

Quantifying factors influencing runoff in mining areas using the SWAT model – a case of the Kuye River in Northern Shaanxi, China

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ABSTRACT

There has been a marked decrease in river runoff in northern China recently, particularly from coal mining areas, but few studies have been able to quantify the factors influencing this phenomenon. Some methods to calculate the reasons for the river runoff decrease are urgently needed, and the degree to guide the river ecology restoration. Taking the Kuye River as an example, this study established a reference period (1960–1979) for a Soil and Water Assessment Tool (SWAT) model, and simulated the runoff changes and distribution. Then, the degree of influence of weather, water and soil conservation, industrial and domestic water consumption, and coal mining on river runoff during a recent period (1999–2010) was quantified. Finally, recent changes in runoff and its distribution were simulated with a modified SWAT model. The results show that in comparison to the reference period, for the recent period $21,987 \times 10^4 \text{ m}^3$ per year of runoff from the Kuye River was attributable to weather, while $8,840 \times 10^4 \text{ m}^3$, $5,346 \times 10^4 \text{ m}^3$ and $13,788 \times 10^4 \text{ m}^3$ was attributable to soil and water conservation measures, industrial and domestic water consumption, and coal mining respectively. The distribution of the runoff in the recent period was similar to that in the reference period, although its value was only half of the latter. These results can serve as an important reference for the ecological restoration of the Kuye River basin.

Key words | coal mining, influence factors, Kuye River, river runoff, SWAT model

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INTRODUCTION

Changes in river runoff are studied under hydrology, and researchers typically adapt basic data to choose a desired statistical, conceptual or distributed hydrological model to study related issues (Mimikou & Baltas 1997; Wang *et al.* 2006). A distributed hydrological model divides a study area into many grids based on rainfall, vegetation, temperature, soil, and elevation to calculate the runoff flow. Distributed hydrological models such as the SHE (System Hydrological European) (Sahoo *et al.* 2006), SWAT (Soil and Water Assessment Tool) (Neitsch *et al.* 2009), and VIC (Variable Infiltration Capacity) (Liang *et al.* 1996) are currently implemented worldwide; the SWAT model, in particular has attained good results.

Since 2000, it has been used widely for simulations of flow, sediment, and non-point source pollution of major rivers and lakes across China (Li 2009).

Most of the coal mining area's original ecosystem is very fragile, including a shortage of water resources in Northern China. Over the past 20 years, large-scale coal mining has increased rapidly in China. Coal mining requires water, coal washing, coal-fired power generation, and the entire coal chemical industry also has a great demand for water. As a result, the strain on water supplies from increased demand has become very serious in coal mining areas, with river runoff reduced or completely depleted (Zhang *et al.* 2017). Water resources protection is the biggest

challenge of the mining areas, and coal mining specifically has become an important factor affecting river runoff (Jiang *et al.* 2010). But no uniform and mature method exists to accurately evaluate the impact of coal mining activities and other factors on water resources (Zipper *et al.* 1997). This study takes the Kuye River as a test case, and uses the SWAT model to calculate the degree of influence of coal mining as well as other factors on river runoff in a recent period, in order to provide a scientific basis for ecological restoration in the area.

MATERIALS AND METHODS

Study area

The Kuye River is a tributary of the Yellow River in its middle reaches, originating in the province of Inner Mongolia and flowing through Shaanxi province, as shown in

Figure 1. The river is 242 km long and the area of the basin is 8,706 km². The average annual evaporation is 1,788 mm per year, the precipitation and runoff levels are 413 mm and 510 million m³ per year. Industrial water consumption increased nearly 10 times in the study area from 1980–2010, but agricultural water consumption levels did not change, and the water and soil conservation area rose from 15% to 40%. Total water consumption stood at about 110 million m³ in 2010. The Kuye River basin is rich in coal resources; nearly 3.12 million tons were mined per year in the 1980s. However, large-scale mining from 2000 onwards saw that figure reach 161 million tons in 2010 (Cheng *et al.* 2009).

Materials

Spatial databases

According to the demands of the SWAT model, all spatial data across geographic coordinates and projections are unified and converted into raster data with the same resolution using ArcGIS software (Ou & Wang 2011).

DEM (Digital Elevation Model): the Kuye River basin DEM comes from the 'International Scientific Data Service Platform' hosted by the Chinese Academy of Sciences. According to the scope of the Kuye River basin, four mirror images located at the coordinates 38°–40°N and 109°–111°E were converted into a single 30 m × 30 m grid. The DEM (Qiu *et al.* 2012) of the Kuye River basin was then extracted using the boundary of the watershed.

Land Use Map: A map featuring six types of land use was downloaded from 'China's Western Environmental and Ecological Science Data Center' (Liu *et al.* 2003), and land use data for the Kuye River basin were extracted. Due to the limited availability of data, this study used 1985 land use data to represent the average of the reference period and 2010 data to represent the recent period. During these two periods, land use in the Kuye River basin underwent some changes, as shown in Table 1.

Soil Map: A soil map of China (1:1,000,000) was downloaded from 'China's Western Environmental and Ecological Science Data Center' hosted by the Chinese Academy of Sciences. A map of soil types in the Kuye River basin, at a resolution of 1 km, was extracted using

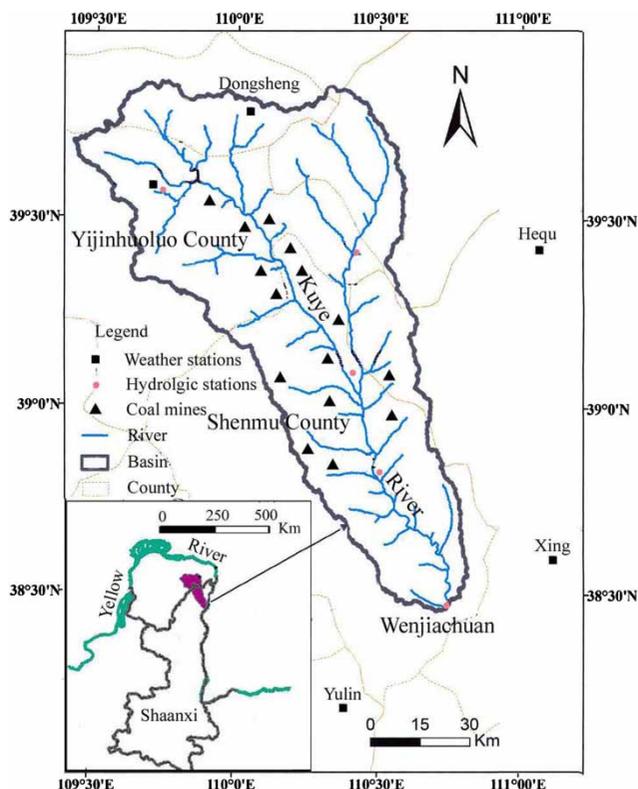


Figure 1 | The study area, hydrological stations, and weather stations.

Table 1 | Land use changes in the Kuye River basin

Land use	1985		2010	
	Area (km ²)	Percent of coverage (%)	Area (km ²)	Percent of coverage (%)
Cultivated land	1,724.3	19.80	1,644.79	18.89
Woodland	384.11	4.41	423.02	4.86
Grassland	5,394.16	61.95	5,763.4	66.19
Water bodies	259.27	2.98	208.4	2.39
Residential land	84.66	0.97	118.38	1.36
Wasteland	860.58	9.88	549.12	6.31
Total	8,707.07	100	8,707.07	100

ArcGIS (Geographic Information System); the FAO (Food and Agriculture Organization)-90 soil classification system was used (Qi *et al.* 2011). The main soil types in the Kuye River basin included Calcaric Cambisols, Calcaric Arenosols, Haplic Kastanozems, and Cambic Arenosols; all the other soil types taken together accounted for only about 30%.

Meteorological data

Meteorological data, including average daily rainfall, maximum and minimum air temperature, solar radiation, wind speed and relative humidity, were gathered from the 'China Meteorological Science Data Sharing Network' hosted by the Chinese Meteorological Bureau. This study made use of the daily monitoring data (1960–2010) of five weather stations – Yulin, Yijinhuluo, Dongsheng, Hequ, and Xing – located near the Kuye River. The location of each station is shown in Figure 1.

Division of sub-catchments and allocation of hydrological response units

Considering the calculation efficiency and actual situation of the Kuye River basin, the threshold area was 100 km², accounting for 1.15% of the total area, with the entire basin divided into 47 sub-catchments. The SWAT divided each sub-catchment into Hydrological Response Units (HRUs) before modeling. This study set the minimum threshold of land use and soil area to 4% (Qin 2012), and the Kuye River basin was divided into 452 HRUs.

Methods

Conflicts over water are also accompanied by changes in climate, land use, and human activity, among others (Bronstert *et al.* 2002; Postel & Richter 2003). In recent decades, changes in climate have caused impacts on natural and human systems on all continents. A report by the Intergovernmental Panel on Climate Change noted that the quantity and quality of water resources at global, regional, and local scales were being affected (Intergovernmental Panel on Climate Change 2014). Looking at the time series of runoff in the Kuye River, human activities are considered as playing an important role in the short-term quality and quantity of river runoff. The time series can be divided into three periods: a reference period (1961–1979), a middle period (1980–1998), and a recent period (1999–2010) (Wu *et al.* 2014).

This study used the following procedure:

- (1) Establish, calibrate, and verify the SWAT model of Kuye River runoff for the reference period.
- (2) Integrate meteorological data from the recent period into the established SWAT model; the difference between the value simulated for the two periods is considered the water reduction caused by weather related factors.
- (3) Continue to apply recent period land use data to the SWAT model; the difference in the simulated value denotes the water reduction caused by soil and water conservation measures. In this study, it is assumed that these measures can be accurately reflected by land use data.
- (4) For the recent period, the different between measured value and simulated values for runoff is considered the water reduction caused by other factors; subtracting the increased industrial and domestic water consumption, the rest is attributed to coal mining and other factors.

Figure 2 shows the procedure for calculating water reductions attributable to different factors. By adjusting some parameters, a SWAT runoff model is obtained for the Kuye River in the recent period; from this, the spatial and temporal distribution of runoff in each period can be obtained.

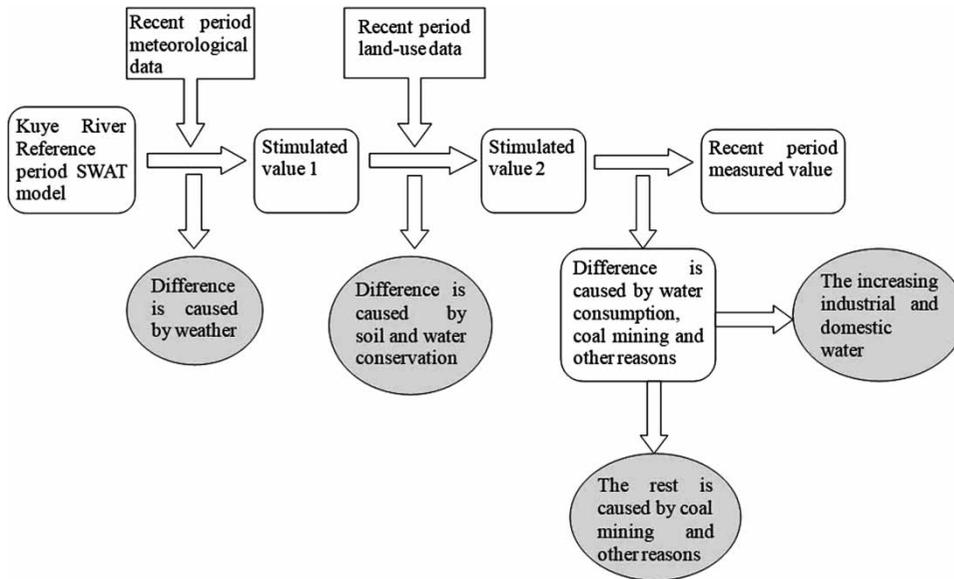


Figure 2 | The procedure for calculating water reductions attributable to different factors.

RESULTS AND DISCUSSION

SWAT model for the reference period

The Kuye River SWAT runoff model was built for the reference period using the basic established database. The model was then calibrated and verified repeatedly by adjusting the sensitive parameters until the applicability evaluation was passed. Finally, the model was used to simulate the spatial distribution of the river runoff.

Parameter sensitivity analysis and applicability evaluation

In this study, the LH-OAT (Latin Hypercube and One-factor-at-A-Time) (Morris 1991), which was included in the SWAT model, was used to analyze the sensitivity of each parameter. It combines the advantages of the Latin Hypercube (LH) and One-factor-at-A-Time (OAT) sampling methods (Van Griensven *et al.* 2002). The most sensitive parameters of the SWAT model are CN2, ESCO, GWQMN, SLOPE, SOL_K, SOL_AWC, SOL_Z, rchrg_dp. These parameters were used only for referencing, and some of these need adjusting in the actual calibration; the parameters description is shown in Table 3.

There are three methods to ascertain the applicability evaluation: RE (Relative Error), R^2 (Deterministic Coefficient),

and Ens (Nash–Sutcliffe Efficiency Coefficient) (Zhu & Zhang 2005); these values should ideally be $<20\%$, ≥ 0.6 , and ≥ 0.5 , respectively. White & Chaubey (2005) believed that it was possible to obtain the same result by adjusting one of the many parameters, although only some of those, which best encapsulated the process, were needed; otherwise there was a risk of not reflecting the real system process.

Runoff calibration and verification

The model calibration used runoff data from 1961–1972, and the verification used data from 1973–1979. According to the results of the sensitivity analysis and other studies (Qin *et al.* 2010), the parameters were adjusted to coincide the runoff simulation values and measured values, first annually then monthly. According to comparisons of the simulated and measured values, the parameters can be adjusted based on their correlation with the runoff data, and a good result can be achieved (Du 2013). Table 2 shows the result of the applicability evaluation of calibration and verification; the discharge values are average values, from which it can be concluded that the SWAT model is well adapted to the Kuye River runoff for the reference period. Figure 3 shows the fitted curve of the measured and simulated values of monthly runoff.

Table 2 | The values of the runoff during the calibration and verification periods.

Periods	Measured value (m ³ /s)	Simulated value (m ³ /s)	RE (%)	Ens	R ²
Calibration period (1961–1972)	23.57	21.02	−11	0.72	0.77
Verification period (1973–1979)	22.63	23.17	2	0.73	0.77

The calibrated and verified parameter values for the Kuye River SWAT runoff model for the reference period (1961–1979) are shown in Table 3.

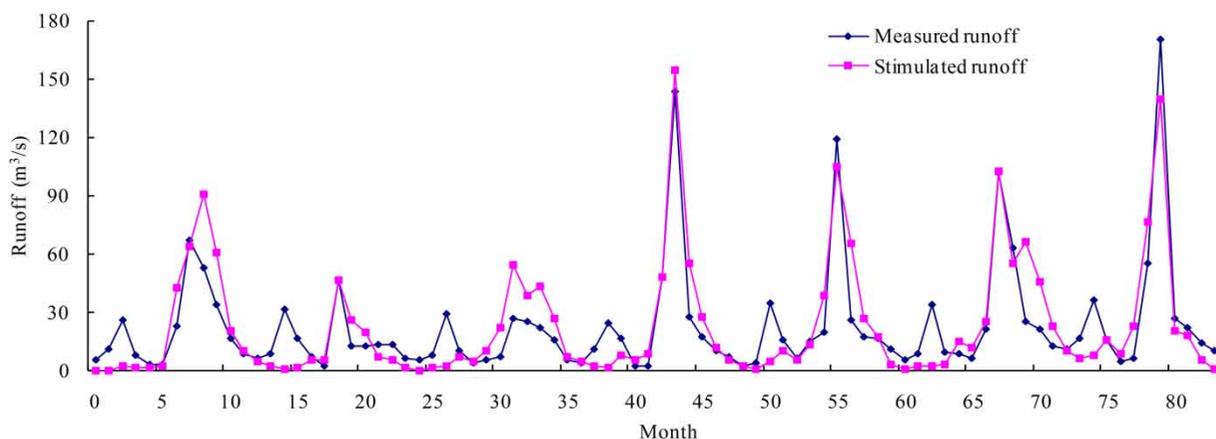
Spatial distribution of runoff

The distribution of the Kuye River basin runoff is closely related to precipitation, soil properties, land use, and

topography (Li & Sheng 1996). Since there was no change in land use and vegetation cover, the spatial variations in the runoff were primarily determined by precipitation levels. From 1961–1979, the peak precipitation area of the Kuye River basin was located mainly downstream, with precipitation levels gradually increasing from northwest to southeast. The upstream desert grassland was conducive to surface water infiltration, resulting in lower runoff depth, with the runoff coefficient being only 0.16. However, the terrain of the loess gully area downstream was steep and difficult for surface water to infiltrate for storage; thus, the runoff was deeper and the coefficient was about 0.25. The areas of the Kuye River basin with the lowest runoff depth were located in the northwest (55–59 mm) followed by the northeast (59–94 mm); downstream areas had the maximum runoff

Table 3 | Results of the SWAT model parameter calibrations

No.	Parameters	Parameter description	Original value	Value range	Final value
1	CN2	SCS runoff curve number	35–98	±8	−4.5
2	ESCO	Soil evaporation compensation factor	0.00	0–1	0.43
3	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H ₂ O)	0.00	0–5000	20
4	SLOPE	Average slope (%)	0.055	0–0.6	0.47
5	SOL_K	Saturated hydraulic conductivity (mm/h)	12.45	0–200	101
6	SOL_AWC	Available water capacity of the soil layer (mm H ₂ O/mm soil)	0.15	0–1	0.17
7	SOL_Z	Depth from soil surface to bottom layer (mm)	100.00	0–3000	401
8	RCHRG_DP	Deep aquifer percolation fraction	0.05	0–1	0.05

**Figure 3** | Kuye River measured and simulated runoff during the verification period (1973–1979).

depths, between 94 and 138 mm, because they received the most precipitation and had the highest slopes.

Calculation of water reduction in the recent period

In many locations, climate change may significantly reduce river runoff and urban water supplies (Fane & Turner 2010). Many recent studies have also shown that human activities, including land use change (Mirhosseini *et al.* 2018), agricultural irrigation, reservoir storage, coal mining, industrial and domestic water consumption, have become the main reasons for effects on surface water resources (Luo *et al.* 2018). According to previous research results (Wu *et al.* 2014, 2016), the main factors affecting the Kuye River runoff were weather, soil and water conservation measures, coal mining, and water consumption for industrial and domestic use.

Calculation of water reduction

By including meteorological and land use data from the recent period in the SWAT model, the runoff reduction caused by weather and soil and water conservation in the Kuye River basin during the recent period was calculated. After this, the difference between the simulated and measured runoff values was considered to be the runoff changes caused by industrial and domestic water consumption, coal mining, and other factors. It was found that water consumption increased by $5,346 \times 10^4 \text{ m}^3$ per year during the recent period (Yellow River Water Conservancy Commission 2014). The water reduction in the Kuye River basin was caused by various factors during the recent period, as shown in Table 4.

From Table 4, it can be seen that in the recent period (1999–2010), as compared to the reference period (1961–1979), Kuye River water reduction caused by weather factors is $21,987 \times 10^4 \text{ m}^3$ per year, that is the simulated value in the reference period subtract the meteorological

simulated value; soil and water conservation measures accounted for $8,840 \times 10^4 \text{ m}^3$ per year; that is, the meteorological simulated value subtract the land use simulated value; industrial and domestic increased water consumption contributed $5,346 \times 10^4 \text{ m}^3$ per year, that comes from the known statistical data (Yellow River Water Conservancy Commission 2014); the coal mining and other factors were responsible for $13,788 \times 10^4 \text{ m}^3$ per year; that is, land use simulated value subtract the measured value and increased water consumption. In my previous research the Kuye River basin average water requirement was found to be 1.34 m^3 per ton of coal mining in the recent period (1999–2010), (Wu *et al.* 2014), and 9000×10^4 tons of annual coal production, there was $12,060 \times 10^4 \text{ m}^3$ water reduction caused by coal mining.

From these results, human activities are considered the main reasons for short-term changes in river runoff, while natural factors also have an important effect. The limited availability of primary data meant that only the main factors influencing these changes were considered, although the coal mining factor should essentially include everything except weather, water and soil conservation, and industrial and domestic water consumption.

SWAT model of the recent period

After simulating the values of the recent period using the SWAT model, the measured runoff values were used to verify the parameters before they were adjusted for re-simulation. The results are shown in Table 5.

The simulated runoff value of the recent period was $11.28 \text{ m}^3/\text{s}$, the RE was 116%, and the Ens was -10.42 ; R^2 was 0.28, which was less than the accuracy required for this model. This was attributed primarily to the fact that human activities have had a greater influence on the Kuye River runoff during the recent period, which is different from the reference period when weather was the main influencing factor.

Table 4 | Calculations of water reduction in the Kuye River basin in the recent period (1999–2010)

Unit	Simulated value in reference period	Meteorological data		Land use data		Measured value	Increase in water consumption	Reduction in water from coal mining
		Simulated value	Water reduction	Simulated value	Water reduction			
m^3/s	21.05	14.08	6.97	11.28	2.80	5.21	1.70	4.37
$10^4 \text{ m}^3/\text{y}$	66,383	44,403	21,981	35,563	8840	16,430	5346	13,787

Table 5 | The valuation of runoff of the Kuye River from 1999–2010

Item	Measured value (m ³ /s)	Simulated value (m ³ /s)	RE (%)	Ens	R ²
Reference Period Model	5.21	11.28	116	-10.42	0.28
Adjusted Parameters Model		5.92	14	0.32	0.46

To improve the accuracy of the SWAT model simulation of the recent period, the parameters needed to be adjusted to adapt to the recent enhanced human activity. This was achieved primarily by adjusting the SOL_AWC, SOL_K, and SOL_Z parameters; the simulated result is shown in Table 5. However, because the factors influencing the Kuye River runoff are very complex, it was difficult for the SWAT model to meet all the accuracy requirements, although it has improved greatly.

Spatial distribution of the runoff

In the recent period, precipitation levels upstream of the Kuye River were minimal while downstream precipitation was at maximum. The average precipitation seen in the recent period was 337–457 mm, which was less than the 350–505 mm seen during the reference period. The average runoff is positively correlated with precipitation, and upstream and midstream distribution was different compared to the reference period. The maximum runoff depth was seen mainly in downstream areas, which witnessed more rainfall (about 31–62 mm), and had a runoff coefficient of 0.15; on the other hand, the midstream runoff depth was 23–31 mm. Meanwhile, the upstream runoff depth was 18–23 mm, and its runoff coefficient was only 0.06. In the recent period, the Kuye River basin had a runoff depth that was only about half that of the reference period, and the runoff coefficient also greatly decreased.

Uncertainty of the results

In this study, the SWAT model was used to quantify the factors influencing river runoff within the northern Shaanxi

coal mining area, although there were the following uncertainties:

- (1) The basic data were insufficient, which may have led to calculation errors in the model. For example, land use data for every year and weather station data for every day were not found easily.
- (2) The SWAT model had a low accuracy in simulating the recent runoff. The model needs improvement when simulating the period with a greater impact of human activities.
- (3) Many factors affect river runoff, but this study considered just four: weather, soil and water conservation measures, industrial and domestic water consumption, and coal mining. The water reduction caused by coal mining should actually have included all factors except the first three.

Although there were some uncertainties in this study, this calculation method has taken into consideration the main factors that influence the river runoff as calculated by the SWAT model, and has a good theoretical basis. After collecting all the relevant data, it will be feasible to quantify the factors influencing river runoff in coal mining areas.

CONCLUSIONS

- (1) Based on a spatial database of the Kuye River basin, a SWAT model of a reference period (1961–1979) was established and the spatial distributions of precipitation and runoff were simulated. By adjusting some parameters in the SWAT model, the runoff distribution of a recent period was seen to be similar to that of the reference period, although the value was only half.
- (2) Compared to the reference period, weather in the recent period caused $21,987 \times 10^4 \text{ m}^3$ reduction in water in the Kuye River basin, and soil and water conservation measures accounted for a reduction of $8,840 \times 10^4 \text{ m}^3$. On the other hand, industrial and domestic water consumption increased by $5,346 \times 10^4 \text{ m}^3$ and coal mining and other factors contributed $13,788 \times 10^4 \text{ m}^3$.
- (3) Although there were some uncertainties in this study, the calculation method has a good theoretical basis; thus, it will be feasible to quantify the factors influencing river

runoff in coal mining areas, and this can serve as an important reference for ecological restoration in this area.

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