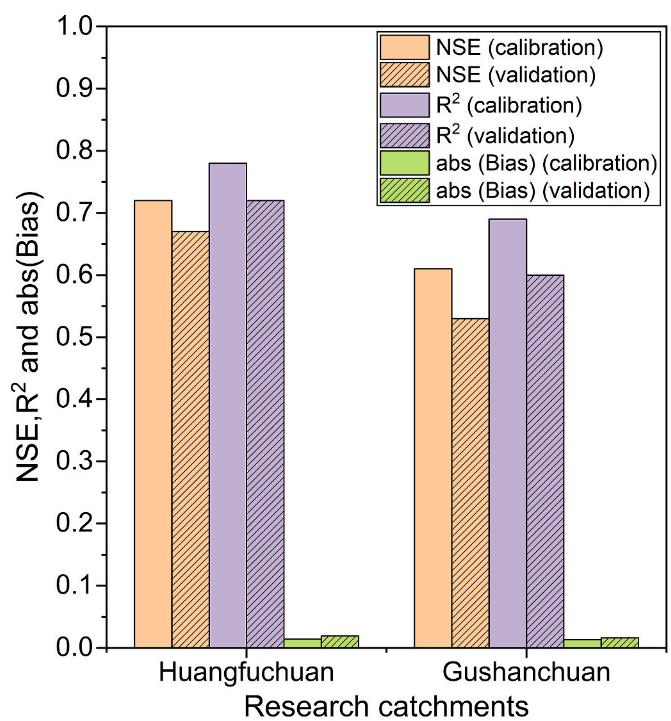

Fig. 3. The calibrated and validated results of the SIMHYD-PML incorporating groundwater infiltration in two catchments including Huangfuchuan and Gushanchuan.

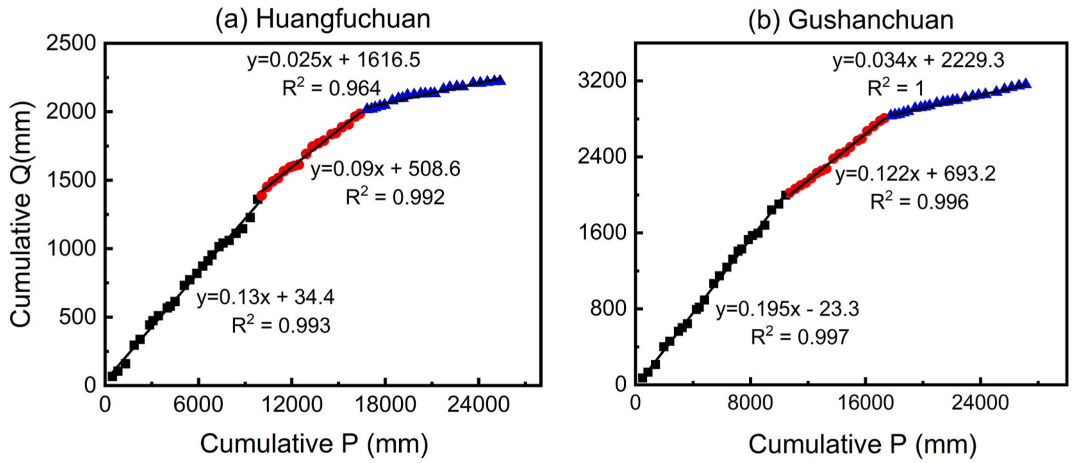

Fig. 4. Precipitation-streamflow double mass curve in the two catchments including (a) Huangfuchuan and (b) Gushanchuan.

during 1980–1997, and further decreased to 0.034 during 1998–2020. In such a short period, the cumulative slope had declined quite rapidly, only the natural factors alone cannot account for such an abrupt change of streamflow, so coal mining may be the main cause of the sharp decrease in streamflow.

3.2. Precipitation-streamflow relationship in three periods

The precipitation-streamflow relationship for two catchments across three distinct temporal periods are depicted in Fig. 5. It is evident that substantial alterations have occurred in the precipitation-streamflow dynamics across these three periods, with a notable decrease in streamflow, particularly during the period spanning from 1998 to 2020. Hence, the division of the entire temporal span into three discrete segments appears justifiable.

3.3. Simulation results of different scenarios

By carefully choosing the model parameters, the simulation was run for the three scenarios. Fig. 6 illustrates the simulated outputs of three scenarios of SIMHYD-PML model augmented with a vertical groundwater percolation component and observed annual streamflow from 2000 to 2020 for both catchments. The simulated scenarios S1 to S3 shown in Fig. 6 in agreement with those presented in Table 1. The simulation results for all the scenarios exhibit consistency, with scenario S3 yielding the highest streamflow depth, followed by S2, and finally S1. For the years characterized by elevated streamflow, significant disparities emerge among the various simulated scenarios, whereas during years of diminished streamflow, disparities among the scenarios are less pronounced. Overall, the dissimilarity between scenarios S2 and S1 exceeds that of between S3 and S2, thus indicating the comparatively greater influence of coal mining activities on the streamflow process in contrast to large-scale vegetation restoration projects. Fig. 7 displays the measured and simulated monthly streamflow processes for three different scenarios, showing similar patterns to the annual streamflow processes in Fig. 6. Larger discrepancies are observed between the three scenarios during months with higher streamflow, while smaller differences are evident during months with lower streamflow.

3.4. Separating the impacts of coal mining on streamflow from vegetation change

Fig. 8 illustrates the annual average observed streamflow and simulated streamflow depths from 2000 to 2020 across different scenarios. The discrepancy between S1 and S2 manifest the impact of coal mining activities on streamflow depth, while the difference between S2 and S3 signifies the impact of vegetation restoration on streamflow depth. For the Huangfuchuan catchment, the annual average streamflow depths under scenarios S1, S2, and S3 are 9.9 mm, 16.2 mm, and 20.7 mm, respectively. In the Gushanchuan catchment, the annual average

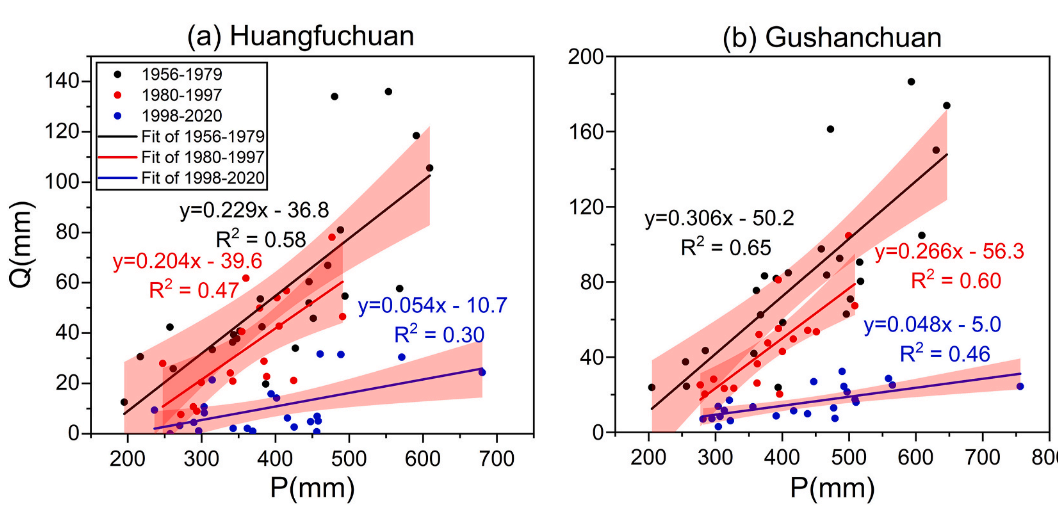

Fig. 5. Precipitation-streamflow relationship in the two catchments including (a) Huangfuchuan and (b) Gushanchuan over three time periods of 1956–1979, 1980–1997 and 1998–2020.

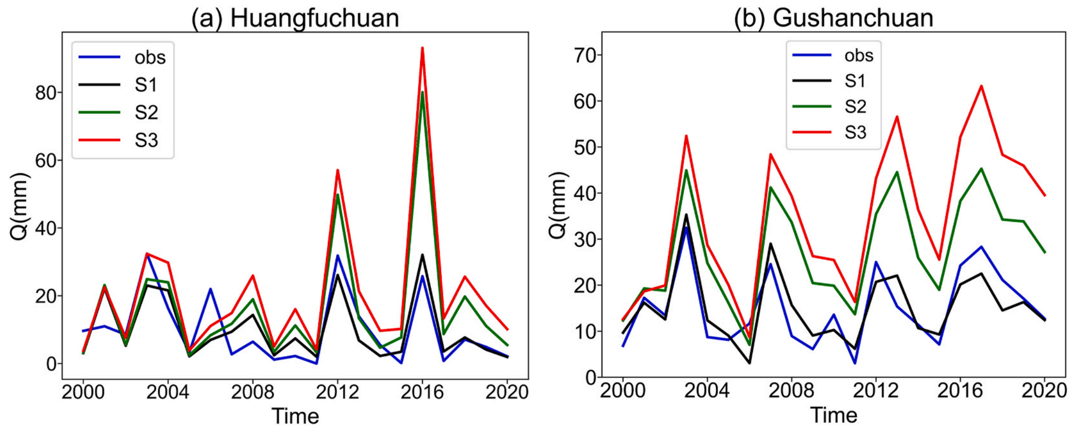

Fig. 6. The observed and the simulated annual streamflow under different scenarios in two catchments including (a) Huangfuchuan and (b) Gushanchuan.

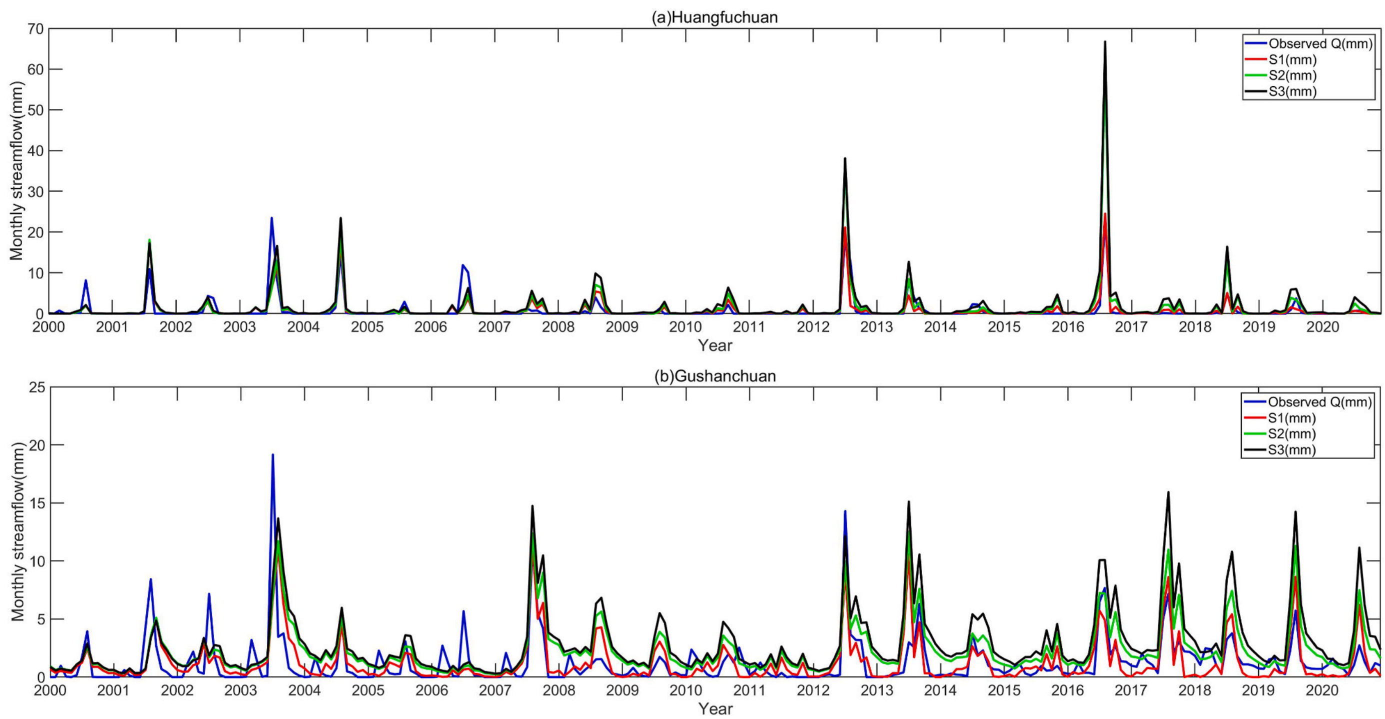

Fig. 7. The observed and the simulated monthly streamflow under different scenarios in two catchments including (a) Huangfuchuan and (b) Gushanchuan.

streamflow depths under scenarios S1 to S3 are 15.1 mm, 27.4 mm, and 34.7 mm, respectively.

Fig. 9 illustrates the reductions in streamflow attributed to various influencing factors, along with their corresponding reduction ratios. In the Huangfuchuan catchment, coal mining activities result in streamflow reduction of 6.3 mm/year, while vegetation restoration contributes to streamflow reduction of 4.5 mm/year. Similarly, in the Gushanchuan catchment, coal mining activities lead to streamflow reduction of 12.3 mm/year, while vegetation restoration contributes to streamflow reduction of 7.2 mm/year. The reduction rates due to coal mining activities in the Huangfuchuan and Gushanchuan catchments are 58.6 % and 63.0 %, respectively, while those due to vegetation restoration are 41.4 % and 37.0 %, respectively. It is evident that, compared to vegetation restoration measures, coal mining activities have a greater impact on flow volumes.

4. Discussion

4.1. A comparative analysis with previous studies and advancements of the present research framework

Most studies have examined the impacts of human activities and climate variations on changes in streamflow within a catchment. These factors play significant roles in altering streamflow processes, leading to notable changes in the spatial-temporal distribution of water availability (Dey and Mishra, 2017; Jehanzaib et al., 2020; Kong et al., 2016). A multitude of studies have identified human activities as the primary factor driving streamflow changes in the YRB (Chang et al., 2016; Feng et al., 2018; Li et al., 2018; Li et al., 2021a,b; Luan et al., 2022a, 2022b, 2021; Wei et al., 2016; Yin et al., 2018). The DMC method for precipitation-streamflow analysis indicates abrupt change points in streamflow changes, suggesting that the variations in catchment streamflow from 1997 to 2020 were predominantly caused by human activities rather than climate change. The streamflow variations in the

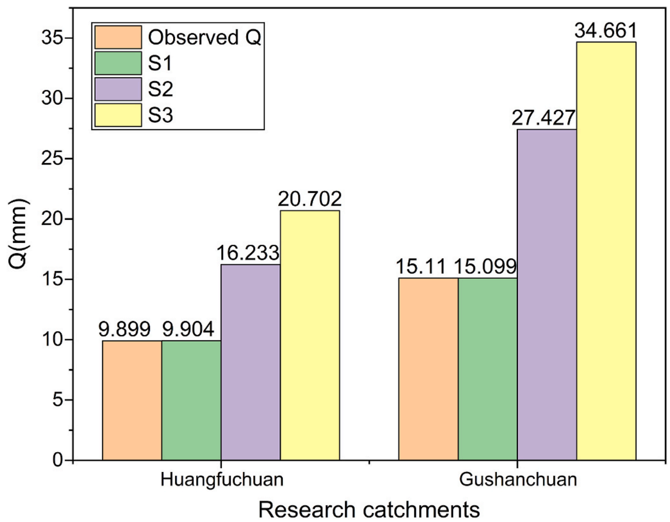

Fig. 8. The measured and the simulated annual average streamflow under different scenarios in two catchments including the Huangfuchuan and the Gushanchuan. S1 was driven by vegetation change and coal mining. S2 was driven by vegetation change without coal mining. S3 was the non-impact scenario.

Huangfuchuan and Gushanchuan catchments, as well as other surrounding tributaries of the YRB, are primarily attributed to human activities, consistent with prior research findings (Feng et al., 2018; Luan et al., 2020, 2021; Yin et al., 2018). The primary human activities in these two catchments include large-scale vegetation restoration, water and soil conservation measures, as well as coal mining activities. Previous studies have indicated that in the adjacent Kuye River Basin, coal mining has been identified as the predominant factor contributing to the decline in streamflow (Guo et al., 2019; Luan et al., 2020; Song et al., 2021).

To enhance the vegetation coverage in the Loess Plateau and reduce soil erosion, the

large-scale vegetation restoration program was initiated in the late 1990s, which included the "Natural Forest Protection Program" and the "Grain for Green Program" (Cao et al., 2011; Chen et al., 2019; Li et al., 2020; Wang et al., 2016a). Over 20 years since its implementation, the vegetation coverage on the Loess Plateau has significantly improved. This has also led to China contributing 25 % of the global increase in leaf area index from 2000 to 2017 (Chen et al., 2019). The LAI in the two study catchments has shown a rapid increase in recent years (Fig. 10). The changes in vegetation impacted the water cycle by altering canopy transpiration, canopy interception, soil moisture infiltration, root water uptake, and energy distribution processes. As vegetation plays a vital role in water conservation (Bai et al., 2020), the runoff decreases continuously with the increase in vegetation. While soil and water conservation measures alleviate soil erosion and increase total biomass and economic yield, they also intercept a portion of surface runoff that would have been lost before the implementation of these measures, transforming it into soil water or groundwater. This results in higher utilization of natural rainfall and runoff, leading to a decrease in basin runoff volume. Our results are consistent with this theory and the previous studies, which showed that the increase in vegetation had significantly reduced the runoff on the Loess Plateau.

Although previous studies have incorporated human activities into hydrological modeling frameworks, most have relied on empirical or scenario-based approaches that loosely couple human-induced processes with hydrological components. In contrast, this study introduces a targeted and physically interpretable improvement to the SIMHYD-PML model by embedding a groundwater seepage module that reflects subsurface water losses associated with coal mining-induced subsidence. This modification not only enhances the model's capability to simulate flow reductions in mining-intensive basins but also provides a quantifiable mechanism to distinguish mining effects from those of ecological restoration. Compared to generic parameter adjustments or lumped disturbance indices used in earlier research, our approach offers improved process representation and diagnostic power in attributing streamflow changes. Moreover, quantifying the hydrological impacts of coal mining at larger basin scale generally demands comprehensive hydrogeological and mining operation data. Under conditions of data scarcity, this study establishes a robust modeling framework that enables the quantitative assessment of mining-induced runoff alterations, offering both a methodological reference and empirical foundation for future large-scale investigations. This advancement is particularly significant for data-scarce and geologically sensitive regions such as the Loess Plateau, where mining activities interact intricately with hydrological regime.

This study did not employ streamflow change attribution analysis framework, which involved delineating abrupt changes in streamflow

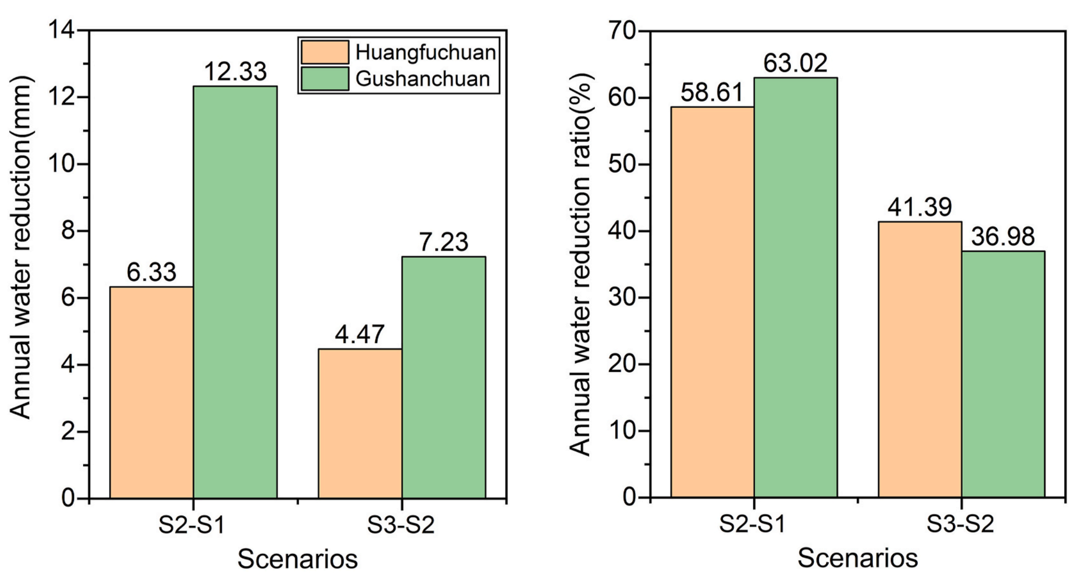

Fig. 9. The water reduction and corresponding water reduction ratio by different influencing factors in two catchments including the Huangfuchuan and the Gushanchuan. S2-S1 represents the impact of coal mining on streamflow and S3-S2 represents the impact of vegetation restoration on streamflow.

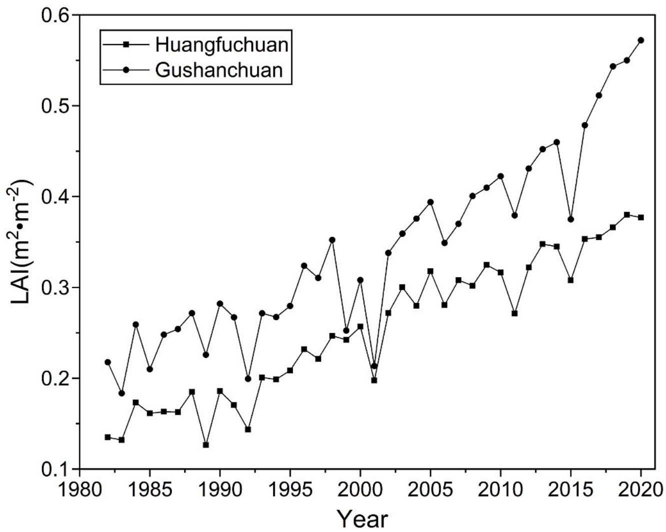

Fig. 10. Variations in the annual mean LAI during 1982–2020 in the two catchments including the Huangfuchuan and the Gushanchuan.

and using the baseline period's streamflow processes to calibrate and validate the model. In such a framework, the difference between measured and simulated streamflow processes represents the impact of human activities. For instance, in the case of a specific human activity such as coal mining, the model is calibrated during the baseline period (considered a natural period without human activity influence), and then the watershed hydrological model is applied with a coupled reservoir module (where the parameters of the reservoir module do not require calibration, i.e., a parameterized reservoir model) to simulate runoff processes. By comparing the model simulation results with and without the reservoir module, the impact of reservoir construction on watershed hydrological processes can be assessed and analyzed. Due to difficulty in quantitatively representing and incorporating complex coal mining related activities in the simulation models, this study employs hydrological models that consider two typical human activity processes within the watershed to calibrate model parameters.

4.2. Mechanisms underlying the impacts of coal mining on surface water and groundwater

Coal mining has a continuous and significant impact on hydrological processes and riverine ecosystems (Viney et al., 2021). During the initial stages of coal mining, the underground void area is relatively small, with water-bearing fractures not extending to the surface but exhibiting bending deformation. When precipitation generates surface runoff, the runoff from the slopes converges into the subsidence basin, which acts as a beneficial surface water storage area. This amplifies the loss of depression water in the hydrological processes of runoff, reducing the basin's surface runoff and directly leading to a decrease in river flow (Acharya and Kharel, 2020; Tang et al., 2021; Yang et al., 2023). Furthermore, the formation of fractures allow surface runoff to infiltrate into deeper soil layers through these fractures. As rainfall continues, if the wet front advances beyond the depth of the fractures, the formation of fractures will no longer affect surface runoff (Wang and Wang, 2020). In recent years, there has been a significant increase in the production of raw coal in Ordos and Yulin. Around 2020, coal mining levels were more than 50 times higher than those in the 1990s. The intensive mining activities have resulted in the formation of increased void areas, where the collapse of overlying rocks in these void areas has led to the enlargement of geological fractures, creating numerous cracks and collapses. At this stage, water-bearing fractures extend to the surface, serving as pathways for surface water to replenish the groundwater flow in the void areas. This process results in a reduction in surface runoff throughout the entire runoff process, and increase in groundwater flow. When fractures reach a certain level of development, they can redirect all surface runoff from rainfall to the groundwater flow. The formation of numerous ground fractures and collapses during the process of coal mining has increased the infiltration coefficient, leading to a greater and faster seepage of rainfall into the ground. As a result, there is a reduction in the water supply to the rivers.

The impact of coal mining collapses on baseflow includes the collapse of mine roofs, alterations in aquifer structures, direct linkages to mine pits, substantial declines in groundwater levels, localized formation of drawdown cones, and the direct discharge of substantial quantities of groundwater through mine pit dewatering systems (Meredith, 2016; Sun et al., 2020; Yang et al., 2023). This significantly impacts the discharge of groundwater, ultimately decrease in baseflow. Additionally, all industries related to coal mining consume high amount of water, for instance, a coal chemical project with an annual production of 1 million tons typically consumes ten million tons of water per year. Therefore, coal mining is considered one of the primary factors contributing to the reduction of water resources in mining areas.

4.3. Limitations, uncertainties and suggestions for future studies

Since the SIMHYD model is a conceptual hydrological model, it does not explicitly account for complex physical processes such as land subsidence or dynamic interactions between surface water and groundwater. The introduced leakage parameter *K2* is intended to represent the effect of fracture propagation, with fracture propagation assumed to increase linearly with cumulative coal production volume. This approach draws on the structure of the original SIMHYD model, in which vertical percolation from the soil to groundwater is governed by a similar empirical parameter *K*. However, we acknowledge that this assumption may lack a robust physical or empirical basis, potentially introducing bias into the model outputs. The primary objective of this study is to investigate the impacts of coal mining on streamflow in two larger, representative coal-mining catchments. Given the lack of detailed spatial data on mining distribution, coal seam geometry, and mining depth, it is challenging to develop a physically based model. Therefore, a conceptual modeling approach was adopted, although this inevitably limits our ability to rigorously evaluate the validity of the leakage parameter.

While the model primarily focuses on the impact of coal mining and vegetation restoration on streamflow, it is important to recognize the potential influence of other factors that could affect the hydrological outcomes. For example, groundwater pumping and other human interventions, such as terracing, urbanization, reservoir construction and land-use changes unrelated to vegetation restoration or coal mining, could also significantly alter streamflow dynamics. These factors, however, were not incorporated in the current study due to data limitations and the focus on isolating the primary influences of coal mining and vegetation change.

Regarding the model's limitations, the primary source of uncertainty arises from the inability to fully represent all anthropogenic influencing streamflow. While the model does account for vegetation restoration and coal mining by incorporating the K factor (a proxy for coal mining activity), other influences such as groundwater extraction, changes in agricultural practices, or infrastructure development may also contribute to variations in runoff, albeit to a lesser extent in this study.

Future studies should aim to expand the model by including additional variables (e.g., groundwater extraction, irrigation practices) and more comprehensive calibration/validation datasets to improve its predictive capacity and account for such interactions more rigorously. Moreover, a broader range of representative coal mining-affected catchments should be incorporated, including varying mining intensities and spatial extents. Such an approach would enable a more comprehensive comparison and evaluation of the generalizability of the results.

5. Conclusions

By coupling the groundwater leakage term, this study developed an improved SIMHYD-PML hydrological model to explicitly quantify the impact of coal mining on streamflow changes in the Loess Plateau. The Huangfuchuan and Gushanchuan catchments in this region were selected as two typical examples. Our results show that the streamflow reduction caused by coal mining became increasingly pronounced from 2000 to 2020. Over the past 21 years, coal mining contributed to 58.6 %–63 % of the total streamflow reduction, while vegetation restoration accounted for 37.0 %–41.4 % in both catchments. The corresponding decreases in streamflow were 6.3–12.3 mm yr^{-1} for coal mining and 4.47–7.23 mm yr^{-1} for vegetation restoration. This suggests that the impact of coal mining on runoff processes is greater than that of vegetation restoration, making it the primary factor leading to decreased runoff. The insights from this study emphasize the need to balance coal mining activities with water resource management in heavily mined areas, which is crucial for achieving the United Nations' Sustainable Development Goals in these regions. Although this model was applied to two specific catchments, it holds potential for broader application in other regions with similar human activities.

We acknowledge that a key limitation of the proposed modeling approach lies in the broad assumptions adopted to isolate the impacts of vegetation changes and coal mining activities, whereby other anthropogenic interventions were not explicitly accounted for, potentially introducing uncertainty in the attribution of observed changes.

CRediT authorship contribution statement

Jinkai Luan: Investigation, Formal analysis, Data curation, Conceptualization, Writing – original draft, Methodology. **Ning Ma:** Writing – review & editing, Resources, Project administration, Methodology, Conceptualization. **Ran Zhang:** Writing – review & editing. **Wei Li:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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