

Impacts of climate change and human activities on sediment load in Longchuan River Basin, China

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ABSTRACT

Study region: Longchuan River Basin in the Hengduan mountain region, China.

Study focus: With the decrease in annual precipitation, the sediment yield on the slope and sediment delivery ratio (*SDR*) in the river channel, both play a critical role in runoff and sediment load change. However, the response mechanism of *SDR* to climate change and human activities remains unclear. The RUSLE model was used to calculate the sediment yield on the slope, and the *SDR* is quantified by the ratio of sediment load in the channel to the sediment yield on the slope. *New hydrological insights for the region:* Under climate change, the reduced annual rainfall caused a significant decrease in annual runoff and sediment load in the Longchuan River Basin (LRB), since 2003. The RUSLE model was used to calculate the sediment yield on the slope in LRB, and the sediment delivery ratio (*SDR*) was calculated by the ratio of sediment load to sediment yield. We found a new approach relevant to the relationship of *SDR* with annual runoff and sediment yield, which can indicate the response mechanism of *SDR* to climate change. In anthropogenic activities, reservoir interception is the main reason for the sediment load reduction, instead of the land use and land cover change. With a large reservoir built in the LRB, the average *SDR* is reduced by 83.04 % and the average trap efficiency of the reservoir is 0.96, which was calculated by the Brune equation. This study provides a feasible method to evaluate the effect of different factors on the runoff and sediment load change in the basin.

1. Introduction

Longchuan River Basin (LRB) is a typical dry hot valley region in the Jinsha River Basin (JRB), the main sediment resource of the Yangtze River, China. Under the lower vegetation cover conditions, runoff plays a greater role in sediment load change, with climate change and human activities being the primary drivers of runoff and sediment load changes in LRB (Alfonso-Torreno et al., 2022). The runoff and sediment transport process consists of slope erosion and channel transport (Alhama et al., 2022; Antoniazza et al., 2022; Batista et al., 2017). The sediment yield on the slope is caused by variables such as rainfall, topography, land use, soil constituents, etc

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(Battista et al., 2022; Bekin et al., 2021; Beveridge et al., 2020). The sediment delivery ratio (*SDR*), the ratio of sediment yield on the slope to the sediment load in the channel outlet, is influenced by the relationship between runoff and sediment yield entering the channel and also the trap efficiency (*TE*) of reservoirs. In systems where sediment yield is the material source of sediment load, *SDR* represents the sediment transfer efficiency in LRB, it is important to discover the law that *SDR* changes with the climate and human activities (Boano et al., 2014; Borga et al., 2014; Borrelli et al., 2014).

Runoff and sediment load in the watershed is affected by multiple factors, such as rainfall, topography, land use and land cover (LULC), soil constituents, etc. The sediment load is calculated worldwide using current models (Boyce, 1974; Brune, 1953; Camporeale et al., 2007), including the USLE model (Universal Soil Loss Equation), its modified version (RUSLE model), and SWAT (Soil and Water Assessment Tool). The RUSLE model is an empirical model to compute the sediment yield on the slope, despite being widely implemented to represent the catchment sediment load. SWAT is a deformation of the USLE in additional consideration of flood elements, but it does not divide the slope erosion and sediment transport process (Caroni et al., 1984; Chang et al., 2011; Chen et al., 2019; Chen et al., 2014). Above models account for sediment load in large-scale basins with low accuracy, as a result, the deposition of sediment in transport is neglected (dos Santos et al., 2021; East et al., 2021; Ferro and Minacapilli, 1995). *SDR* is a significant measure to describe the sediment transport process, and it is associated with the difference in runoff shear rate to sediment between slope and stream in the mountain river basins (Gassman et al., 2014; Hiwa et al., 2020; Arash et al., 2021).

There are two approaches for computing *SDR* (Ghosal and Das Bhattacharya, 2020; Guo et al., 2020), one method focuses on the effect of basin area on *SDR* (Ferro and Minacapilli, 1995), and the other proposes a semi-empirical equation for *SDR* and movement duration of runoff along the channel, as known as SEDD (sediment delivery distributed model) (Gwapedza et al., 2021; Hassan et al., 2008). However, a large distinction appears between calculated results and actual values on *SDR*, due to regardless of sediment yield change with different basin scales and climate conditions (Jiang et al., 2021; Jinze and Qingmei, 1981; Jothiprakash and Vaibhav, 2008). So far, many studies have shown that, besides the uncertainty in extreme rainfall cases, human activities just as soil and water conservation, and hydropower plants, leading the change law of *SDR* to be more complicated (Klein et al., 2013; Li et al., 2015; Liu et al., 2020). With the acceleration of anthropogenic disturbances, the impact of trap efficiency of reservoirs has become the foremost cause of sediment load change (Liu et al., 2019; Lu et al., 2006; Lv et al., 2021). Nevertheless, less research follows how reservoir management and climate change affect the *SDR* (Magilligan et al., 2021; McCool et al., 1987; Meng et al., 2020).

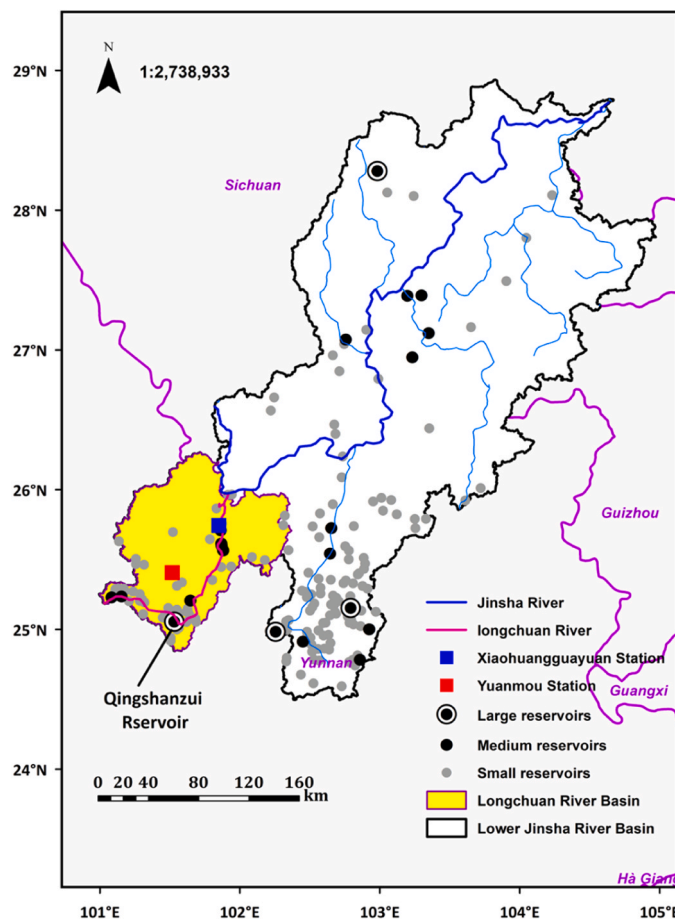


Fig. 1. The geographical distribution of the Longchuan River basin and reservoirs.

In this study, we provide a new method based on the RUSLE model and definition of *SDR*, which may be used to forecast sediment load in LRB under various climatic scenarios. Exploiting this novel tool, we address the following research questions:

- (i) How do runoff and sediment load in LRB vary in time?
- (ii) What are the key factors and how do they impact the runoff and sediment load in LRB?
- (iii) What is the relationship between *SDR*, sediment yield, and annual runoff?

2. Materials and methods

2.1. Study area

The study area is located in the Longchuan River Basin (LRB), Southwest China (24°50'–26°20'N, 101°0'–102°30'E). To explain the impact of climate change and human activities on change in sediment load, the LRB was picked as the focus of the study due to its typical geological characteristics of the dry-hot valley (Qiankun et al., 2022). In general, the lowlands and valleys are developed as paddy fields, while the slopes are either exposed as barren ground with gullies and other erosion features or populated by a few scattered trees (Zhou et al., 2004). As a result, the composite vertical vegetation structures have limited influence on soil erosion in LRB. The total sediment transport processes in LRB, including sediment yield on the slope and sediment transport in the channel, were investigated to reveal the nonlinear relationship between sediment load and natural conditions in LRB. On the slope, the change in sediment yield on the slope associated with rainfall conditions as well as land use and land cover (LULC). In river channels, *SDR* is related to the sediment-carrying capacity of annual runoff and the reservoir sediment trap efficiency. Limited by multi-process coupling, sediment load change in LRB contains a complex physical mechanism.

Longchuan River is the first-order tributary of the Jinsha River (Fig. 1), the elevations in LRB range from 963 m to 2907 m, with an average slope of 16.73°. Long-term (1953–2019) average annual precipitation across LRB was 828.90 mm, with a minimum of 485.8 mm in the year 1980 and a maximum of 1342.8 mm in the year 2001. Considering the construction of reservoirs, there are 180 reservoirs distributed in LRB until 2013, with a total reservoir capacity of 369.60 million m³, including one large reservoir (108.1 million m³), 9 medium-sized reservoirs (157.9 million m³), and 170 small reservoirs (103.7 million m³).

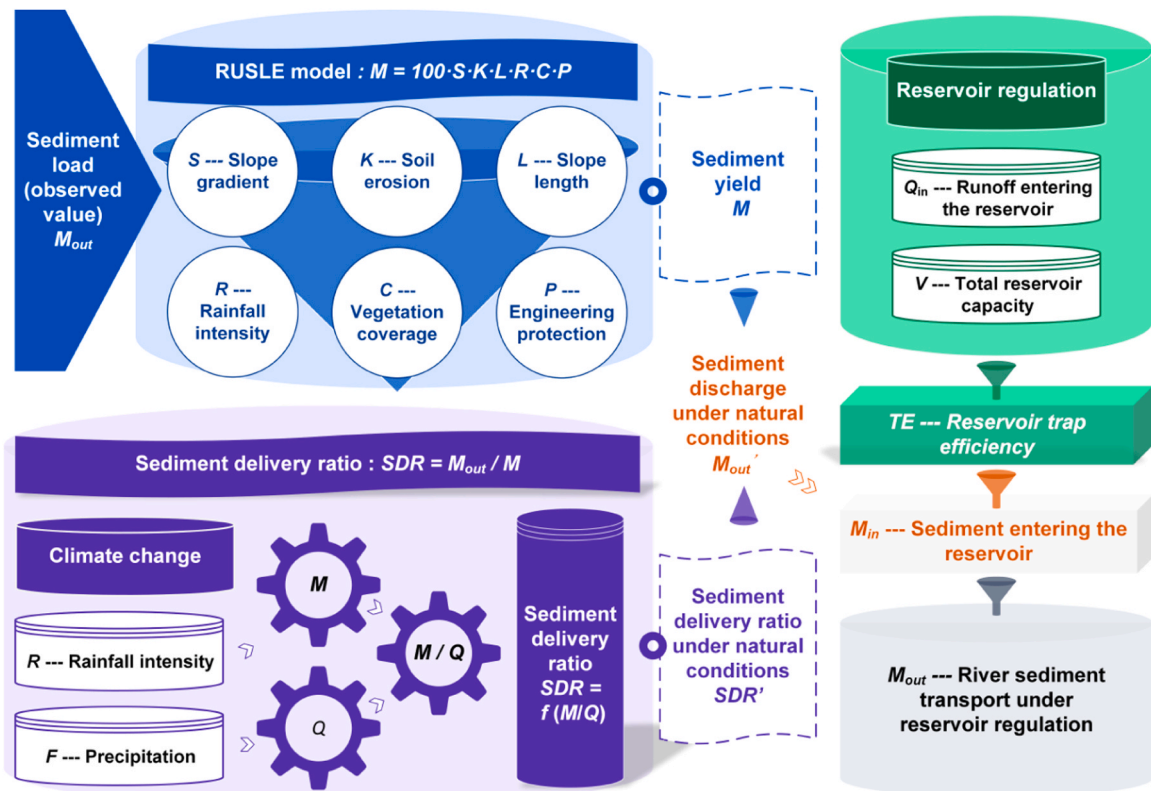


Fig. 2. The runoff and sediment transport in the basin under climate change and human activities.

2.2. Data source and analyses

The runoff and sediment load in LRB is obtained from the Xiaohuangguayuan Hydrological Station (XHGY), a controlled station in the basin outlet, which has an area of 5551 km². To calculate sediment yield on the slope, climatic data consisting of daily precipitation is obtained from the Yuanmou Station, the only national meteorological station in LRB. The topographic and land use data for the basin were derived from the Resource and Environmental Science and Data Centre (<https://www.resdc.cn/Default.aspx>). The growth process of the total reservoir capacity over time in LRB came from the first Chinese water conservancy survey bulletin.

The double mass curve method is used to find the trend change of runoff and sediment load in LRB. For a given time series ($X = X_1, X_2, \dots, X_N$), the flux of the variable can be calculated as:

$$X'_T = \sum_{T=1}^N X_T \quad (1)$$

Generally, the runoff flux and sediment load flux have a linear relationship. As the linear slope changes, the equilibrium between runoff and sediment load is broken, and the changing trend of sediment load is the same as the slope change trend.

2.3. Impact factors

The mechanism of runoff and sediment load change in the watershed as a result of climate change and human activities. The impact of climate change mainly contains rainfall intensity and annual precipitation. The effects of human activities mainly include reservoir sedimentation and soil and water conservation projects, which can be characterized by changes in land use and land cover (LULC). Based on the sediment transport process in the basin, the influence of climate change and human activities on the sediment load is divided into three parts, including sediment erosion on the slope, sediment transport in the channel, and sediment interception in the reservoirs. In Fig. 2, climate change affects the sediment yield on the slope and runoff, through rainfall intensity and annual precipitation, respectively. For anthropogenic activities, the land use and land cover change is indicated by the vegetation coverage change (the C factor in the RUSLE model); and the sediment interception in reservoirs is calculated by the Brune formula.

In this study, The RUSLE model is used to calculate the sediment yield on the slope, with the rainfall intensity and LULC playing a major role. Since the transport process of sediment in the watershed is unstable, the sediment yield and runoff both affect the sediment load in the basin outlet. To assess the sediment transport capacity in the channel, SDR is estimated by the ratio of observed sediment load to sediment yield.

$$SDR = M_{out}/M \quad (2)$$

SDR is the sediment delivery ratio of the basin, M_{out} is the annual sediment load (million t), and M is the annual sediment yield (million t). We found an empirical relationship among SDR , runoff, and sediment yield, which can simulate sediment load in the channel under different climatic conditions. Meanwhile, the trap efficiency of a specific reservoir is determined by both the inflow runoff and total capacity, based on the Brune formula. Therefore, the sediment load in the basin outlet can be structured in two parts: the natural sediment load, which is attributed to runoff and sediment yield, and the sediment siltation, which is dependent on the trap efficiency and sediment access to the reservoir.

2.4. RUSLE model

The RUSLE model was used in this work to calculate sediment yield in the LRB. In the model, the annual sediment yield on the slope - M (t•a⁻¹) and the rainfall erosion factor - R (MJ•mm•h⁻²•h⁻¹•a⁻¹), the soil erosion factor - K (t•ha•h•ha⁻¹•MJ⁻¹•mm⁻¹), the slope length factor - L , slope factor - S , vegetation cover factor - C , and engineering protection measures factor - P , satisfy the following functional relationships (Liu et al., 2020):

$$M = 100 \cdot R \cdot K \cdot L \cdot S \cdot C \cdot P \cdot A \quad (3)$$

2.4.1. Rainfall erosion factor - R

Xie(Xie et al., 2016) provided the formula for calculating the rainfall erosion factor R .

$$R_i = \sum_{j=1}^{24} R_{ij} \quad (4)$$

$$R_{ij} = \sum_{k=1}^n \sum_{h=1}^m (\alpha \cdot F_{j,k,h}^{1.7265}) / n \quad (5)$$

Where R_i is the rainfall erosion factor in the i th year; R_{ij} is the rainfall erosion factor for the j th half month in the i th year; as known as R_{ij} is the cumulative value of the rainfall erosion force for the 24 half months in the i th year; k is the days of rainfall included in the j th half month; h is the days with rainfall greater than 10 mm; and $F_{j,k,h}$ is the rainfall intensity of the erosion. The α is a dimensionless

correction parameter; when the rainfall occurs from May to September, the value of α is 0.3957, and the value of α for the rest of the months, the value of α is 0.3101.

2.4.2. Soil erosion factor - K

The soil erosion factor K is based on the EPIC equation (Williams et al., 1989) for calculation.

$$K = \{0.2 + 0.3e^{-0.0256 \cdot SAN(1-SIL/100)}\} \cdot \left(\frac{SIL}{CLA + SIL}\right)^{0.3} \cdot \left[1 - \frac{0.25 \cdot SOC}{SOC + e^{3.72-2.95 \cdot SOC}}\right] \cdot \left[1 - \frac{0.7 \cdot SN_1}{SN_1 + e^{-5.51+22.9 \cdot SN_1}}\right] \quad (6)$$

$$SN_1 = 1 - SAN/100 \quad (7)$$

SAN (%) is the volume fraction of sand and gravel in the soil; SIL (%) is the volume fraction of clayey soil, SOC (%) is the volume fraction of soil organic carbon and SN_1 is the total volume fraction of soil excluding the sand and gravel component. Guo et al. gave a soil erosion factor of $K = 0.0286$ for the red soil zone in southern China, using Yunnan Province, China as a study area.

2.4.3. Slope length factor - L

Wischmeier (Wischmeier and Smith, 1958, 1960) proposed a method for calculating the slope length factor L .

$$L = \left(\frac{\lambda}{22.13}\right)^m \quad (8)$$

$$m = \beta/(\beta + 1) \quad (9)$$

$$\beta = (\sin \theta / 0.0896) / [3.0 \times (\sin \theta) 0.8 + 0.56] \quad (10)$$

Where λ is the slope length (m) and θ is the slope angle ($^\circ$). The average slope length in the LRB is 72.02 m, corresponding to a slope length factor of $L = 2.34$.

2.4.4. Slope factor - S

McCool (McCool et al., 1987) gave the formula for the slope factor S .

$$S = 10.8 \cdot \sin \theta + 0.03 \quad \theta < 5^\circ \quad (11)$$

$$S = 16.8 \cdot \sin \theta - 0.5 \quad 5^\circ < \theta < 10^\circ \quad (12)$$

$$S = 21.9 \cdot \sin \theta - 0.96 \quad \theta \geq 10^\circ \quad (13)$$

The average slope angle in LRB is 16.73° , and Eq. (13) is used to calculate the slope factor as 5.34.

2.4.5. Vegetation cover factor - C

The vegetation cover factor is associated with land-use types. Wischmeier et. (Wischmeier and Smith, 1978) summarised the corresponding C values for different types of land use, including arable land, orchards, woodland, shrubs, grassland, water area, and urban land. The vegetation cover factors corresponding to different land types are given in Table 1.

2.4.6. Engineering protection measures factor - P

Wener (Wenner, 1983) put forward a linear relationship between the factor of engineering protection measures and the percentage of slope.

$$P = 0.2 + 0.03 \times \tan \theta \times 100 \quad (14)$$

The P is calculated as 1.10 based on the slope angle of LRB.

Table 1
Vegetation cover factors for different types of land in the LRB.

Type of land use	C factor
Arable land	0.05
Orchard	0.08
Woodland	0.001
Shrubs	0.05
Grassland	0.1
Water area	0
Urban sites	0.05

3. Results

3.1. Variation trend of runoff and sediment load in LRB

The temporal changes in annual runoff and sediment load in LRB from 1959 to 2019 are presented in Fig. 3. The average annual runoff is 687 million m^3 , with a range of variation from 120 million m^3 to 2140 million m^3 . The multi-year average of sediment load is 4.06 million t, with a range of variation from 0.13 million t to 14.72 million t. The annual runoff and sediment load in LRB, between 1959 and 2019, both had a significant decrease after 2003. The double mass curve method indicated that the change point occurred around 2003, which divides the total period into two parts, namely, 1959–2003 and 2004–2019. In the early period (1959–2003), the average annual runoff in LRB was 815.25 million m^3 , and the average annual sediment load in LRB was 5.16 million t; in the latter period (2004–2019), the average annual runoff reduced to 382.31 million m^3 , and the average of annual sediment load fell to 1.23 million t. With the linear slope sharp decline in Fig. 3b, the average annual sediment content decreased from 6.33 kg/m^3 to 3.22 kg/m^3 .

Fig. 4 shows the change in annual rainfall, and annual runoff for LRB, which present the climate influence on runoff. The trend of annual runoff remains the same as annual rainfall from 1953 to 2019. The annual rainfall in LRB ranges from 458.70 mm to 916.30 mm, and the average annual rainfall is 635.52 mm. The annual runoff and annual rainfall in LRB satisfy a power function as:

$$Q = 6.01 \times 10^{-6}(F - 377.23)^{1.88} \quad (15)$$

Where Q is the annual runoff (billion m^3) and F is the annual rainfall (mm). With the annual runoff falling after 2003, the average annual rainfall decreased from 646.37 mm (1953–2003) to 604.34 mm (2004–2019). This means that the reduced annual rainfall is one of the key climatic factors, that impact the runoff and sediment load change in LRB.

3.2. Sediment yield under different LULC

By considering the land use and land cover (LULC) altered by soil and water conservation projects, the RUSLE is used to calculate the sediment yield in LRB. Due to the less variation of topographic conditions (slope factor, slope length factor), and soil composition (soil erosion factor), the changing characteristics of LULC in LRB can reflect the influence of human activities on sediment yield. The LULC in the LRB varied from 1980 to 2020 as shown in Fig. 5. The main land use types in the basin are arable land, forest land, shrubs, and grassland, of which the proportion of the arable land area is 0.24, forest land area is 0.18, shrubs area is 0.34, and grassland area is 0.22.

The vegetation cover factor in LRB is calculated according to Table 1, which has not changed significantly in the last 40 years. As a result, the vegetation cover factor ranged from 0.0516 to 0.0519, and the mean value was 0.0517, from 1980 to 2020. However, the average annual rainfall erosion factor in LRB is 886.88 $\text{MJ}\cdot\text{mm}\cdot\text{hm}^{-2}\cdot\text{h}^{-1}\cdot\text{a}^{-1}$, with a minimum value of 202.05 $\text{MJ}\cdot\text{mm}\cdot\text{hm}^{-2}\cdot\text{h}^{-1}\cdot\text{a}^{-1}$ in 1967 and a maximum value of 1495.22 $\text{MJ}\cdot\text{mm}\cdot\text{hm}^{-2}\cdot\text{h}^{-1}\cdot\text{a}^{-1}$ in 1986. It is apparent that the change of sediment yield in LRB is not caused by LULC but instead by rainfall erosion, based on the structure of the RUSLE model (Table 2).

Sediment yield in the LRB was calculated based on the rainfall erosion factor and vegetation cover factor, and the results are shown in Fig. 6. Sediment yield in the LRB did not change significantly over time from 1953 to 2019, although sediment load decreased significantly after 2003. The average annual sediment yield in LRB is 10.79 million t. There is no significant difference in average annual sediment yield between 1959 and 2003 and 2004–2019, which is 10.82 million t and 10.70 million t. Since the sediment load had an obvious decrease after 2003 (Fig. 6b), the factors connected with the sediment yield on the slope are not the main reasons for sediment load change in LRB.

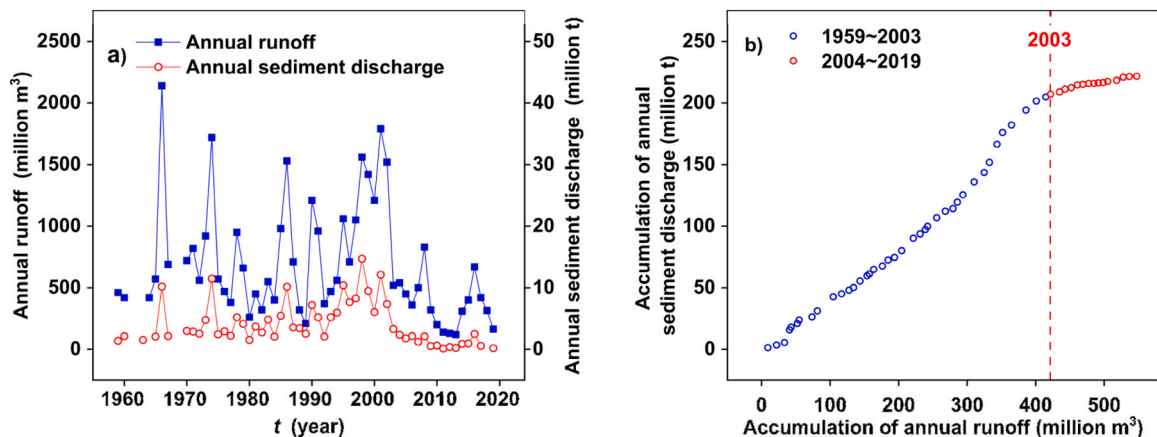


Fig. 3. Relationship between the processes of runoff and sediment load in LRB.

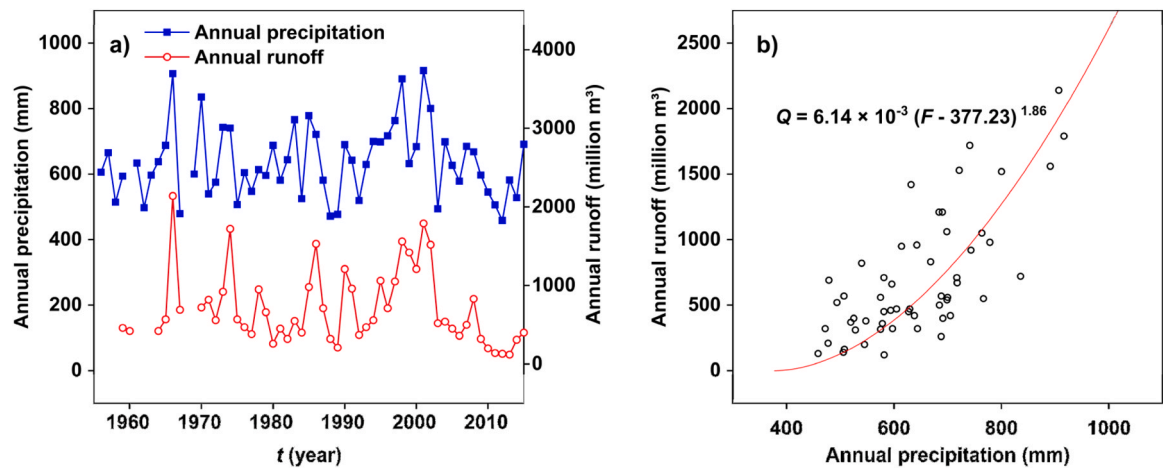


Fig. 4. Relationship between annual runoff and annual rainfall in LRB.

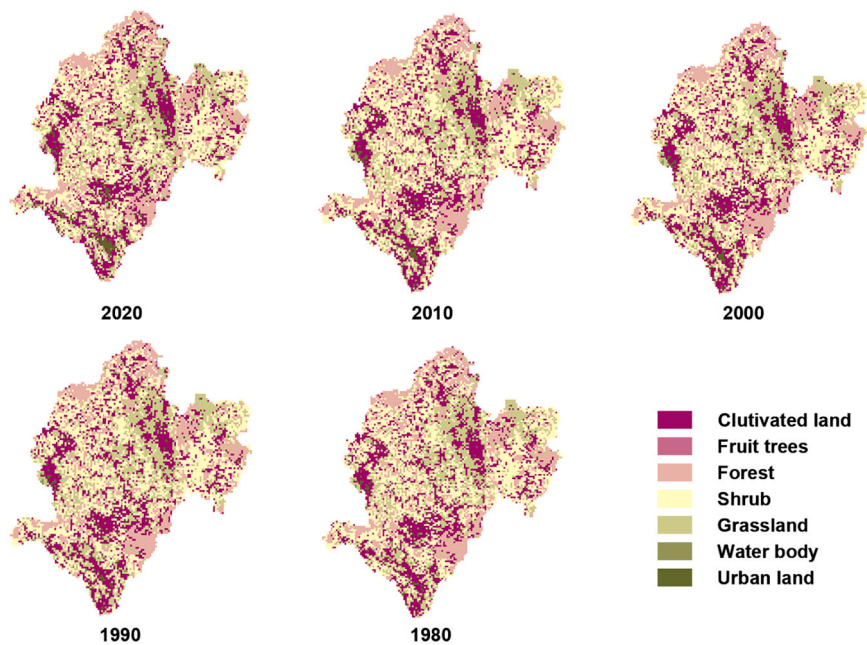


Fig. 5. Land use and land cover (LULC) changes in LRB.

Table 2
Vegetation cover factor for different types of land in LRB.

Type of land use	1980	1990	2000	2010	2020	mean
Arable land	0.24	0.24	0.24	0.24	0.24	0.24
Orchard	0.00	0.00	0.00	0.00	0.00	0.00
Woodland	0.18	0.18	0.18	0.18	0.18	0.18
Shrubs	0.34	0.34	0.34	0.35	0.33	0.34
Grassland	0.22	0.22	0.22	0.22	0.22	0.22
Water area	0.01	0.01	0.01	0.01	0.01	0.01
Urban sites	0.01	0.01	0.01	0.01	0.01	0.01
C	0.0517	0.0518	0.0517	0.0516	0.0519	0.0517

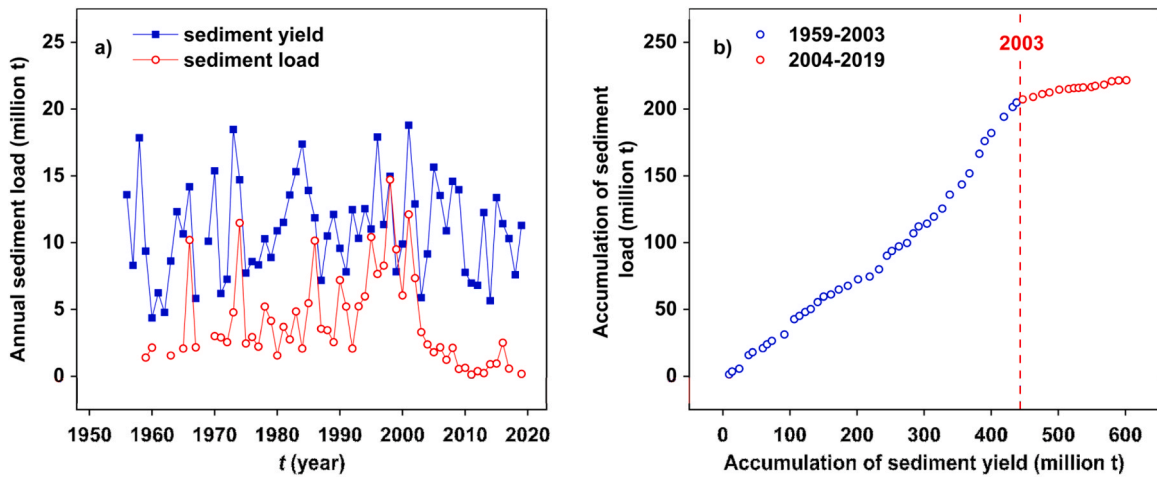


Fig. 6. Relationship between sediment yield and sediment load in LRB.

3.3. Sediment delivery ratio (SDR)

The *SDR* of the LRB is calculated as the ratio of sediment load to sediment yield. Although the *SDR* in most basins is between 0 and 1, the *SDR* in flood years may be greater than 1. Combined with the physical meaning of *SDR*, it can be found to be the sediment-carrying capacity of the runoff between the slope and channel. In general, the *SDR* is less than 1 indicating the reduced sediment-carrying capacity of runoff along the slope to the channel. In contrast, when *SDR* is greater than 1, the sediment load comprises both the sediment yield from the slope and the channel erosion.

From 1959–2019, the average annual *SDR* in LRB was 0.37, with the maximum being 1.22 in 1999 and the minimum being 0.016 in 2019. The MK mutation test is used to analyze the trend of *SDR* over time, respectively, *UF* and *UB* are the positive and negative *SDR* test statistics (Fig. 7b). The *SDR* in LRB revealed a rising trend when *UF* was above 0, but a decreasing trend when *UF* was below 0. While the *UF* is lower than the significance limit, it suggests that the trend is drastically gradually reducing.

The overall trend of the *SDR* decreased from 1959 to 2019, as shown in Fig. 7b. The Trend of *SDR* in LRB changed to decreasing in 2003, and it showed a significant decline after 2009. The average *SDR* in LRB for the periods 1953–2003 and 2004–2019 was 0.47 and 0.10 (Fig. 7a), as a result, the *SDR* is the main cause of the drop in *SDR* in LRB. During the two periods, the average annual runoff decreased by 55.01 %, whereas the *SDR* decreased by 78.20 %. Fig. 7b shows a significant decline in *SDR* in 2009, with the *SDR* decreasing by 95.35 % and the runoff decreasing by 45.92 %. Anthropogenic activities besides climate change have an impact on *SDR* since a decline in *SDR* is significantly greater than a decrease in the runoff.

Therefore, the sediment load change process over time consists of two phases: the natural change phase (1959–2008) and the period affected by human activities (2009–2019). From 1959–2008, rainfall and runoff were the main variables impacting *SDR* in LRB, but human activities played a crucial role from 2009 to 2019.

SDR is equivalent to the ratio of sediment content between slope runoff and river runoff in instances of similar runoff between the

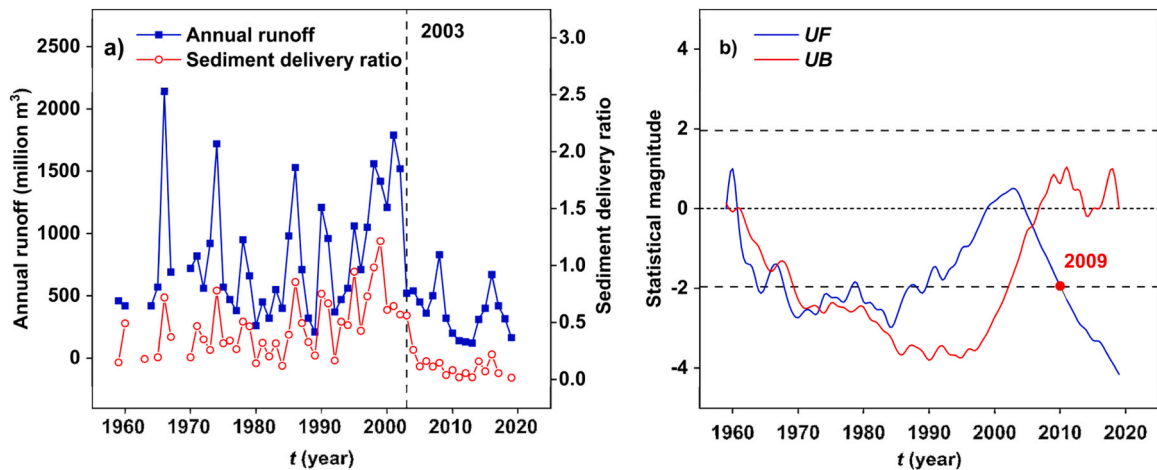


Fig. 7. Process of *SDR* and runoff changes in the LRB from 1959 to 2019.

slope and channel. As a result, the *SDR* and the sediment content of slope runoff have a strong negative relationship, with the *SDR* decreasing as sediment yield increases and runoff decreases. Fig. 8 shows the relationship between *SDR* and sediment content of the slope runoff (M/Q), during the natural phase (1959–2008). The M/Q in LRB from 1959 to 2008 varied from 5.51 to 57.67 kg/m^3 , and the average M/Q was 19.31 kg/m^3 . When the M/Q is close to 0, the *SDR* in LRB is at its greatest, whereas when the M/Q is more than 0.05, the *SDR* tends to be close to 0.

A logistic model is used in this study to fit the expression for the sediment delivery ratio.

$$SDR = 1.50 / [1 + (M/Q/9.26)^2] \quad (16)$$

Eq. (16) and Eq. (2) are solved together to get a computed expression for the sediment load under the natural phase.

$$M_{out} = 1.50 \times M / [1 + (M/Q/9.26)^2] \quad (17)$$

To confirm the results, the predicted natural sediment load in the LRB from 1959 to 2008 was compared to the observed sediment load at XHGS (Fig. 9). The determinable coefficient between the estimated sediment load and the actual value in Fig. 9 is 0.82 and *NSE* is 0.77, indicating that Eq. (17) has high accuracy.

3.4. Reservoir sedimentation

The total reservoir capacity in LRB had a relatively slow change trend before and after 2009 (Fig. 10). The total reservoir capacity increased significantly in 2009 as a result of the building of Qingshanzui Reservoir (QSZ), the exclusive large reservoir in LRB. The operation of QSZ (110 million m^3) led to a reduction in *SDR* instantly,

The average annual runoff into Qingshanzui Reservoir (QSZ) from 2009 to 2015 was 180 million m^3 , and the annual inflow runoff of QSZ was determined based on the ratio of the average annual inflow to the average annual runoff from the basin.

$$Q_{in,t} / Q_t = \overline{Q_{in,t}} / \sum_{t=2009}^{2015} (Q_t/7) \quad (18)$$

Where $Q_{in,t}$ is the runoff entering the QSZ in year t (million m^3), Q_t is the runoff in year t (million m^3), $\overline{Q_{in,t}}$ is the average annual runoff (million m^3) entering the reservoir from 2009 to 2015. Since there is a linear connection between runoff and sediment load accumulation in Fig. 3b, the annual sediment load into QSZ to LRB sediment load ratio is similar to the runoff ratio.

$$M_{in,t} / M'_{out,t} = Q_{in,t} / Q_t \quad (19)$$

Where $M_{in,t}$ is the sediment load entering QSZ in year t (million m^3) and $M'_{out,t}$ is the sediment load in LRB in year t (million t) under natural conditions. Eqs. (18) and (19) are used to calculate the sediment load entering the reservoir after 2009. Considering the effect of deposition on the trap efficiency of QSZ, the modified Brune formula is used to calculate sediment retention.

$$TE_t = 1 - 0.05 / \sqrt{Q_{in,t} / V_t} \quad (20)$$

$$V_t = V_{t-1} - M_{in,t} \times TE_t / \rho \quad (21)$$

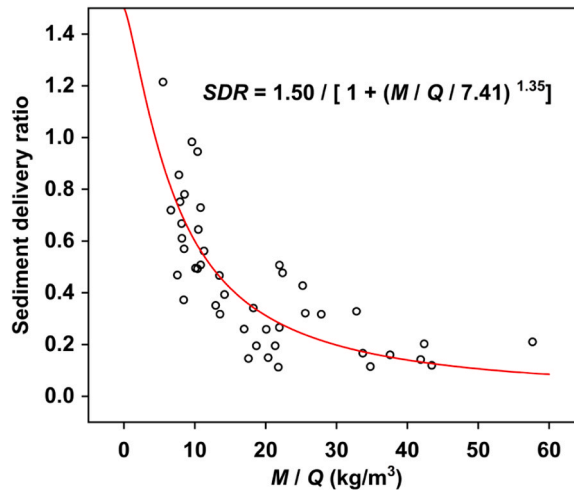


Fig. 8. Relationship between *SDR* and M/Q during the natural phase (1959–2008).

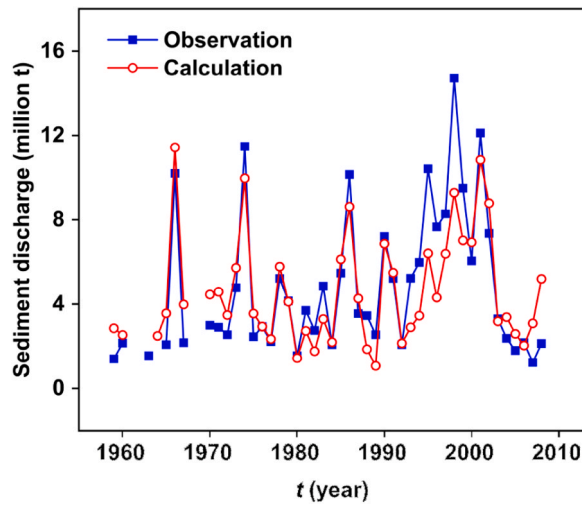


Fig. 9. Validation results of the sediment load calculated formula.

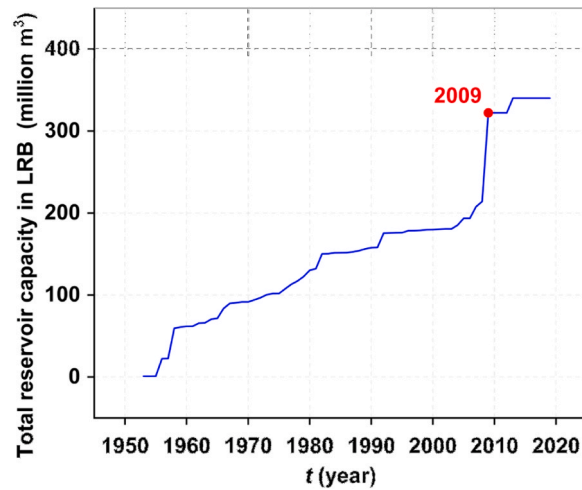


Fig. 10. The curve of total reservoir capacity in the LRB over time.

Where TE_t is the trap efficiency of QSZ in year t , V_t is the effective reservoir volume in year t (million m^3), V_{t-1} is the reservoir capacity in year $t-1$ (million m^3) and ρ is the density of silt in the reservoir $1100 \text{ kg}/m^3$. Combine Eq. (19) and Eq. (20) to calculate the reservoir siltation.

Table 3

Results of sand retention calculations for large reservoirs.

t (year)	Q_t (million m^3)	$M'_{out,t}$ (million t)	$Q_{in,t}$ (million m^3)	$M_{in,t}$ (million t)	V_t (million m^3)	TE_t	P_t (million t)
2009	320.00	1.75	249.28	1.37	110.00	0.97	1.32
2010	200.00	1.12	155.80	0.88	108.80	0.96	0.84
2011	140.00	0.74	109.06	0.58	108.04	0.95	0.55
2012	130.00	0.68	101.27	0.53	107.54	0.95	0.50
2013	120.00	0.52	93.48	0.40	107.08	0.95	0.38
2014	310.00	1.94	241.49	1.51	106.73	0.97	1.46
2015	400.00	2.32	311.60	1.81	105.41	0.97	1.75
2016	670.00	4.20	521.93	3.27	103.81	0.98	3.20
2017	420.00	2.56	327.18	2.00	100.90	0.97	1.94
2018	315.00	1.93	245.39	1.50	99.14	0.97	1.45
2019	163.70	0.79	127.52	0.62	97.82	0.96	0.59

$$P_t = TE_t \times Q_{in,t} / Q_t \times M'_{out,t} \quad (22)$$

P_t is the sediment load intercepted by the reservoir in year t (billion t). The average annual runoff entering the reservoir from 2009 to 2019 is 225.82 million m^3 , and the average annual sediment load entering the reservoir is 226 million t. The average annual sediment load intercepted by the reservoir is 1.27 million t, and the average reservoir trap efficiency is 0.96. The loss of reservoir volume due to siltation in the reservoir as of 2019 is 12.18 million m^3 , accounting for 11.07 % of the total volume of the reservoir capacity (Table 3).

The total amount of sediment load from the LRB and the amount of sediment retained by the reservoir were calculated after 2009, and the sediment load in the LRB under natural conditions was restored and compared with the results of Eq. (16), and the results are shown in Fig. 11. The results are shown in Fig. 11. The restored natural sediment load and the calculated results match each other, and the Nash coefficient and the determinable coefficient of both are calculated respectively to verify the accuracy of the calculated results of Eq. (22).

$$NSE = 1 - \frac{\sum_{t=2009}^{2019} (M'_{out,t} - P_t - M_{out,t})^2}{\sum_{t=2009}^{2019} (M_{out,t} - \overline{M_{out,t}})^2} \quad (23)$$

$$R^2 = \left(\sum_{t=2009}^{2019} [(M_{out,t} - \overline{M_{out,t}}) \times (M'_{out,t} - \overline{M'_{out,t}})] \right)^2 / \left[\sum_{t=2009}^{2019} (M_{out,t} - \overline{M_{out,t}})^2 \sum_{t=2009}^{2019} (M'_{out,t} - \overline{M'_{out,t}})^2 \right] \quad (24)$$

Where NSE is the Nash coefficient, R^2 is the goodness of fit. In Fig. 11, the R^2 between the calculated sediment load and observation, from 2009 to 2019, is 0.96, and NSE is 0.87, which can be found with high accuracy in Eq. (17) and Eq. (22).

4. Discussion

4.1. Impacts of climate change on runoff and sediment load changes in LRB

The climatic impacts on runoff and sediment load in LRB are mainly contained by rainfall conditions, including annual precipitation and rainfall intensity (Orlińska-Woźniak et al., 2020; Pfeiffer et al., 2017; Polyakov et al., 2010). The annual precipitation is connected with annual runoff with a positive correlation, as shown in Fig. 4. Since the annual runoff and annual sediment load both had a significant decrease after 2003, the reduction of annual precipitation was the key factor for the annual runoff change. However, the sediment load in LRB is influenced by the sediment yield, which presents slope erosion, and the SDR , which presents the sediment transport in the channel. Fig. 6 shows that the sediment yield in LRB does not have an apparent change from 1959 to 2019, as a result, the change in sediment load is mainly caused by the variation of SDR in LRB. There is a similar change trend between the process of annual runoff and SDR over time, which indicates that the annual precipitation or annual runoff is associated with the sediment load change in 2003.

To reveal the change mechanism of SDR , many studies attended to the relationship between SDR and annual runoff (Qiankun et al., 2022; Qin et al., 2018; Rengers et al., 2016; Roba et al., 2021). But, there are few studies on the impact of sediment yield on sediment load. In this paper, we found a negative correlation between SDR and sediment content on the slope, which can be calculated by the ratio of annual sediment yield and annual runoff (Fig. 8). A logistic model is used to predict the SDR under different sediment content on the slope. As a result, the sediment load in LRB, during the natural change period (1959–2008), is determined by climatic conditions, including the annual precipitation and rainfall intensity, based on Eq. (17). This finding suggests that a major variable affecting changes in sediment load is the fluctuation of rainfall intensity within the year. The sediment load becomes larger as the increased frequency of extreme rainfall events, with the same conditions of annual precipitation and annual runoff.

4.2. Impact of human activities on runoff and sediment load changes in LRB

Two types of human activities influence the annual runoff and sediment load changes in LRB, respectively, water and soil conservation engineering, and construction and operation of reservoirs. The changing characteristics of land use and land cover (LULC) can represent the effect of water and soil conservation engineering (Sedighi et al., 2021; Singh and Krstanovic, 1987; Souza et al., 2012). With the LULC in LRB did not exhibit significant changes over time (Fig. 5), the major impact of human activities on sediment load in LRB was caused by reservoir regulation. Considering the continually increased total storage capacity of reservoirs in LRB over time, it is difficult to distinguish the impacts on sediment load, between climate change and reservoir regulation. The MK trend test method is used to analyze the changing rule of SDR in LRB. The result shows a significant decline in SDR in 2009, as a result of the construction of a large reservoir in LRB, and the total storage capacity of reservoirs increased dramatically. Large reservoirs, rather than small and medium-sized reservoirs, are the main drivers for the subsequent reduction of SDR .

The Brune formula (Xie et al., 2016; Yamaguchi et al., 2019; Yesuf et al., 2015) is used to calculate the trap efficiency of the large reservoir. The average annual sediment trap efficiency of the reservoir is 0.96, suggesting that the majority of the sediment load is trapped inside the reservoir. The sediment load under natural conditions, calculated by the addition of reservoir sediment interception and observed sediment load, is about the same as the calculation of Eq. (16). It is evidenced that the main cause for sediment load

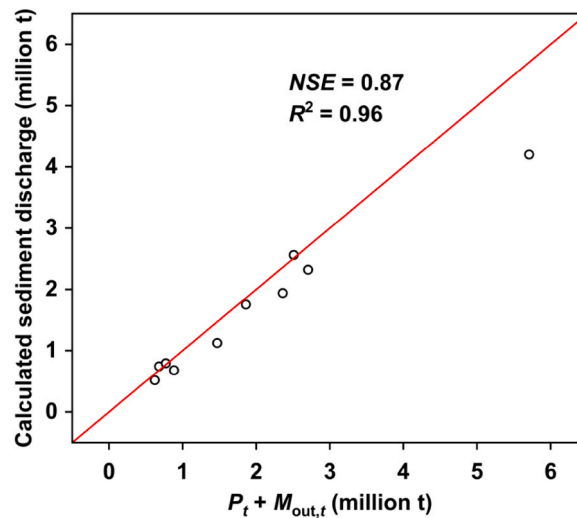


Fig. 11. Verification of natural sediment load and reservoir interception in the basin.

reduction from 2009 to 2019 is the operation of a large reservoir in LRB. Combined with the other studies, the year 2009 is also considered to be the abrupt change point of sediment load in LRB. Climate change is widely reported as the main cause of the change in sediment load in LRB due to the extreme drought years from 2009 to 2012, but the trap efficiency of the large reservoir is neglected (Fig. 7). The fact is that the annual runoff and annual precipitation gradually reduced, from 2003 to 2019, and the sediment load also had an apparent decrease after 2003. Therefore climate change is not the key factor for the sediment load dramatic change in LRB in 2009.

In this study, the RUSLE model and definition of *SDR* were used to distinguish the impact of climate change and human activities on the sediment load change in LRB (Fig. 2). Although we propose a relationship between *SDR* and sediment content on the slope, this study is limited in the following two ways: on the one hand, the RUSLE model is a yearly-timescale model, which can not reflect the impact of rainfall process on the sediment load (Zhang et al., 2022; Zhang et al., 2020; Zhao et al., 2022); on the other hand, the change rule of *SDR* along basin scale should be investigated in further study.

5. Conclusions

5.1. Main findings of the paper

We investigated the changing law of annual runoff and sediment load in the LRB. The study indicated that the annual runoff and sediment load decreased significantly since 2003, which was caused by the reduction of the sediment delivery ratio (*SDR*). Taking into account the effect of runoff on *SDR*, we found a negative relationship between *SDR* and sediment content, calculated by the ratio of sediment yield to runoff. Based on the sediment load under climate change, the Brune equation was used to calculate the trap efficiency of a only large reservoir in LRB, and the average trap efficiency of the reservoir was 0.96 from 2009 to 2019.

5.2. Limitations of this work

This study has the great advantage of revealing the changing law of runoff and sediment change in the basin, on a year time scale. However, the RUSLE model can not reflect the effect of extreme rainfall events on the sediment load in the channel, within an hour time scale. Meanwhile, the *SDR* model in this paper only stands for the relationship of sediment transport from the slope to the channel, with non-account for the impact of Spatial heterogeneity of terrain on the *SDR*.

5.3. Broader impacts

Applying the methods proposed in this paper, the impact of climate change and human activities on different physical processes of sediment transport in a basin can be explained. Compared with the traditional *SDR* model, we present a new perspective that the sediment content on the slope has a negative relationship with *SDR*. According to the novel model of *SDR*, we can predict sediment load in basins under different climate conditions.

CRediT authorship contribution statement

Guoshuai Zhang: Conceptualization, Methodology, Software, Investigation, Formal Analysis, Writing - Original Draft, Anjun Deng:

Data Curation, Writing - Original Draft; Jianguo Chen: Resources, Supervision Dangwei Wang: Conceptualization, Funding Acquisition, Resources, Supervision, Writing - Review & Editing. Ye Yin: Software, Validation Hantao Wang: Visualization, 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.

Data availability

Data will be made available on request.

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