Socioeconomic development mitigates runoff and sediment yields in a subtropical agricultural watershed in southern China

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Keywords: runoff and sediment yields, biophysical factors, socio-economic factors, structural equation modelling, Gongshui watershed

Abstract

Although the effects of biophysical factors on runoff and sediment yields have been studied extensively, the influences of anthropogenic factors, such as economic development and population growth, which might be crucial causes of soil erosion, are still unclear. To decouple the influences of biophysical and socioeconomic variables on runoff and sediment yields, observational data on runoff and sediment from 1985 to 2015 in seven hydrological stations in Gongshui Watershed, Jiangxi Province, China, and meteorological and socioeconomic statistics during the same period were collected. A structural equation model was constructed to evaluate the effects of biophysical factors and socioeconomic factors on runoff and sediment yields. The results showed that soil erosion in the Gongshui Watershed was significantly mitigated in the past 30 years and remarkable change points occurred. Both biophysical and anthropogenic factors had significant effects on soil erosion in the watershed, and the path coefficient changed dramatically with socioeconomic development. Economic development was the most important controlling factor, and the path coefficient decreased from $-0.3863$ in stage I (before the change point) to $-0.6174$ in stage II (after the change point). The promoting effect of agricultural production mainly stemmed from its expansion brought about by agricultural output, with the total effect increasing from 0.489 in stage I to 1.017 in stage II. The contradiction between socioeconomic development and soil erosion control in the Gongshui watershed was alleviated, and the gradually formatted synergy could provide continuous support for soil erosion control.

1. Introduction

Soil erosion is one of the most urgent global environmental problems, which causes both on-site damage, such as land degradation and poverty, and off-site damage, such as water pollution. It is affected by both biophysical and anthropogenic factors (Poesen 2018). These factors and their interactions couple tightly to form various specific ecosystems and can mitigate or aggravate soil erosion (Nearing et al. 2005). Soil properties, precipitation, and vegetation are the direct biophysical factors, which determine soil erosion potential and processes. Economic development, population growth, and agricultural production might be underlying anthropogenic driving forces (Udayakumara et al. 2010) that influence its change. Decoupling the contribution of these factors to soil erosion is valuable and needs more effort, which could help regulate human activities and coordinate their relationship with nature, fundamentally reduce soil erosion.

Biophysical factors are direct causes of soil erosion (Zhou et al. 2019). Many studies have been devoted to explore the generation mechanism, spatial-temporal patterns of runoff and sediment yields (Novara et al. 2018) and to seek technical measures to control soil erosion (Keestra et al. 2016, Xiong et al. 2018). Energy distribution and material migration under different management and land-use scenarios have been
the typical perspectives to analyse the generation mechanisms of runoff and sediment and to identify factors influencing detachment, transport and deposition processes (Zhou et al. 2019). The effect of rainfall kinetic energy on sediment transport, individual land-use changes in sediment yield, and the combined effects of land use and physiography on sediment yield have been intensively studied (Yan et al. 2013, Wang et al. 2014, Mhazo et al. 2016). Furthermore, the interactions among biophysical factors increase the uncertainties and complexity of runoff and sediment generation, requiring more integrated interpretations (Montgomery 2007, Chamizo et al. 2012).

Land-use structure, soil management, and tillage in arable land are direct anthropogenic causes of soil erosion (Amundson et al. 2015, Anache et al. 2018, Luetzenburg et al. 2020), although they might not be the fundamental driving forces and are not sufficient to prevent or mitigate soil erosion completely (Borrelli et al. 2017). Indirect socioeconomic variables, such as poverty, population growth, policy and political systems, might be the deeper causes of regional soil erosion (Dotterweich 2013, Nesme et al. 2018, Vávra et al. 2019). They determine the production modes and the intensity of resource utilization, influence the implementation of soil erosion control planning and allocation of governance investments, and affect people’s enthusiasm to participate in governance (Odongo et al. 2014, Vu et al. 2014, Wuepper et al. 2020). The interrelationship between soil erosion and socioeconomic development is coupled and interacted, which has been explored from different perspectives. Rodrigo-Comino et al. (2018) concluded that pedon scale behaves, e.g. reduced tillage, were vital for controlling soil erosion. Sartori et al. (2019) estimated the economic impact of soil erosion on the world economy, and found that soil erosion incurred a global annual cost of 8 billion US dollars. However, the decoupling of the interactions is still insufficient, since the relationships are vague, complicated, and far from being understood (Marques et al. 2019, Wuepper et al. 2020).

A methodological challenge is observed when combing both biophysical and socioeconomic factors in a framework to analyse their interactions and impacts on soil erosion (Borrelli et al. 2017, Poesen 2018). Structural equation modelling (SEM), which focuses on understanding direct and indirect pathways through the use of latent variables, is considered the natural language for representing and studying causal relations (Grace et al. 2012). SEM has been increasingly used to analyse the relationship between biophysical factors and runoff and sediment yield, such as hydrological drivers and runoff generation and water erosion (Rodriguez-Caballero et al. 2014), erosive ecological structure (Zhou et al. 2019), vegetation coverage and the reduction of soil erosion (Hou et al. 2020). However, the interactions between biophysical and socioeconomic factors and their effects on soil erosion have seldom been studied with SEM.

To clarify the impact of biophysical and socioeconomic factors on runoff and sediment yields and to seek efficient ways to control soil erosion, a conceptual model was proposed and then validated with SEM. The long-term monitoring data from hydrological and meteorological station, include annually runoff, sediment, and precipitation of the Gongshui watershed, Jiangxi Province, China, and regional socioeconomic statistics for the same period were used for model construction to (a) quantitatively assess the direct and indirect effects of latent biophysical and socioeconomic variables on runoff and sediment yields, (b) analyse the evolution of the driving mechanism of biophysical and anthropogenic factors on runoff and sediment yields at different stages, and (c) identify the key socioeconomic factors that influence runoff and sediment yields in the watershed.

2. Materials and methods

2.1. Study area

The Gongshui watershed is located in South China, with latitudes from 25°40′16″N to 27°30′13″N and longitudes from 114°46′40″E to 116°38′03″E, and the total area is 27,095 km², belonging to the hilly region of southern China (figure 1). The topography,
of the watershed is complicated with basins, hills and rolling mountains, which is high in the southeast and south, and northwest is relatively low in elevation. It has a humid subtropical monsoon climate characterized by abundant precipitation and high accumulated temperatures. The annual average precipitation is 1647 mm, about 40% and 33% of the precipitation occurs in spring and summer (Huang and Liu 2020).

The Gongshui watershed is an important agricultural production area in Jiangxi Province, China. The total population is 9.29 million in 2015, and the rural population accounted for more than 80%. The high-density population, the ecological resource-dependent economy, and the relatively fragile ecosystem made Gongshui watershed a severely eroded region of southern China (Zhao et al 2018).

In recent years, with the implementation of a series of ecological restoration and soil erosion control projects, the expansion of eroded areas has initially been contained (Zhao et al 2018). However, in the context of continuous population growth and rapid economic development, the pressure on ecosystems is increasing, and conflicts between economic development and ecological protection still exist (Wang et al 2020).

2.2. Structural equation modelling
SEM was employed to decouple the influences of biophysical and socioeconomic variables on runoff and sediment yields.

2.2.1. Conceptual model
General hypothesized relationships among soil erosion and biophysical or socioeconomic factors were presented in an a priori conceptual model (figure 2). The model included six latent variables: economic development (ECO), agricultural input (MOD), agricultural output (PRO), land use (LU), biophysical environment (ENV), and soil erosion (Y). The directed arrows indicate causal relationships based on published studies or reasonable inferences (described in table S1 (available online at stacks.iop.org/ERL/16/024053/mmedia)).

The gross domestic production and total population were selected as the manifest variables to represent the latent variable ECO. Total fertilizer application, total agricultural machinery power, and rural electric power consumption were used to demonstrate the latent variable of MOD. The total grain production and gross agricultural output value were selected as manifest variables for the latent variable PRO. The latent variable LU was interpreted by the area of arable land, area of forest and grassland, and area of construction land. Vegetation coverage greater than 60% and total annual precipitation were the observed variables for the latent variable ENV. The latent variable Y consisted of two manifest variables: runoff and sediment yield.

2.2.2. Change-point analysis
The trends of the long-term time series of runoff and sediment in all subwatersheds were analysed using the nonparametric Mann–Kendall trend test (Hipel and McLeod 1994), which is widely used to determine the monotonic trends of hydro meteorological time series. If monotonic trends exist, the sequential version of the Mann–Kendall test statistic for progressive and retrograde series, named $U_{F_k}$ and $U_{B_k}$
The change points of runoff and/or sediment determined here for each subwatershed will be used to divide the whole period into two stages.

2.2.3. Model development
Since socioeconomic indicators were time series with year as a covariate, they might have pairwise correlations. To eliminate this influence, a univariate linear regression was established with each socioeconomic indicator as the dependent variable and year as the independent variable. The residual of the fitted model, which was a substitute for the original variables, was used to construct the SEM model.

Because of the non-normal distribution of most manifest variables, the partial least squares approach was used to build the PLS-SEM model with respect to the conceptual model based on the manifest variables (Rigdon 2013). A permutation test was performed to compare the path coefficient and the direct and indirect effects of environmental and socioeconomic variables within the stage before and after sediment yield change point.

2.2.4. Model assessments and validation
The validity of the measurement model was assessed by three main indices: Cronbach’s alpha (α), Dillon–Goldstein’s rho (ρ), and eigenvalues of the correlation matrix of manifest variables (Sanchez 2013). If ρ and ρ are both larger than 0.7, and the first eigenvalue (λ₁) is larger than 1, while the second eigenvalue (λ₂) is smaller than 1, the corresponding latent variable was considered a reliable and acceptable representation of manifest variables.

The quality of the structural model was evaluated by four indices or quality metrics, including the average variance (AVE), the coefficient of determination (R²), the redundancy index (Re), and the goodness-of-fit (GoF). As a rule of thumb, when the AVE, R², and GoF are greater than 0.5, 0.6, and 0.8, respectively, the structural model was considered acceptable and valid. Re reflected the ability of a set of independent latent variables to explain the variation in the dependent latent variable. A high Re indicated a high predication ability.

Bootstrapping, a resampling procedure, was used to validate the structural model by assessing the variability of the parameter estimates, i.e. standard error (SE), which was used to assess the significance level of the parameters (Davison and Hinkley 1997). The bootstrap procedure was as follows: 10,001 samples were obtained by sampling with replacement from the original dataset with the same sample size. For each generated sample, each parameter in the PLS-SEM was estimated.

The nonparametric Mann–Kendall trend test was implemented with package trend (Pohlert 2020), and the sequential version of the Mann–Kendall test statistic was calculated with package trend-change (Patakamuri and Das 2019). The construction and analysis of the PLS-SEM and permutation test between two stages were carried out using the package plspm (Sanchez et al 2017). All packages are based on R (R Core Team 2020).

2.3. Data collection and preparation
The watershed was divided into seven subwatersheds according to the existing hydrological stations, including the Yangxin River (YXJ), Xiashan (XS), Mazhou (MZ), Julongtan (JLT), Hanlin Bridge (HLQ), Fenkeng (FK), and Chayuan (CY) (figure 1). Socioeconomic parameters were measured within administrative units, while biophysical factors were calculated based on natural units. To address the spatial mismatch between administrative and natural units, the socioeconomic data were first allocated evenly to each unit area within each county and then summed within each subwatershed to obtain the final watershed-scaled socioeconomic data, which matched with the runoff, sediment and biophysical data.

The time span of the collected data were from 1985 to 2015. In total, 201 samples were obtained due to the missing data (1985–1999) from CY. Datasets of each socioeconomic variable were obtained from the Jiangxi Statistical Yearbook, and the China Statistical Yearbook was used to complement any missing data during the same period. The runoff and sediment data were obtained from the abovementioned seven hydrological stations. The precipitation data were obtained from six meteorological stations in the whole watershed (figure 1). Digital elevation model, vegetation coverage and land-use data of the watershed were obtained from the geospatial data cloud platform of the Computer Network Information Center of the Chinese Academy of Sciences (www.gscloud.cn).

3. Results
3.1. Temporal changes in runoff and sediment
From 1985 to 2015, the sediments of seven subwatersheds presented significant downward trends except for YXJ, which had an upward trend (table 1), while the runoff during the same period did not present a significant monotonic trend (table 1).

The sequential version of the Mann–Kendall test statistic for progressive and retrograde series presented in figure 3 clearly shows the approximate change point of a developing trend. The beginning time of the upwards trend for YXJ was 1994, which was the
Table 1. Non-parametric Mann–Kendall trend test for runoff and sediment load of each subwatershed during 1985–2015, and the mean sediment load (10⁸ kg yr⁻¹) experienced at major breaking times.

| Sub-watershed | Z-score | Runoff | Sediments | Year of shift (A) | Mean sediment load |
|---------------|---------|--------|-----------|------------------|-------------------|
| YXJ           | -1.68   | 3.18** | 1994      | 0.370            | 1.28              |
| XS            | -0.15   | -2.55* | 2002      | 28.80            | 17.60             |
| MZ            | -0.43   | -3.18**| 2000      | 3.10             | 1.85              |
| JLT           | -0.78   | -4.42***| 2006      | 14.00            | 2.87              |
| HLQ           | 0.75    | -2.50* | 1998      | 7.48             | 4.66              |
| FK            | 0.31    | -1.89  | 2002      | 11.50            | 7.15              |
| CY            | -0.30   | -2.38* | 2007      | 6.00             | 2.87              |

*a* significance level indicated by *, ** and *** when probability less than 0.05, 0.01 and 0.001, respectively.

Figure 3. Sequential Mann–Kendall test statistic for progressive and retrograde series of sediment load for seven subwatersheds in the Gongshui watershed. Progressive and retrograde series are shown in red and blue, respectively. The dashed line indicates the 97.5% and/or 2.5% quantile of the standard normal distribution.

earliest among all subwatersheds and had a significant increase in sediment load (table 1). JLT and CY had the latest beginning times of downwards trends in 2006 and 2007, respectively. MZ, XS, HLQ and FK all had shifted downwards trends near 2000 (table 1).

3.2. Assessment and validation of the PLS-SEM

The PLS-SEM used to decouple the driving forces of biophysical and socioeconomic factors on runoff and sediment yields was constructed based on the conceptual model with the observed runoff and sediment data during 1985–2015 and corresponding socioeconomic statistics from the same period in the Gongshui watershed (figure 4).

The validity of every latent variable in the measurement model was quantified with α, ρ and λ₁ and λ₂ of the correlation matrix (table 2). The α and ρ of all latent variables were greater than 0.75 and 0.85, respectively, which passed their criteria for a valid measurement model. Furthermore, λ₁ were greater than 1, while λ₂ were smaller than 1. These indices also support the unidimensionality of the measurement model.

The quality of the structural model was measured with AVE and R² for each latent variable, which were both larger than 0.80 (table 2). Furthermore, the model had high predictive ability with mean Re of the latent variables that were greater than 0.75 (table 2). The GoF was 0.897 and indicated that the model has good quality for both the measurement and the structural models.

The variability of all path coefficients or direct effects was assessed with a bootstrapping procedure (figure 4), and all path coefficients had significance with p < 0.05. Furthermore, the variability of total and indirect effects between latent variables in the PLS-SEM were evaluated quantitatively with a bootstrapping procedure (table 3). The values estimated by PLS-SEM were very close to those estimated by the bootstrapping procedure (table 3 and figure S1).

3.3. Biophysical and socioeconomic driving forces

The runoff and sediment yields in the watershed were significantly affected by both biophysical and
Figure 4. Structural model for the driving forces on soil erosion. ECO, MOD, PRO, LU, ENV and Y are the latent variables of economic development, agricultural input, agricultural output, land use, biophysical environment, and soil erosion, respectively. The lines between latent variables are paths, and the width of each line is proportional to the corresponding path coefficients or loadings. The blue and orange lines indicate positive and negative path coefficients, respectively. Numbers in brackets are the Z-score, and *, ** and *** indicate significance levels of \( p < 0.05, 0.01 \) and 0.001, respectively.

Table 2. Unidimensionality indices for measurement model and quality indices for structural model used in the PLS-SEM.

| Latent variable | \( \alpha \) | \( \rho \) | \( \lambda_1 \) | \( \lambda_2 \) | \( R^2 \) | \( Re \) | AVE |
|----------------|------------|------------|----------------|----------------|------------|--------|-----|
| ECO            | 0.809      | 0.913      | 1.679          | 0.321          | n.a.\(^a\) | 0.000  | 0.838 |
| MOD            | 0.925      | 0.953      | 2.610          | 0.300          | 0.912      | 0.792  | 0.869 |
| ENV            | 0.762      | 0.894      | 1.615          | 0.385          | n.a. \(^a\) | 0.000  | 0.803 |
| LU             | 0.955      | 0.971      | 2.753          | 0.244          | 0.927      | 0.850  | 0.918 |
| PRO            | 0.890      | 0.948      | 1.802          | 0.198          | 0.974      | 0.877  | 0.901 |
| Y              | 0.957      | 0.979      | 1.917          | 0.083          | 0.830      | 0.795  | 0.958 |

\(^a\) n.a. means the value is not available.

socioeconomic factors. ENV had a significant indirect promoting effect (represented by positive path coefficient) of 0.668 through LU and PRO (table 3), along with a prominent direct promoting effect of 0.610 (figure 4).

ECO was an important socioeconomic factor that controlling (represented by negative path coefficient) runoff and sediment yields, and it had the highest direct path coefficient of \(-0.714\) (figure 4). It also had an indirect promoting effect of 0.239 through MOD and LU (table 3).

MOD had a significant direct controlling effect of \(-0.297\), while PRO and LU had considerable promoting effects, with direct effects of 0.579 and 0.638, respectively (figure 4).

3.4. Evolution of driving forces at different stages
The trends of sediment load in the watershed were divided into two stages based on the beginning time of the shift in sediment loads in each subwatershed. Two subgrouping PLS-SEMs for stages before (stage I, \( n = 105 \)) and after (stage II, \( n = 96 \)) the shift time were constructed to explore the changes in driving forces. The GoF of the two subgroups of PLS-SEM were 0.897 and 0.931, respectively. Both models were valid and reliable based on the various assessment indices.

ENV had promoting effects on runoff and sediment yields in both stages (table 4). The direct impact was dramatically enhanced in stage II, and the path coefficient increased from 0.451 to 1.954. The indirect
Table 3. Total and indirect effects of the original PLS-SEM model, and their corresponding estimates, variability (SE) and Z-score assessed by the bootstrap procedure.

| Paths | Total effects | Indirect effects |
|-------|---------------|------------------|
|       | Original      | Bootstrap | SE   | Z-score | Original | Bootstrap | SE   | Z-score |
| ECO→MOD | 0.955         | 0.955   | 0.006 | 154.890***<sup>a</sup> | n.a.      | n.a.     | n.a. | n.a. |
| ECO→PRO | 0.903         | 0.901   | 0.022 | 40.956*** | 0.144    | 0.151   | 0.057 | 2.538* |
| ECO→Y | −0.475        | −0.478  | 0.094 | −5.029*** | 0.239    | 0.239   | 0.210 | 1.141- |
| MOD→PRO | 0.151        | 0.158   | 0.059 | 2.554*    | n.a.     | n.a.    | n.a. | n.a. |
| MOD→Y | −0.209        | −0.212  | 0.154 | −1.360-   | 0.087    | 0.093   | 0.090 | 1.737- |
| ENV→LU | 0.963         | 0.963   | 0.005 | 204.268*** | n.a.     | n.a.    | n.a. | n.a. |
| ENV→PRO | 0.093        | 0.095   | 0.024 | 3.943***  | 0.093    | 0.095   | 0.024 | 3.943*** |
| ENV→Y | 1.277         | 1.281   | 0.077 | 16.585***  | 0.668    | 0.672   | 0.135 | 4.954*** |
| LU→PRO | 0.097         | 0.098   | 0.025 | 3.937***   | n.a.     | n.a.    | n.a. | n.a. |
| LU→Y | 0.694         | 0.698   | 0.140 | 4.961***   | 0.056    | 0.058   | 0.027 | 2.090*  |
| PRO→Y | 0.579         | 0.588   | 0.218 | 2.659**    | n.a.     | n.a.    | n.a. | n.a. |

<sup>a</sup> significance level indicated by *, ** and *** when probability less than 0.05, 0.01 and 0.001, respectively; ‘—’ means no significance.

<sup>b</sup>n.a. means the value is not available.
Table 4. Direct (path coefficients), indirect and total effects of biophysical and socio-economic latent variables on soil erosion at two different stages.

| Paths       | Direct effects | Indirect effects | Total effects |
|-------------|----------------|------------------|---------------|
|             | Stage I        | Stage II         | Sig.          | Stage I        | Stage II         | Sig.          |
| ECO→MOD     | 0.961          | 0.963            | —             | n.a.           | n.a.             | n.a.          | 0.961          | 0.963            | —             |
| ECO→PRO     | 0.780          | 0.653            | —             | −0.180         | 0.109            | *             | 0.600          | 0.762            | ***            |
| ECO→Y       | −0.872         | −1.086           | −0.180        | −0.104         | 0.080            | —             | −0.367         | −0.998           | ***            |
| MOD→PRO     | −0.187         | 0.113            | *             | n.a.           | n.a.             | n.a.          | −0.187         | 0.113            | *             |
| MOD→Y       | 0.178          | −0.469           | —             | −0.074         | −0.388           | —             | 0.931          | 0.985            | ***            |
| ENV→LU      | 0.931          | 0.985            | ***           | n.a.           | n.a.             | n.a.          | 0.363          | 0.232            | **             |
| ENV→PRO     | n.a.           | n.a.             | n.a.          | 0.363          | 0.232            | **             | 0.363          | 0.232            | **             |
| ENV→Y       | 0.451          | 1.954            | ***           | 0.761          | −0.124           | ***           | 1.211          | 1.830            | ***            |
| LU→PRO      | 0.389          | 0.236            | **            | n.a.           | n.a.             | n.a.          | 0.389          | 0.236            | **             |
| LU→Y        | 0.600          | −0.293           | **            | 0.217          | 0.166            | —             | 0.817          | −0.126           | ***            |
| PRO→Y       | 0.557          | 0.707            | —             | n.a.           | n.a.             | n.a.          | 0.557          | 0.707            | —             |

*Sig. means significance; 'n.a.' means the value is not available; ‘—’ means no significance. Significance level indicated by *, ** and *** when \( p < 0.05, 0.01 \) and 0.001, respectively.
impact through LU and PRO gradually weakened, from 0.761 in stage I to −0.124 in stage II. The differences in direct, indirect and total effects between the two stages were significant.

Although no significant differences were found in the controlling effects of economic development on runoff and sediment yields between the two stages, ECO was always the most important controlling factor in the Gongshui watershed, with path coefficients of −0.872 and −1.086, respectively.

The effects of MOD and PRO on runoff and sediment yields in both stages did not have significant differences (table 4). MOD had a promoting effect in stage I (0.074) and a controlling effect in stage II (−0.388), while PRO had a promoting effect in both stages, with total effects of 0.557 and 0.707, respectively.

Significant differences were found for the direct and total effects of LU on runoff and sediment yields between the two stages (table 4). The direct and total effects changed from a promoting influence of 0.600 and 0.817, respectively, to a controlling influence of −0.293 and −0.126, respectively.

4. Discussion

4.1. Agricultural production and runoff and sediment yields

Agricultural production has been widely accepted as an important anthropogenic factor affecting runoff and sediment yields (Chen et al 2014, Auerswald et al 2018). The PLS-SEM results in Gongshui watershed indicated that both MOD and PRO had significant impacts on runoff and sediment yields in both stages (figure 4 and table 4). The direct effect of MOD changed from promoting factors in stage I to significant controlling forces in stage II, which mainly stemmed from the intensified agricultural input. The intensity of chemical fertilizer utilization in Gongshui watershed increased from 112 kg per hectare in 1985 to 318 kg per hectare in 2015. Previous studies demonstrated that proper chemical fertilizer could help improve soil fertility, modify soil structure, restore vegetation, and finally mitigate runoff and sediment yields (Amundson et al 2015, Keesstra et al 2016). The agricultural machinery power increased by 8.45-fold during 1985–2015, which facilitated the utilization of mechanical method of soil erosion control, such as terracing, contour farming and could decrease runoff and sediment yield dramatically.

PRO promoted runoff and sediment yields, with path coefficient increase from 0.557 in stage I to 0.707 in stage II. It reflected farmers’ profits in agricultural production and their economic status, and influenced their willingness to invest in agricultural production, including soil erosion control (Wang et al 2020). Boardman et al (2003) pointed out that good economic benefits are a prerequisite for farmers to implement soil conservation measures. Meanwhile, high returns would stimulate farmers’ enthusiasm for production, leading to the expansion of agricultural production and triggering new soil erosion. Therefore as Montgomery (2007) demonstrated, PRO had the potential to accelerate erosion.

4.2. Economic development and runoff and sediment yields

Socioeconomic development would increase resource consumption and ecological interference and result in the intensification of ecological problems such as soil erosion (DeFries et al 2010). Furthermore, economic development also optimized industry structure and increased the investment capacity for ecological conservation and soil erosion control (Ping et al 2013, Xiao et al 2015). The relationship between economic development and soil erosion might depend on the trade-off between interference and protection and had spatiotemporal variability (Vávra et al 2019).

Economic development was proven to be an important controlling factor in the Gongshui watershed (figure 4), and the total effects changed from −0.367 in stage I to −0.998 in stage II, with statistical significance (table 4). In the 1980s, agriculture was the most important economic source. The destruction of native vegetation for agricultural expansion led to serious soil erosion (Liu et al 2008). With economic development, the industrial structure had been optimized, and the proportion of agricultural, which is resource-consuming and strong ecosystem disturbance, had gradually decreased. The proportion of agricultural output value in the Gongshui watershed declined from 77% in 1985 to 30% in 2015. Economic growth was no longer dependent on agricultural expansion, which was considered the most important cause of soil erosion mitigation. In addition, with economic development, the government’s investment capacity in ecological restoration and soil erosion control strengthened dramatically. A series of ecological conservation projects, such as the grain for green and small watershed management projects, also changed the relationship between economic development and ecological protection (Xiao et al 2015, Duan et al 2020).

Population is an important manifest variable of economic development in PLS-SEM (figure 2). Population growth had the potential to increase disturbance to ecosystems and promote runoff and sediment yields (Zaman et al 2011). In addition, sufficient labour was the basic condition for regional economic development, industrial structure upgrading and urbanization. The results of PLS-SEM indicated that population growth indirectly alleviates the pressure of agricultural production on ecosystems and controls runoff and sediment yields (table 4). The absorbing of rural labour to tertiary industry might be one of the main reasons (Wang et al 2020).
The labour-migration accelerated urbanization and increased per capita income, which in turn improved the ability of soil erosion management (Chen et al 2014).

4.3. Evolution of the interactions  
Runoff and sediment yields were a combined result of biophysical and anthropogenic factors. Biophysical factors were the direct inducement of runoff and sediment yields, while anthropogenic factors determined its evolution trend (figure 4 and table 4).

Over the past 30 years, soil erosion in the Gongshui watershed was mitigated significantly (table 1). The mitigation was due to the controlling effects of socioeconomic factors, since the direct promoting effects of biophysical factors increased in stage II (table 4). As the influences of biophysical factors on agricultural production and land use tended to stabilize or weaken (figure S2), the final effects might only be driven by socioeconomic factors, which were beneficial to soil erosion control. Borelli et al (2017) found that the wealthy countries had the least erosion while poorest tropical countries were most susceptible to high levels of soil erosion.

The relationship between the latent variables of socioeconomic factors and runoff and sediment yields for the two stages had significant differences. The controlling effect of ECO was strengthened, and the promoting effects of MOD and LU were weakened (table 4 and figure S2). The increasing investment, continuous implementation of ecological conservation projects was the most important driving forces (Wang et al 2020). Furthermore, economic development also brought about changes in farmers’ lifestyles. For example, less farmers were inclined to cut trees or collect litter as fuel, which conducive to reducing ecological disturbance and controlling soil erosion (Wang et al 2020). Agricultural technology, including conservation tillage, terracing, and groundcover management, had been widely used in the watershed (Duan et al 2020). The results of PLS-SEM and change point analysis indicated that the contradiction between socioeconomic development and soil erosion control in the Gongshui watershed was beginning to be alleviated, and a synergy had gradually emerged.

5. Conclusion

The amount of sediment yields in all subwatersheds except one is significantly reduced in the Gongshui watershed. Both biophysical and socioeconomic factors have prominent effects on runoff and sediment yields. Biophysical factors are direct driving forces, while socioeconomic factors are undoubtedly the latent controlling factors of runoff and sediment yields.

Agricultural production activity is an important anthropogenic factor affecting runoff and sediment yields. Agricultural input controlled the runoff and sediment yields with a path coefficient of −0.209. Agricultural output promoted runoff and sediment yields with coefficient of 0.579, and the influence intensified with increasing benefits from agricultural production. Improving the input reasonably, and controlling the expansion of agricultural production were feasible methods of mitigating soil erosion in the Gongshui watershed.

Economic development was an important controlling force on runoff and sediment yields in Gongshui watershed, with a path coefficient of −0.475, and the total effects enhanced significantly from −0.367 in stage I to −0.998 in stage II. Economic development aggravated ecological interference, and it also promotes industrial structure adjustment and enhanced the investment ability in ecological protection. The ultimate effects depend on their trade-offs. For areas severely affected by soil erosion, such as the Gongshui watershed in southern China, the synergy of economic development and ecological conservation could provide continuous support for soil erosion control.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [41877070, 41525003] and the National Key Research and Development Program of China [2017YFC0505406].

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