Correction of measurement errors on sediment concentration sampled by stirring-sampling method from traditional runoff collection tanks

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Abstract: Stirring-sampling method is a widely adopted method to measure sediment concentrations in collection tanks of runoff plots, but with high systematic measurement errors. This research aimed to advance an approach for building correction equations to remove measurement errors in designed sediment concentration range. Experimental data of sediment measurement from the stirring-sampling method, with four representative soils, under the designed sediment concentrations (1, 2, 5, 8, 10, 20, 50, 80, 100, 200, 500, 800, and 1000 kg/m^3) were used to demonstrate the correction methodological process. Two correction methods (step-wise correction and universal correction) were suggested for the trial in this study based on the distribution of measurement errors. In the step-wise correction, the correction equations were made with a series of linear functions without intercept for the low concentration group (0-20 kg/m^3), a series of linear functions with intercept for the high (20-200 kg/m^3) and extremely high (200-1000 kg/m^3) concentration groups, consecutively. The correction equations were a series of power functions in the universal correction. For the step-wise correction, most of the relative errors of correction sediment concentrations were smaller than 15% and 10% under high and extremely high concentration groups, but the corrected accuracy was not good in the sediment concentration of 1, 2, 5 kg/m^3 with the corrected relative errors of 0.20%-206.07%. For the universal correction, the corrected relative errors (0.19%-31.81%) of the four soils were low under the condition of extremely high sediment concentrations, but other corrected accuracies weren't good with the corrected relative errors of 0.68%-1154.71%. The corrected accuracy of step-wise correction is higher than that of the universal correction, but the universal correction is more convenient. These results indicated that the correction equations could efficiently revise the measurement errors of the tested soils and that this method can be generalized to other soil types and was meaningful in monitoring soil erosion.

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1 Introduction

Soil erosion is widely regarded as a global issue[1], because soil erosion causes huge economic losses every year and has led to the continuous deterioration of ecology and environment[2]. Thus, studies on soil erosion are very essential. Monitoring soil and water loss using the runoff plot have long been widely used in many research methods[3]. The Universal Soil Loss Equation (USLE) was developed based on the dataset obtained through runoff plots[4]. In China, 152 water and soil conservation field stations and more than 6000 runoff plots have been built in recent decades[5]. Therefore, accurate measurement of the basic dataset is considerably important in the estimation of soil erosion. Because measurement errors of sediment concentration affect the dataset used to estimate the amounts of soil loss, accurate measurement of sediment concentration in the collection tank is significant.

Many methods have been proposed to accurately measure sediment concentrations in collection tanks, including γ ray fluoroscopy[6], laser scanning[7], capacitance method[8], and stirring-sampling method[9]. However, most of these methods have not been widely adopted to measure sediment concentrations because of the high cost and poor instrument stability. The stirring-sampling method has long been a traditional measurement method for sediment concentration in collection tanks. Although many operating procedures of the stirring-sampling method have

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been proposed, the stirring-sampling method is still the most common method because of its low cost. The stirring-sampling method collects sediment-laden water samples after thoroughly stirring and mixing, then oven-drying to measure sediment concentrations[5,10,11]. The measurement accuracy of the stirring-sampling method has been the focus of considerable attention because of many artificial factors.

Scientists have studied the measurement errors of stirring-sampling method and its influencing factors. Bagarello and Ferro[12] studied the mixed sampling procedure and the effects of sediment concentration, the volume of the collection tank, and the time duration of sampling on measurement accuracy. Lang[13] designed a series of sediment concentrations (1-187 kg/m^3) in eleven collection tanks and used bottle and pipette samplers to take sediment-laden water samples. The measurement errors of the two samplers were 45% and 75%, respectively. Zöbisch et al.[10] designed a range of sediment concentrations (10-100 kg/m^3) and found the range of measurement error to be from 4.7% to 83%. Ciesiolka et al.[14] designed the sediment concentration of 20 kg/m^3 and used four soil types to study measurement error. They found that the range of the measurement error from 18% to 85% was due to different soil types, although at same designed sediment concentration. Fu et al.[15] designed the range of sediment concentration from 4 to 120 kg/m^3 and found the average measurement error of 83.05%. Although these scientists designed the different sediment concentrations and used different sampling containers, all the measured sediment concentrations were smaller than the designed sediment concentrations. Therefore, it is hard to achieve uniform sampling in the collection tank, especially in the vertical direction with obvious differences.

Many scientists tried to develop new sampling containers or sampling technologies due to high measurement errors of the stirring-sampling method. Ye et al.[16] designed a sampling container composed of sampling tube and external handle, fixed ring and chassis and their results indicated that the accuracy of this sampling container was better than the traditional stirring-sampling method. Most of the measurement errors remained smaller than 20%. But their method did not popularize due to operational issues. Nikkami[17] designed a cylindrical sampler that was more accurate than bottle and pipette sampling. The average measurement error of cylindrical sampler was reduced to 11.32%. Fu et al.[15] proposed a stratified measurement method and demonstrated that the average measurement error was 2.77%. Bagarello and Ferro[12] installed water taps along the vertical direction of the collection tank with an interval of 0.1 m for stratified sampling. They defined a standardized sampling procedure based on designed collection tank and built a calibration curve. Carollo et al.[18] designed a cylindrical sampler with a shut-off valve at the bottom to conduct two series of experiments. Their results indicated that the sampling sediment concentration along vertical direction were very close to the actual sediment concentration. Although the measurement accuracy had been improved considerably by refining procedures and equipment, the costs, time, and manpower also increased relatively. Thus, Ciesiolka et al.[14] proposed an equation based on the sedimentation theory, which eliminated the error caused by the time delay between stirring and sampling. Compared with above-mentioned methods, it is an important issue whether the errors in the measured sediment concentrations could be corrected using some correction equations, which was simple and effective. Huang et al.[5] demonstrated the correction possibility of the measured sediment concentrations in collection tanks of runoff plots.

Most scientists only performed a qualitative analysis of measurement errors, or reduced measurement errors by improving traditional procedures. Few studies that directly correct the measurement errors of sediment concentrations, especially high sediment concentration, have been conducted. In erosion-prone soil areas, the highest sediment concentration could reach 1000 kg/m^3[19]. Therefore, studies on the correction of high sediment concentration cannot be ignored. The sediment concentrations of entire concentration range measured by the stirring-sampling method need to be corrected under conditions of different soil types, which could provide an accurate dataset to build soil erosion models for estimating the soil losses[14] and provide a scientific basis for the decision-making of regional ecology and environment[20].

In this article, four representative soils in China were applied to study the correction equation of sediment concentrations measured by the stirring-sampling method in a wide enough range. The aims are to 1) analyze the distribution of systematic measurement errors in wide sediment concentration range of 1-1000 kg/m^3, 2) obtain a series of correction equations of step-wise correction and universal correction, and 3) analyze the applicability of the step-wise correction and the universal correction methods.

2 Materials and method

2.1 Experimental materials

A series of laboratory experiments were conducted using four typical soils in China. The tested four soils were measured and classified in accordance with the U.S. Department of Agriculture (USDA) soil classification system. The first soil is black soil, which is a silt loam distributed on the Northeast China Plain and used mainly to farm[21,22]. The second soil is silt loess, which is a silt loam distributed on the northern part of the Chinese Loess Plateau and accounts for 32.5% of the total soil area in this region[23]. The third soil is lou soil, which is a silty clay loam distributed on the Guanzhong Plain and nearby areas in the southern part of the Loess Plateau and used mainly to farm[24]. The fourth soil is purple soil, which is clay loam distributed on the Sichuan Basin in the subtropical area and is an important agricultural soil[25]. The four soils are important types of agricultural soil in China, and encounter many problems in soil erosion. These soil materials were air-dried and then passed through a 2 mm sieve. Soil textures were measured in Table 1.

Table 1 Particle size distribution of four tested soils[5]

Soil type	Sand (>0.05-2 mm)/%	Silt (0.002-0.05 mm)/%	Clay (<0.002 mm)/%
Black soil	14.10	63.90	22.00
Silt loess	21.60	63.90	14.50
Lou soil	7.40	65.70	26.90
Purple soil	21.70	51.40	26.90

2.2 Experimental design

The experiments involved a large sediment concentration gradient (1, 2, 5, 8, 10, 20, 50, 80, 100, 200, 500, 800, 1000 kg/m^3) that include all possible sediment concentrations found in field conditions in the runoff collection tank. These experiments were performed in the laboratory and used circular plastic buckets with an approximate 150 L volume to simulate the collection tank. The circular plastic bucket was 75 cm in height, 79 cm in diameter at the top, and 45 cm in diameter at the bottom. Two sediment-laden runoff volumes of 50 L and 100 L were designed to conduct experiments under each designed sediment concentration, and all experimental treatments were repeated thrice. More details of sample preparation were introduced by Huang et al.[5]

2.3 Sampling and measuring sediment concentration

The experiments conducted stirring and sampling following the traditional procedures of collection tank in the field. Before the beginning of stirring and sampling, empty steel cups with a 500 mL volume were weighed and recorded. After stirring with the traditional method, five samples were taken at 15-20 cm below the surface of the water in the bucket. The procedure was repeated thrice to collect 15 samples of each sediment concentration. These samples were precipitated for 24 h before their supernatants were filtered out. Then, the remaining sediments were dried out at 105 ℃ for 24 h, and weighed after cooling to room temperature (25 ℃). Therefore, sediment concentration could be calculated as the following equations:

$$C = M_s / V \tag{1}$$

$$M_s = M_{sc} - M_c \tag{2}$$

$$V = [(M_{swc} - M_{sc}) / \rho_w + (M_{sc} - M_c) / \rho_s] \times 10^{-3} \tag{3}$$

where, C denotes the measured sediment concentration, kg/m^3; M_s refers to the mass of dry sediments in the sample, g; V represents the sample volume of the sediment-water mixture, L; M_{swc} denotes the mass of water and sediment sample and an empty cup, g; M_{sc} stands for the mass of dry sediment and an empty cup, g; M_c refers to the mass of empty cup, g; ρ_w (1.00 g/cm^3) and ρ_s (2.65 g/cm^3) are densities of pure water and soil, respectively.

The average sediment concentrations were calculated using Equation (4) for each sediment concentration treatment.

$$\overline{C} = \frac{1}{15}\sum_{i=1}^{15} C_i \tag{4}$$

where, $\overline{C}$ represents the mean value of measured sediment concentrations, kg/m^3 and C_i refers to each sediment concentration of 15 measurements for each designed sediment concentration, kg/m^3. The results under the conditions of two sediment-laden runoff volumes were measured and calculated by Huang et al.[5]

2.4 Systemic error calculation

Systematic error refers to the difference between the average measured value and its true one following infinite repeatability under the same condition. The systematic error is caused by the measuring methods or equipment, and the change in the measuring environment, etc.[5] Thus, the systematic error between designed and measured sediment concentrations was calculated using Equation (5):

$$\mu = \overline{C} - C \tag{5}$$

where, μ represents the systemic error, kg/m^3 and C_0 refers to the designed sediment concentration, kg/m^3.

The systemic errors under the conditions of two sediment-laden runoff volumes are calculated by Huang et al.[5]. If μ is negative, the average measured value of sediment concentration is lower than the designed sediment concentration. If μ is positive, the average measured value of sediment concentration is higher than the designed sediment concentration. Based on the results obtained by Huang et al.[5], the measured sediment concentrations were all smaller than the designed values, which indicated the limitation of the traditional stirring-sampling procedure.

2.5 Relative error calculation

The relative error is generally regarded as an error parameter that can better reflect the reliability of the measurement[5]. The relative errors between designed and measured/corrected sediment concentrations were calculated using Equation (6).

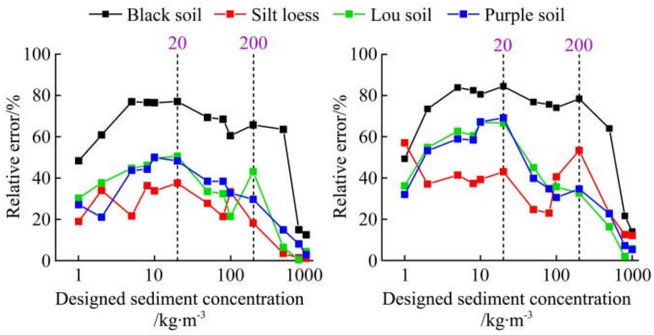
$$\delta = \frac{\left|\overline{C} - C_0\right|}{C_0} \times 100\% \tag{6}$$

where, δ denotes relative error, %.

2.6 Correction method

2.6.1 Step-wise correction

Step-wise correction refers to correcting the measured sediment concentrations by using piecewise function built based on the distribution of relative errors of the measured values. In this research, measurement errors differed among the different ranges of designed sediment concentration (1-1000 kg/m^3). In accordance with the distribution of relative errors of the measured values (Figure 1), the designed sediment concentrations of each soil type were divided into three groups to obtain accurate calibration of sediment concentrations, as low concentration group (1-20 kg/m^3), high concentration group (20-200 kg/m^3), and extremely high concentration group (200-1000 kg/m^3). The measured sediment concentrations of four soil types were significantly different ($p < 0.001$) in all three groups. The calibration for each soil type in each group was carried out.



a. Total sediment-laden volumes of 50 L b. Total sediment-laden volumes of 100 L

Figure 1 Distribution of relative errors of measured sediment concentrations under two total sediment-laden volumes

Thus, a piecewise linear function was obtained to correct the measured sediment concentration, as follows:

$$y = \begin{cases} ax, & 1 \le x \le 20 \\ ax + b, & 20 < x \le 1000 \end{cases} \tag{7}$$

where, y represents the corrected sediment concentration, kg/m^3; x refers to the measured sediment concentration, kg/m^3 and a, b denotes the correlation parameters.

2.6.2 Universal correction

Universal correction refers to correcting the measured sediment concentrations by using a function built based on the range of sediment concentration. Based on the change trend of measured sediment concentrations, a power function was proposed to correct the measured values, as follows:

$$y = d + g(h + jx)^{1/2} \tag{8}$$

where, d, g, h, j denotes the correlation parameters.

3 Results

3.1 Step-wise correction

3.1.1 Low concentration group

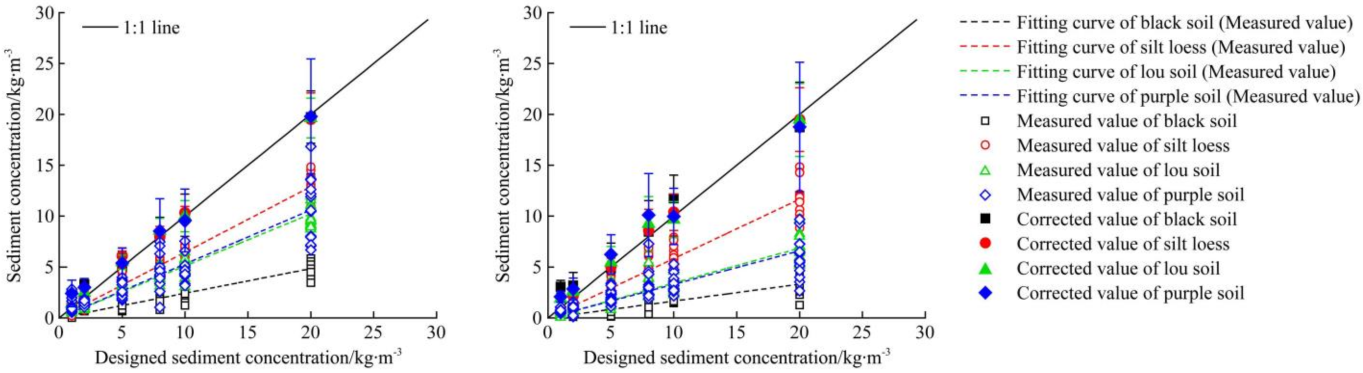
The measured sediment concentrations were less than the designed values in the low concentration group. Based on the results by Huang et al.[5], the sediment-laden runoff volume of 100 L had smaller measured sediment concentrations than that of

50 L, which caused larger systematic measurement errors. Thus, a series of linear correction equations without intercept were obtained by using Equation (7) in accordance with the distribution of systematic measurement errors of each soil type in the low concentration group. These correction equations are listed in Table 2.

The sediment concentrations of the four soil types in low concentration group were corrected based on these correction equations in Table 2. The corrected systematic measurement errors were much closer to the 1:1 line under sediment-laden runoff volumes of 50 L (Figure 2a) and 100 L (Figure 2b). Compared with relative measurement errors, corrected relative errors of four soils were distinctly decreased under two sediment-laden runoff volumes, except for the designed sediment concentrations of 1 and 2 kg/m^3 (Table 3). Due to too low sediment concentration, the random error was too large to easily correct and eliminate. Overall, these correction values were much closer to designed sediment concentrations than the measured values, which illustrated these correction equations were effective.

Table 2 Correction equations of four soil types in low concentration group

Soil type	Total volume/L	Correction equation	Determining coefficient/R^2	Prob>F
Black soil	50	y=4.13x	0.99	6.71×10^{-7}
	100	y=6.04x	0.98	1.38×10^{-5}
Silt loess	50	y=1.55x	0.99	1.33×10^{-7}
	100	y=1.71x	0.99	2.52×10^{-8}
Lou soil	50	y=1.96x	0.99	3.97×10^{-8}
	100	y=2.92x	0.99	7.51×10^{-7}
Purple soil	50	y=1.89x	0.99	9.37×10^{-7}
	100	y=3.04x	0.98	1.01×10^{-5}



a. Total sediment-laden volumes of 50 L   b. Total sediment-laden volumes of 100 L

Figure 2 Corrected and measured sediment concentration of four soil types in low concentration group

Table 3 Corrected systematic errors and measured and corrected relative errors in low concentration group

Soil type	Designed sediment concentration /kg m^{-3}	Total volume of 50 L			Total volume of 100 L		
		Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%	Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%
Black soil	1	47.68	1.16	116.08	49.33	2.06	206.07
	2	60.08	1.30	64.89	73.51	1.20	59.97
	5	76.00	–0.04	0.87	83.84	–0.12	2.39
	8	75.66	0.04	0.52	82.51	0.45	5.66
	10	75.56	0.09	0.92	80.56	1.74	17.41
	20	76.11	–0.27	1.33	84.49	–1.27	6.34
Silt loess	1	18.63	0.26	26.13	57.05	–0.27	26.56
	2	33.52	0.06	3.05	37.05	0.15	7.64
	5	21.27	1.10	22.02	41.40	0.01	0.20
	8	35.78	–0.04	0.46	37.33	0.57	7.17
	10	33.27	0.34	3.43	39.24	0.39	3.90
	20	37.01	–0.47	2.37	43.02	–0.51	2.56
Lou soil	1	29.80	0.38	37.59	36.21	0.86	86.27
	2	37.12	0.46	23.24	54.83	0.64	31.89
	5	44.13	0.48	9.51	62.7	0.45	8.91
	8	45.52	0.54	6.78	60.5	1.23	15.35
	10	49.03	–0.01	0.09	66.94	–0.35	3.46
	20	49.90	–0.36	1.80	66.67	–0.54	2.68
Purple soil	1	26.69	1.39	139.44	31.99	1.07	106.76
	2	20.68	1.00	49.91	53.23	0.84	42.18
	5	43.07	0.38	7.60	58.97	1.24	24.74
	8	43.65	0.52	6.50	58.42	2.11	26.39
	10	49.35	–0.43	4.28	67.21	–0.03	0.31
	20	47.64	–0.21	1.04	69.13	–1.23	6.14

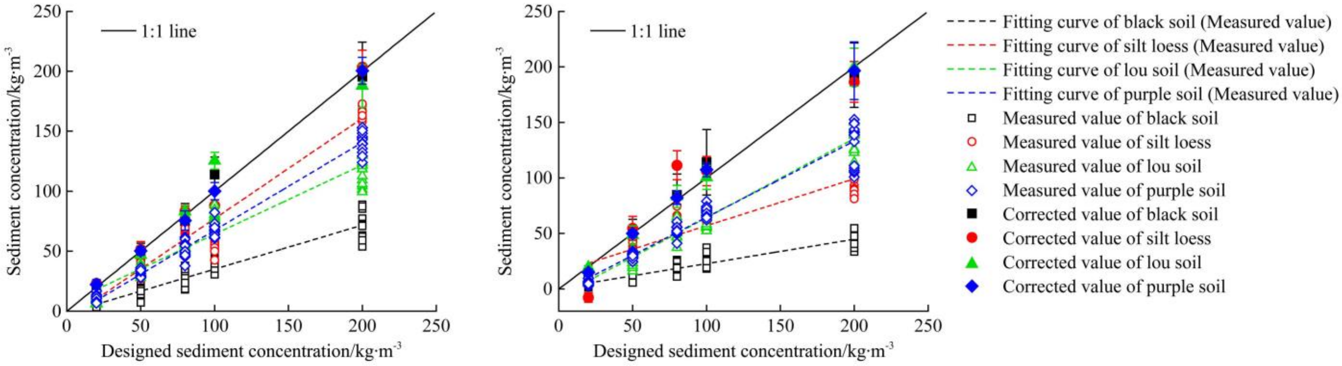
3.1.2 High concentration group

The measured sediment concentrations were smaller than the designed values in the high concentration group, which was similar to the low concentration group. According to the results by Huang et al.[5], sediment-laden runoff volume of 100 L had systematic measurement errors larger than that of 50 L, and the systematic measurement errors increased with designed sediment concentration increase. A series of linear functions were obtained by using Equation (7) to correct the measured sediment concentrations in the high concentration group according to the distribution of the systematic measurement errors of each soil type. These correction equations were listed in Table 4.

The sediment concentrations of the four soil types in high concentration group were corrected based on the correction equations in Table 4. Similar to the low concentration group, the corrected systematic measurement errors were much closer to the 1:1 line under sediment-laden runoff volumes of 50 L (Figure 3a) and 100 L (Figure 3b). Compared with relative measurement errors, most of the corrected relative errors of the four soils reduced to less than 15% under two sediment-laden runoff volumes (Table 5). Thus, these results illustrated that the correction equations were very effective.

Table 4 Correction equations of four soil types in high concentration group

Soil type	Total volume /L	Correction equation	Determining coefficient/R^2	Prob>F
Black soil	50	y=2.72x+4.49	0.99	6.55×10^{-4}
	100	y=4.56x-4.05	0.98	1.18×10^{-3}
Silt loess	50	y=1.19x+8.06	0.99	3.88×10^{-4}
	100	y=2.37x−34.77	0.90	1.30×10^{-2}
Lou soil	50	y=1.73x−11.12	0.94	5.0×10^{-3}
	100	y=1.41x+9.77	0.99	8.75×10^{-6}
Purple soil	50	y=1.36x+7.98	0.99	1.97×10^{-5}
	100	y=1.46x+5.90	0.99	1.53×10^{-4}



a. Total sediment-laden volumes of 50 L b. Total sediment-laden volumes of 100 L

Figure 3 Corrected and measured sediment concentration of four soil types in the high concentration group

Table 5 Corrected systematic errors and measured and corrected relative errors in the high concentration group

Soil type	Designed sediment concentration /kg m^{-3}	Total volume of 50 L			Total volume of 100 L		
		Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error /%	Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%
Black soil	20	76.11	–2.51	12.56	84.49	–9.91	49.54
	50	68.44	–2.59	5.17	76.84	–1.25	2.50
	80	67.61	–5.03	6.28	75.65	4.79	5.99
	100	59.76	13.93	13.93	74.09	14.11	14.11
	200	64.90	–4.55	2.28	78.45	–7.53	3.77
Silt loess	20	37.01	3.05	15.26	43.02	–27.76	138.80
	50	27.28	1.33	2.65	24.68	4.49	8.97
	80	20.99	3.28	4.10	22.91	31.39	39.24
	100	32.83	–12.01	12.01	40.55	6.13	6.13
	200	17.91	3.42	1.71	53.33	–13.55	6.77
Lou soil 50	20	49.90	–13.78	68.92	66.67	–0.83	4.15
	50	33.04	–3.20	6.40	45.04	–1.48	2.96
	80	31.93	3.09	3.86	34.72	3.41	4.26
	100	21.08	25.41	25.41	35.71	0.42	0.42
	200	42.51	–12.19	6.09	32.63	–0.25	0.13
Purple soil 100	20	47.64	2.22	11.11	69.13	–5.08	25.42
	50	37.86	0.24	0.47	39.80	–0.16	0.31
	80	37.86	–4.41	5.51	34.75	2.11	2.64
	100	32.28	0.08	0.08	30.53	7.32	7.32
	200	29.21	0.52	0.26	34.72	–3.48	1.74

3.1.3 Extremely high concentration group

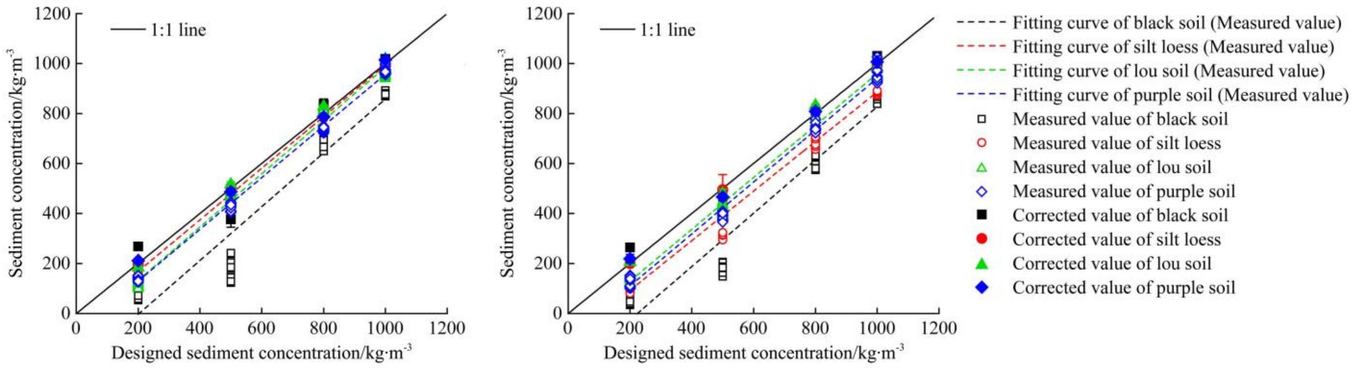
The measured sediment concentrations were less than the designed values in the extremely high concentration group, which was similar to the previous concentration groups. In accordance with the results by Huang et al.[5] , systematic measurement errors increased first and then decreased with the increase in the designed sediment concentration. Based on the distribution of systematic measurement errors of each soil type, a series of linear functions were obtained by using Equation (7) to correct the measured sediment concentrations in extremely high concentration group.

These correction equations were listed in Table 6.

The sediment concentrations of four soil types in the extremely high concentration group were corrected based on the correction equations in Table (6). Similar to the two concentration groups, the corrected systematic measurement errors were much closer to the 1:1 line under sediment-laden runoff volumes of 50 L (Figure 4a) and 100 L (Figure 4b). Compared with the relative measurement errors, most of the corrected relative errors of the four soils were reduced to less than 10% under two sediment-laden runoff volumes (Table 7). Overall, these corrected values were much closer to the designed sediment concentrations than the measured values, which illustrated that these correction equations were effective.

Table 6 Correction equations of four soil types in extremely high concentration group

Soil type	Total volume/L	Correction equation	Determining coefficient/R^2	Prob>F
Black soil	50	y=0.93x+202.84	0.94	2.83×10^{-2}
	100	y=0.94x+223.60	0.96	2.20×10^{-2}
Silt loess	50	y=0.97x+36.90	0.99	9.45×10^{-5}
	100	y=1.01x+105.94	0.99	3.06×10^{-4}
Lou soil	50	y=0.94x+75.71	0.99	2.68×10^{-3}
	100	y=0.96x+75.58	0.99	2.37×10^{-3}
Purple soil	50	y=0.97x+74.20	0.99	8.94×10^{-4}
	100	y=0.96x+93.31	0.99	2.22×10^{-3}



a. Total sediment-laden volumes of 50 L b. Total sediment-laden volumes of 100 L

Figure 4 Corrected and measured sediment concentration of four soil types in the extremely high concentration group

Table 7 Corrected systematic errors and measured and corrected relative errors in extremely high concentration group

Soil type	Designed sediment concentration /kg m^{-3}	Total volume of 50 L			Total volume of 100 L		
		Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%	Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%
Black soil	200	64.90	68.08	34.04	78.45	64.05	32.02
	500	62.71	–123.89	24.78	63.99	–107.41	21.48
	800	14.66	37.40	4.68	21.59	12.32	1.54
	1000	12.25	18.41	1.84	13.97	31.04	3.10
Silt loess	200	17.91	–4.01	2.00	53.33	0.10	0.05
	500	3.34	5.24	1.05	22.87	–5.02	1.00
	800	1.19	2.93	0.37	12.49	12.15	1.52
	1000	1.04	–4.17	0.42	12.09	–7.24	0.72
Lou soil	200	42.51	–16.49	8.24	32.63	5.35	2.68
	500	6.22	15.28	3.06	16.29	–21.29	4.26
	800	0.27	27.76	3.47	1.86	31.82	3.98
	1000	4.24	-26.55	2.65	5.67	–15.88	1.59
Purple soil	200	29.21	11.14	5.57	34.72	19.10	9.55
	500	14.58	–12.69	2.54	22.65	–34.07	6.81
	800	7.87	–12.87	1.61	7.17	8.78	1.10
	1000	2.80	14.40	1.44	5.25	6.19	0.62

According to the results corrected by the correction equations in three concentration groups, the boundary concentrations were not well corrected when the correction equation of higher concentration groups was used. Thus, the correction equation at the boundary should be the equation of lower concentration group to obtain accurate corrected results. Also, the correction of other soils in other areas needed to divide suitable groups of sediment concentration and build appropriate correction equations.

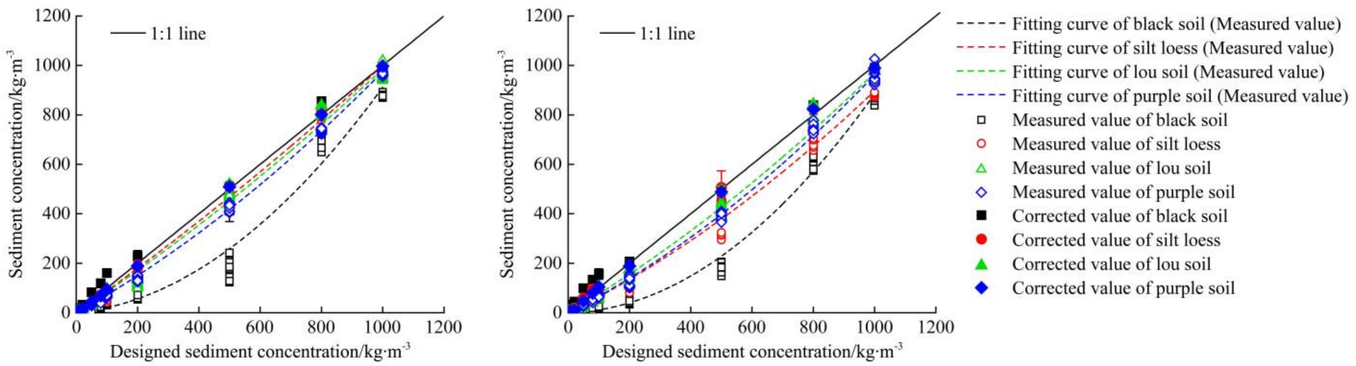
3.2 Universal correction

In accordance with the results of Huang et al.[5], sediment-laden runoff volume of 100 L had higher systematic measurement errors than that of 50 L and systematic measurement errors increased with designed sediment concentration increase. Soil type affected the measured values. Overall, systematic measurement errors increased first to reach peak value and then decreased to steady-state with the increase in the designed sediment concentration. Based on the distribution of systematic measurement errors of each soil type, a universal function was used to attempt to correct systematic measurement errors in the entire range of the designed sediment concentration. Then, a series of power functions could be obtained by using Equation (8) to correct the measured sediment concentrations in the entire range of the designed sediment concentrations. These correction equations are listed in Table 8.

The sediment concentrations of the four soil types in the entire range of designed concentration were corrected based on the correction equations in Table 8. The measured values of silt loess, lou soil, and purple soil were corrected and their systematic measurement errors were reduced (Figure 5). When the designed sediment concentration is low, systematic measurement errors of black soil remained high even after correction. However, the measured values of black soil could be well corrected when the designed sediment concentration is high. Compared with relative measurement errors, the corrected relative errors of the four soils were low under the condition of extremely high sediment concentrations, but other corrected accuracy were not good (Table 9). Overall, the correction accuracy of the step-wise correction was higher than that of universal correction. Although the corrected effects by using universal correction method were ordinary, the universal correction method was convenient to those general users without too high accuracy requirement.

Table 8 Correction equations of four soil types in the entire range of the designed sediment concentrations

Soil type	Total volume/L	Correction equation	Determining coefficient/R^2	Prob>F
Black soil	50	$y=-78.14+634.39\times(0.01517+0.0032x)^{1/2}$	0.99	1.35×10^{-11}
	100	$y=-17.17+584.63\times(0.00086+0.0034x)^{1/2}$	0.99	4.12×10^{-13}
Silt loess	50	$y=-3486.57+3988.89\times(0.764+0.00050x)^{1/2}$	0.99	0.01×10^{-16}
	100	$y=-1112.07+1797.84\times(0.38262+0.0011x)^{1/2}$	0.99	1.89×10^{-15}
Lou soil	50	$y=-2487.24+3031.59\times(0.67312+0.00066x)^{1/2}$	0.99	2.55×10^{-14}
	100	$y=-1539.55+2101.71\times(0.53659+0.00095x)^{1/2}$	0.99	2.66×10^{-15}
Purple soil	50	$y=-1241.4+1785.90\times(0.48318+0.0011x)^{1/2}$	0.99	0.01×10^{-16}
	100	$y=-952.92+1511.33\times(0.39756+0.0013x)^{1/2}$	0.99	0.01×10^{-16}



a. Total sediment-laden volumes of 50 L b. Total sediment-laden volumes of 100 L

Figure 5 Corrected and measured sediment concentrations of four soil types in a whole range of designed sediment concentration

Table 9 Corrected systematic errors and measured and corrected relative errors in a whole range of designed sediment concentration

Soil type	Designed sediment concentration /kg m^{-3}	Total volume of 50 L			Total volume of 100 L		
		Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%	Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%
Black soil	1	47.68	3.13	312.79	49.33	11.55	1154.71
	2	60.08	4.23	211.52	73.51	10.78	538.88
	5	76.00	4.16	83.12	83.84	12.28	245.68
	8	75.66	6.42	80.19	82.51	18.22	227.80
	10	75.56	7.75	77.49	80.56	23.32	233.24
	20	76.11	12.11	60.55	84.49	25.02	125.09
	50	68.44	32.91	65.83	76.84	49.47	98.93
	80	67.61	38.54	48.18	75.65	53.88	67.36
	100	59.76	60.51	60.51	74.09	56.44	56.44
	200	64.90	29.61	14.80	78.45	7.36	3.68
	500	62.71	–87.54	17.51	63.99	–58.51	11.70
	800	14.66	55.73	6.97	21.59	39.23	4.90
	1000	12.25	–20.11	2.01	13.97	–14.10	1.41
Silt loess	1	18.63	–0.07	6.92	57.05	–0.31	30.59
	2	33.52	–0.48	23.96	37.05	0.03	1.66
	5	21.27	–0.50	9.99	41.40	–0.27	5.47
	8	35.78	–2.13	26.59	37.33	0.07	0.93
	10	33.27	–2.37	23.74	39.24	–0.22	2.21
	20	37.01	–5.62	28.09	43.02	–1.73	8.65
	50	27.28	–8.65	17.31	24.68	9.28	18.57
	80	20.99	–8.42	10.53	22.91	15.56	19.45
	100	32.83	–24.01	24.01	40.55	–7.75	7.75
	200	17.91	–17.00	8.50	53.33	–58.19	29.10
	500	3.34	14.90	2.98	22.87	6.25	1.25
	800	1.19	10.23	1.28	12.49	25.33	3.17
	1000	1.04	–8.78	0.88	12.09	–14.98	1.50

Soil type	Designed sediment concentration /kg m^{-3}	Total volume of 50 L			Total volume of 100 L		
		Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%	Measured relative error/%	Corrected systematic error/kg m^{-3}	Corrected relative error/%
Lou soil	1	29.80	–0.14	14.45	36.21	–0.13	12.95
	2	37.12	–0.47	23.38	54.83	–0.77	38.36
	5	44.13	–1.60	31.94	62.70	–2.46	49.13
	8	45.52	–2.69	33.67	60.50	–3.69	46.15
	10	49.03	–3.80	37.95	66.94	–5.49	54.93
	20	49.90	–7.82	39.08	66.67	–10.93	54.64
	50	33.04	–9.53	19.05	45.04	–12.95	25.90
	80	31.93	–14.49	18.11	34.72	–10.31	12.88
	100	21.08	–5.61	5.61	35.71	–14.63	14.63
	200	42.51	–63.61	31.81	32.63	–25.97	12.99
	500	6.22	17.60	3.52	16.29	–7.52	1.50
	800	0.27	36.94	4.62	1.86	41.73	5.22
	1000	4.24	–24.26	2.43	5.67	–22.57	2.26
Purple soil	1	26.69	0.82	82.08	31.99	0.08	7.80
	2	20.68	0.28	14.00	53.23	–0.52	25.89
	5	43.07	–0.91	18.24	58.97	–1.75	35.05
	8	43.65	–1.53	19.17	58.42	–2.74	34.27
	10	49.35	–2.74	27.38	67.21	–4.81	48.15
	20	47.64	–5.03	25.16	69.13	–10.26	51.31
	50	37.86	–6.08	12.17	39.80	–3.41	6.82
	80	37.86	–10.45	13.07	34.75	–0.54	0.68
	100	32.28	–6.14	6.14	30.53	4.43	4.43
	200	29.21	–10.79	5.39	34.72	–11.81	5.91
	500	14.58	9.70	1.94	22.65	–11.77	2.35
	800	7.87	1.55	0.19	7.17	22.64	2.83
	1000	2.80	–2.46	0.25	5.25	–10.82	1.08

4 Discussion

The corrected systematic and relative errors of different concentration groups differed based on the above-corrected results of the step-wise correction. In the low concentration group, the corrected relative errors were still large, especially 1 and 2 kg/m^3. Stirring fewer sediments to distribute them evenly in the collection tanks/buckets was too difficult[26]. Some large soil particles settled down rapidly to the lower part of the collection tank after stirring, which increased the difficulty of the measurement[5]. These reasons made our correction difficult and low sediment concentrations caused variability of relative errors to increase, which made our corrected relative error not good. For the high and extremely high concentration group, too many sediments in the collection tanks/buckets made it easier to sample many sediments without the need for even stirring, thereby decreasing the variability of relative errors. Some easily eroded areas produce large sediment concentrations and required the use of correction equations of high concentration group, as Loess Plateau. For extremely high concentration group, these sediment concentrations always appeared under the condition of extreme rainfall. Thus, general sediment concentrations focused on the low concentration group and the essential step-wise correction was applied.

According to the above-corrected results of the universal correction, most of the measured sediment concentrations of silt loess and purple soil could be corrected by the equations of universal correction. However, the correction effects of the other two soils were not good and the correction effects of the four soils in some low concentrations (1, 2, and 5 kg/m^3) were not good. Though universal correction was convenient, the correction accuracy of step-wise correction was higher than that of universal correction. Hence, the monitoring sediment concentrations were large or the requirement of correction accuracy was low, which could be corrected through the universal correction equations. The monitoring sediment concentrations were small and must be corrected using the step-wise correction equations.

The total volume of sediment-laden water involves stirring uniformity and sampling representativeness[5]. The bigger the water volume, the more difficult the stirring process, and the worse the stirring uniformity. In our research, the most height of the total sediment-laden water in the simulation bucket is close to 0.5 m. However, the height of most traditional collection tanks is close to 1.0 m. The correction equations should be calibrated to a height of 1.0 m of the total sediment-laden water in future studies. Also, the historic data of sediment concentrations in the runoff plots could also be corrected. Measured sediment concentrations could be corrected to provide good datasets, which would be beneficial to building good prediction models of soil erosion. Every typical soil could build a correction equation to obtain best-corrected results and extend to a wide area.

5 Conclusions

Sediment concentrations of four representative soils in China, which were sampled using the stirring-sampling method in runoff plots, were used to study the correction of measurement errors. Through a series of laboratory experiments simulating stirring and sampling in collection tanks, measurement errors of negative values, namely measured sediment concentrations were always smaller than the designed sediment concentrations. Because the range of designed sediment concentration was very wide, two correction methods were used to correct the measurement errors, as step-wise correction and universal correction. In step-wise correction, the correction equations of the low concentration group were a series of linear functions without intercept and that of high and extremely concentration group was a series of linear functions with intercept. In universal correction, the correction equations were a series of power functions. The relative errors of corrected sediment concentrations by step-wise method were smaller than 10% under high and extremely high concentration groups for all four soil types. In the low concentration group, although the relative errors of the corrected sediment concentrations did not decrease significantly, the corrected sediment concentrations were closer to the designed values. The correction accuracy of the step-wise correction was also higher than that of universal correction, though universal correction was convenient. Overall, compared with the sampling containers or sampling technologies of previous studies, the method of correction equations is simple and effective. Thus, the method can be applied to other typical soils to obtain a series of correction equations. Then, this method could be popularized, as a tool for monitoring soil erosion and building soil erosion models.

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