

Article

Applying Photoelectric Sand Meter for Monitoring of Suspended Solid Matter in Rivers

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Abstract: River ecosystems are integral to sustainable environmental development, playing a crucial role in understanding suspended solid matter (SSM) transport dynamics and soil conservation. Accurate monitoring of SSM concentrations in watersheds is foundational for these studies. This research introduces and evaluates a novel HHSW·NUG-1 photoelectric sand meter, specifically designed for SSM measurement. Its reliability was validated at three hydrological stations, including Xiaolangdi. The instrument, based on light scattering principles, is optimized for environments with high SSM loads and rapid flow rates. Laboratory tests indicate a measuring range of 0 to 730 kg/m³, and field trials show effective operation within 0 to 375 kg/m³, meeting the monitoring needs of hydrological stations. Through comparative analysis of measurement data, we established conversion relationships for various SSM concentration ranges, confirming that the instrument's system error is less than 1%. The photoelectric sand meter adheres to standards outlined in the “Guidelines for SSM Test in Rivers”, demonstrating stability in reliability, calibration methods, observation accuracy, real-time monitoring, data storage, and continuous operation. For optimal use, adherence to relevant hydrological instrument standards is recommended, particularly in stations requiring SSM analysis. Standard sampling and calibration of conversion coefficients should be conducted, and proper sensor installation is crucial to avoid interference from flow conditions. In conclusion, the HHSW·NUG-1 optoelectronic sand meter exhibits stable and reliable performance in practical applications, with broad potential for rapid deployment in other river hydrological stations.

Keywords: optoelectronic sand meter; sand content; river systems; hydrological station; sand meter



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1. Introduction

River systems are vital for environmental sustainability, playing key roles in maintaining water quality, biodiversity, and climate regulation [1–3]. Their unique structure and functions support watershed stability and offer valuable services to surrounding areas. However, improper use, development, and management of water resources can disrupt river functions, impacting major water conservation projects. In particular, soil and watershed erosion remain significant concerns [4–7]. Soil erosion in watersheds is widespread globally, involving numerous countries such as China [4,8], India [9], Ethiopia [10], Spain [11], and Georgia [12]. For instance, the renowned Yellow River Basin in China has repeatedly faced severe soil erosion challenges [4,13,14]. Extensive theoretical research has been conducted on this issue in the academic community [15,16], resulting in significant advancements in the understanding of suspended solid matter (SSM)

transport dynamics and soil and water conservation. These studies serve as the foundation for monitoring SSM content in watersheds. Monitoring SSM in rivers is crucial for understanding flow patterns, changes in riverbed morphology, sedimentation, and soil erosion. It also aids in evaluating the effectiveness of management strategies, predicting total SSM loss over time, calculating the erosion modulus, and assessing the severity of watershed erosion. This knowledge is vital for the design and management of major infrastructure projects, water resource management, ecological protection, and sediment assessment. For instance, integrating SSM measurements with modeling studies effectively captures sediment transport dynamics at the watershed scale [16]. Consequently, the demand for monitoring river SSM has significantly increased.

Traditional methods for determining SSM content include direct determination, vibration, ultrasonic, capacitance, and photoelectric techniques. The direct determination method involves further processing of collected samples, such as using drying or specific-gravity methods, to quantify SSM content [17]. However, this approach suffers from significant sampling error due to randomness and variability, is time-consuming, and requires considerable labor, making it unsuitable for mobile surveys and online monitoring [17]. The vibration method estimates SSM content by utilizing the resonance period of a vibrating rod immersed in river water, which correlates linearly with SSM concentration [18]. While this method is effective for measuring SSM at hydrological stations, it is highly sensitive to fluctuating riverine conditions, compromising its stability. Additionally, the bulky nature of vibratory instruments makes them impractical for shallow slope runoff scenarios. The dynamic sediment environment in slope runoff, characterized by varying sediment concentrations and particle sizes, further limits the utility of vibratory instruments, necessitating alternative methods specifically designed for hillslope erosion studies [18]. Ultrasonic technology can effectively detect fine SSM underwater, with good penetration in turbid water, allowing real-time monitoring of runoff sediment. Slope runoff is a major driver of sediment transport, mobilizing soil particles that increase sediment load in adjacent water bodies. However, the intensity of ultrasonic waves can be affected by interactions with SSM, potentially crushing sediment particles and altering their size distribution [19]. Thus, this method is only suitable for low SSM concentrations where interference is minimal. Currently, the promotion of acoustic SSM meters is limited, with only a few mature manufacturers (RDI-Teledyne, Nortek, and Aquatec). Nevertheless, certain instruments, such as the acoustic Doppler current profiler (ADCP) and Aquascap probe, offer significant advantages in monitoring SSM. The ADCP, for example, uses acoustic Doppler principles to measure frequency shifts in scattered signals within stratified water. By applying vector synthesis techniques, it creates vertical profiles of water flow rate, advancing broad-beam control and multifunctional flow measurement technology. However, ADCPs have blind zones due to sidelobe interference, typically occupying 6–12% of the profile area. Additionally, ultrasonic noise from ADCPs may interfere with cetacean navigation and echolocation, which is a common concern for underwater acoustic devices [20,21]. The capacitance method is an electrophysical technique for determining SSM content based on changes in the dielectric constant of a mud–water mixture. However, it is temperature-sensitive, unsuitable for slope runoff systems, and remains in the theoretical research stage. The photoelectric method relies on the absorption and scattering properties of light to measure SSM content in a sandy water stream. However, it is affected by high SSM concentration and particle size, limiting its applicability [22,23].

Many studies currently employ optical and acoustic sensors to measure high concentrations of SSM in rivers. (1) Optical sensors. Bergougnoux et al. [24] developed an optical fiber bundle sensor based on light backscattering to measure high particle concentrations. The sensor's response depends on particle concentration, size, and optical properties, par-

ticularly for silica particles. It has a measurement range of volume concentrations from 10^{-3} to 0.4, covering particle sizes between 1 and 180 μm . Originally designed for Cemagref to monitor solid transport during torrential swelling, the sensor is also applicable in sedimentation and circulating fluidized beds. Additionally, SSM can be determined from echo profiles along horizontally aligned acoustic beams. (2) Acoustic sensors. Aleixo et al. [25] examined the impact of organic matter on variations in backscatter and attenuation during hydrological events, reducing discrepancies between acoustically inferred and sampled concentrations. This improvement required measuring the attenuation-to-backscatter ratio (ABR) alongside sound attenuation. Another study focused on interpreting echo signals suspended within mixed sediments, where sediment fractions varied with height above the bed. The researchers analyzed acoustic scattering characteristics and backscattered signals to extract suspended sediment information, noting that particle size is often overestimated while concentration is underestimated [26]. (3) Overall, Fettweis et al. [27] discussed the benefits and limitations of optical and acoustic backscatter sensors for long-term SSM observations. They highlighted that both sensor types necessitate converting outputs (post-calibration) into mass concentration, relating the sensor output to reference SSM based on protocols, techniques (such as scattering angle), and manufacturers. Variability can occur even among sensors of the same type. Sources of uncertainty include sensor malfunctions, environmental conditions affecting sensor performance without altering SSM, sample collection and analysis, and modeling discrepancies between sensor output and sample SSM, as well as human errors and uncontrolled environmental factors.

Nasr [28] explored passive acoustic monitoring methods for riverbed material flux. Field data collection validated a global calibration curve, and a physical model for the acoustic signal of bed material (SGN) was developed. The study demonstrated that utilizing an acoustic inversion algorithm with a field-calibrated propagation model significantly enhances the correlation between the SGN source signal and measured bed material flux. Therefore, optical and acoustic sensors are essential for accurately measuring SSM in rivers. The optical–electric method not only accommodates various sediment types but also delivers precise results across different concentration ranges. Researchers must choose appropriate sensors according to the sediment characteristics and particle concentration in their study area. For example, the Campbell OBS-5+ measures from 0 to 50 g/L for clay and mud mixtures, while its range extends to 200 g/L for sand [29]. Based on the above problems, this paper focuses on the research and development of a new photoelectric sand meter (HHSW·NUG-1), verified through both theoretical R&D and practical application examples.

2. Instrument Description

2.1. Principle

Conventional photoelectric SSM meters operate based on the principle of light extinction in muddy water [30]. This principle states that as parallel light passes through a uniformly dispersed SSM suspension in water, its intensity diminishes due to absorption and scattering by the solid particles, resulting in only a portion of the incident light being transmitted. By applying Beer's law, we can calculate the transmitted light flux, allowing us to derive the SSM concentration in the water through relative measurements. It is important to note that this instrument primarily relies on relative determinations. While it measures changes in light transmittance and scattering intensity to infer SSM concentration, it does not provide absolute concentration values. Although calibration can yield absolute values in certain cases, the core operation remains relative measurement.

In this study, we utilize the photoelectric sand meter (HHSW·NUG-1), which employs a scattering light measurement method. It detects the intensity of scattered light at multiple angles relative to the incident light, based on the variations in light obstruction caused by solid

particles. These variations depend on factors such as particle concentration, size, shape, and composition. By establishing a core algorithm model that correlates light intensity with SSM concentration, we enhance measurement accuracy. This instrument combines scattered light (forward and backward scattering) and transmitted light detection. However, maintaining a fixed distance between the transmitter and receiver to ensure sensor sensitivity across varying SSM concentrations can be challenging. To address this, our sensor system is designed for flexibility, dynamically adjusting the distance based on real-time SSM measurements. Furthermore, by employing a multi-angle backscattering method and advanced signal processing algorithms—including noise suppression, data filtering, and nonlinear correction—we effectively manage signal distortions caused by high SSM concentrations.

2.2. Composition, Parameters, and Carrier Platforms

The instrument comprises four main components: a host, a data acquisition terminal, a communication terminal, and acquisition software (Figure 1). Its housing is constructed from 304 stainless steel, ensuring corrosion resistance and anti-interference properties. The dimensions of the sensor are 380 mm (L) $\times$ 300 mm (H) $\times$ 170 mm (W), with a weight of 16 kg. Currently, the instrument features three distinct sensors—optical, temperature, and flow rate sensors—with the potential to incorporate pressure sensors in the future. The addition of a pressure sensor could significantly enhance the instrument's functionality by enabling real-time monitoring of water conditions, improving measurement accuracy, and facilitating multi-parameter data fusion. For example, the pressure sensor can detect changes in water pressure, indirectly reflecting water depth and flow velocity. In environments with substantial flow variations, it provides essential data for dynamic adjustments, allowing the instrument to better adapt to diverse aquatic conditions. Furthermore, integrating pressure, light intensity, and SSM concentration data can lead to the development of more sophisticated algorithmic models, optimizing signal processing by refining noise suppression and data filtering strategies to enhance measurement stability in complex environments. Each sensor within our probe has been optimized for specific concentration ranges. These sensors possess different sensitivities and dynamic ranges to accommodate the measurement requirements of suspended sediment matter across varying concentration levels, from low to high. The LCD screen displays the data in real time, and the acquisition terminal is capable of collecting and backing up the data at regular intervals. The communication terminal supports a variety of transmission methods, including direct data connection, Beidou satellite, and 4G/5G network. The collection software system, designed with a B/S (browser/server) framework, facilitates system settings and data queries via a browser, ensuring easy maintenance and strong compatibility. It operates directly on the Windows platform without installation. In China, measurement data are typically uploaded to a designated server through its built-in data collection system, either a cloud server provided by the manufacturer or a locally set up server (Figure S1). For applications abroad, data collection solutions can rely on internet connectivity to transmit data in real time to a specified server or periodically upload it to a remote database. It can process, display, summarize, and set parameters for data such as SSM content and temperature, and can save data at regular intervals. The software has a graphical human–computer interaction interface, can intuitively display the data process and a real-time view of historical data, and generate data reports. The primary operational procedure entails the following (Figure S1): (1) Instrument setup and calibration to ensure its proper functioning. (2) Parameter configuration and detection of scattered light intensity using sensors. (3) Collected data undergo processing and analysis, potentially involving calibration and filtering, and are ultimately transformed into a visual format. (4) The instrument delivers measurement results, typically displayed numerically or transmitted to a computer or other devices via data interfaces. (5) Upon completion of all measurement tasks, the instrument

is properly shut down, followed by necessary cleaning and maintenance procedures. The exceptional performance achieved by this instrument in calibration testing can be attributed to its precision-engineered data acquisition chain. This chain comprises highly sensitive optical sensors, low-noise signal amplifiers, high-resolution analog-to-digital converters, optimized digital signal processing, and precise calibration techniques.

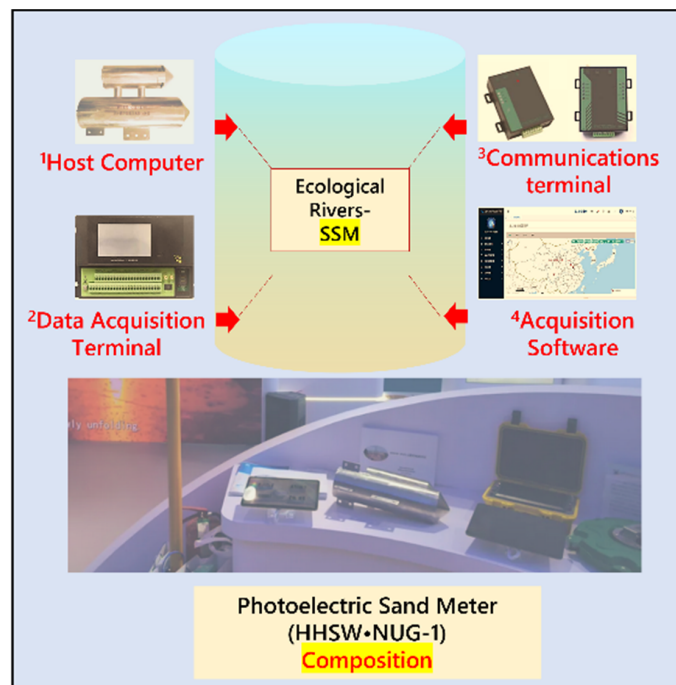


Figure 1. Photoelectric sand meter (HHSW-NUG-1) instrument composition. Superscript 1–4 represents host computer, data acquisition terminal, communications terminal and acquisition software respectively.

Moreover, Table 1 provides a detailed overview of the fundamental parameters of the instrument and the carrying platform. Specifically, the three primary types of carrying platform encompass leadfish carrying, column vertical mounting, and buoy mounting. The emission wavelength of the instrument typically falls within the visible light spectrum, commonly in the red or green wavelengths. Meanwhile, the emission power generally ranges from a few to several tens of milliwatts. During the measurement process, light is emitted along a single axis, employing forward scattering and/or lateral scattering, typically along the vertical or slanting direction relative to the water body. The calibration of the instrument centers on recreating standard SSM concentration fields in the laboratory using a mechanical automatic stirring device, along with a sampling apparatus, to evaluate the uniformity of these fields. The SSM concentration measurement device is positioned within these standard sediment concentration fields, and calibration is achieved by comparing the standard sediment values with the fitted values obtained from segmented fitting curves. This process involves generating the standard sediment concentration fields, placing the measurement device, acquiring and fitting the data, and optimizing the calibration process. Initially, the mechanical stirring device is used to create uniform and precisely controlled standard SSM concentration fields. The optical sediment measurement device is then placed within this field for real-time measurements. The SSM concentration data obtained are processed using segmented fitting curves to enhance accuracy and interpretability. Subsequently, we compare the standard sediment concentration values with the fitted measurement values to assess the measurement accuracy of the instrument. Finally, analyzing the discrepancies between these values helps identify systematic errors and optimize the instrument's settings, thereby enhancing its reliability for practical applications. Furthermore, we have focused

on the specialized development of the instrument's core optical–electronic components and sampling control modules. Emphasis has been placed on researching the sampling mechanism and core algorithms to address the limitations of traditional optical–electronic sediment measurement methods regarding flow rate adaptability and sediment measurement range. Our approach comprises six key steps: (1) Requirement analysis: A clear understanding of the instrument's design objectives and sediment sampling measurement scenarios, along with performance indicators and functional requirements. (2) Selection of optical and electronic components involves the rational selection and optimization of light sources, light receivers, and optical path design to ensure accurate measurement of sediment concentration across varying water quality conditions. The instrument primarily utilizes high-power blue LEDs as the light source and high-sensitivity photodiodes as the light receivers. (3) Hardware design and optimization encompass circuit design, sensor layout, and mechanical structure development. This includes designing waterproof and shock-resistant hardware to meet the demands of specific measurement environments, such as underwater operations and high flow rate conditions. (4) The sampling control module manages the sampling process, allowing for the setting and adjustment of parameters like sampling time, frequency, and quantity, along with the design of associated control algorithms and logic. (5) Study and optimization of the sampling mechanism involve theoretical analysis of sampling principles, hydrodynamic simulation, and experimental validation. This research aims to address the limitations of traditional optical–electronic sediment measurement methods regarding flow rate adaptability and sediment measurement range, thereby enhancing accuracy and stability through improved sampling mechanisms. We utilize a sealed polycarbonate housing with high-quality sealant at the joints to prevent moisture ingress. Waterproof connectors and plugs are designed to ensure the safety of all electrical connections. Additionally, shock resistance is achieved by incorporating damping materials, such as rubber pads, to mitigate external impacts on internal components. A robust mechanical structure and reinforced bracket design further enhance instrument stability in high-flow and turbulent environments. (6) Research and development of core algorithms includes data processing algorithms, calibration algorithms, and inversion algorithms. Due to the novelty and initial application of this instrument, we are unable to fully present the core algorithms of the data. However, we have planned a comprehensive survey of hydrological stations in other regions next summer, which will provide more data and enhance our chances of obtaining permission for the core algorithms.

Table 1. Basic parameters of photoelectric sand meter (HHSW·NUG-1).

Type	Parameters	Setpoints/Ranges	Carrier Platforms
Photoelectric sand meter (HHSW·NUG-1)	Electricity supply	DC12V, solar panel/utility power available	Leadfish carrier
	Probe operating temperature	0~50 °C	
	Working depth	20 m, beyond which the range can be customized according to the water depth	Column vertical installation
	Sand measurement range	0.001~700 kg/m ³	
	Systematic error	<±1%	
	Random error	<±10%	
	Standard deviation	<5%	Buoy mounted
	Random uncertainty	<10%	
	Signal feeder length	100 m	
	recording period	Customized, 6 min flood period recommendation	
	Recommended conversion factors	1.5634, hydrological stations need to be compared for application	
	Power wastage	Whole machine ≤ 150 mA	
	Preheating time	10 s	

3. Results and Discussion

This study conducted comparative testing of the photoelectric sand meter based on the “Specification for SSM Testing of Suspended Mass in Rivers” (National standards issued in 2015), incorporating both indoor tests and field investigations. In the indoor tests, we verified the instrument’s technical parameters and stability, developing a working model aligned with the SSM characteristics of the Yellow River. During the field tests, we analyzed the collected SSM data to accurately evaluate the instrument’s performance and established a working model suitable for flood reporting and data compilation. According to Article 2.2.5 of the specification, each SSM testing instrument must operate within a confirmed comparison range. If the SSM content exceeds this range, standard instruments should be used for sampling, and the conversion factor must be checked and corrected. Together, these approaches provide a comprehensive assessment of the photoelectric sand meter’s performance, ensuring reliable support for its practical application.

3.1. Indoor Comparative Measurements

For the test, we designed and fabricated a 304 stainless steel circular runway-type specimen device to simulate river environments. The device features a streamlined pipeline layout to promote smooth water circulation and is equipped with multiple stirring paddles evenly distributed along the pipeline to effectively mix water and sediment. The optimized paddle design ensures uniform mixing in various flow rates, preventing sediment from settling at the bottom. To address the challenges of uniformly moving water/sediment mixtures, we consider the flow characteristics and fluid dynamics during mixing. Significant energy is required to achieve homogeneous distribution, as the high density of the mixture increases the stirring difficulty, necessitating stronger driving forces. We utilize durable, corrosion-resistant stainless steel materials to prevent damage. Additionally, maintaining mixture uniformity at sampling points is crucial; therefore, we implement optimized stirring designs, real-time monitoring, and strategic sampling point selection. The device dimensions are 3000 mm (long side) by 2000 mm (short side), with a pipe diameter of 600 mm. A 3000 W high-speed motor drives the pump, controlled by a high-speed frequency converter to achieve a maximum flow rate of 5.02 m/s. The adjustable flow rate control system allows for different experimental requirements, while flow meters and sensors monitor the mixture status in real time, adjusting stirring intensity to maintain uniformity near sampling points. The device can simulate various river flow rates, discharge rates, and flow regimes, providing adequate time and channels for sediment mixing. For manual sampling, a horizontal sampler (1000 mL) is used, with samples collected at the probe depth. During the experiments, we set different flow rates, discharges, and sediment concentrations, resulting in 151 data sets. Flow rates are precisely controlled by a frequency converter, ranging from 0.1 to 5.02 m/s, while sediment concentrations are achieved by adding pre-calculated amounts of artificial sediment (SSM), targeting a range of 0.25 to 736.00 kg/m³. Prior to sampling, we ensure thorough mixing to achieve uniform distribution and monitor mixture consistency in real time. All experiments are conducted under identical environmental conditions, with operational parameters and environmental states recorded to ensure repeatability. Statistical methods are employed for data analysis to assess the impact of different conditions on the results, ensuring reliability. To enhance consistency, multiple replications and cross-validation are performed, identifying potential sources of error. These measures contribute to the high reliability of the 151 data sets, facilitating future experimental repetitions and result verification. Future improvements to the device will comprehensively consider various factors to enhance community understanding. The study results indicate a significant linear relationship between the SSM

content (y) from manual sampling and the SSM content (x) measured by the photoelectric sand meter: $y = 1.56x$ ($R^2 = 0.99$) (Figure 2).

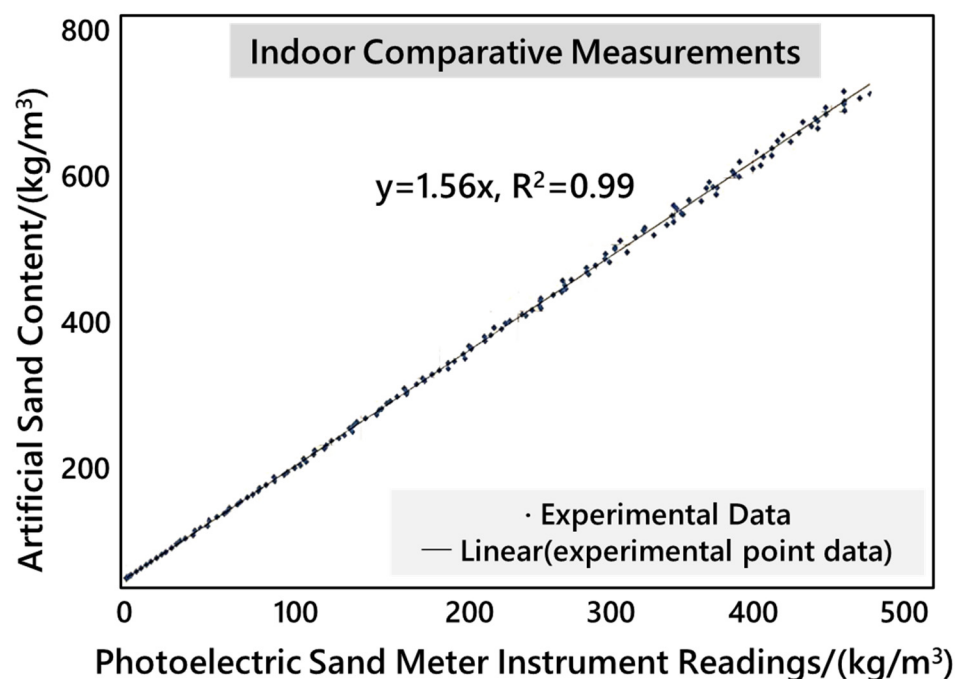


Figure 2. Laboratory photoelectric sand meter rate diagram (linear).

With a conversion factor (k) of 1.56, the systematic error, standard deviation, and maximum error are -0.15% , 1.60% , and 6.05% , respectively, while random uncertainty is 3.30% . The probe meets compliance with specifications through three validation tests. The accuracy of the probe's measurements relies on the quality of regressions between concentration values from aliquot samples and direct measurements. Statistical thresholds for these regressions align with Chinese regulations. The validation framework includes three key tests: the sign test, goodness-of-fit test, and numerical deviation test, which assess system bias, standard deviation, and random uncertainty per the "Hydrological Data Compilation Specification (2020 version)". This specification encompasses three main standards: "Technical Requirements for Reliability of Hydrological Instruments", "Basic Parameters and General Technical Conditions of Hydrological Instruments", and "Hydrological Patrol Devices". The photoelectric sand meter must comply with these standards to conduct the necessary tests. Details are provided as follows: (1) Sign Test: The sign test is conducted to determine if there is a statistically significant difference between the sample measurements and probe measurements. The threshold criterion is that the number of positive and negative signs should be approximately equal, with a deviation not exceeding 5% , ensuring that the probe measurements are unbiased. (2) Goodness-of-Fit Test: The goodness-of-fit test evaluates how well the regression line fits the data points obtained from the sample and probe measurements. The coefficient of determination (R^2) should be greater than 0.95 , indicating a very high correlation between the measured values and the regression model. (3) Numerical Deviation Test: The numerical deviation test quantifies the deviations between the sample measurements and the probe measurements. For calibration models, the random error in sediment concentration must be less than 5% . For field application validation, the random error should be less than 10% . The standards mandate that for establishing calibration models, the random error in sediment concentration must be less than 5% and the systematic error must be less than 1% . For field application validation, the random error in sediment concentration must be less

than 10%, the systematic error must be less than 1%, and the random uncertainty must be less than 10%. Through the optimization analysis, we found that when k is taken as 1.56, the systematic error, standard deviation, and maximum error are reduced to 0.00%, 1.60%, and 6.22% respectively, and the random uncertainty is 3.3%. This shows the three tests were passed, so, in the indoor test, it is recommended to use a conversion factor k of 1.56. It is important to acknowledge that, despite our efforts to minimize uncertainty in sediment measurement through device design and operation, factors such as microbubbles, water quality fluctuations, and the stability of light sources and detectors may still introduce interference. Therefore, optimizing device design and water flow paths can significantly mitigate the impact of these uncertainties on experimental results. For instance, the photoelectric sand meter should be installed in areas with relatively gentle water flow to avoid interference from vessels and trestles. In summary, we concentrated on the specialized development of core photoelectric components, the sampling control module, and other hardware. Our efforts focused on refining the sampling mechanism and core algorithms, overcoming traditional limitations in adapting to varying flow rates and SSM measurement ranges. This instrument is particularly well suited for environments with high SSM content and substantial flow rates. Its stability, calibration, measurement accuracy, real-time monitoring, data storage, and continuous operation meet the standards outlined in the “Specification for SSM Measurement in Rivers (National standards issued in 2015)”. This advancement significantly enhances riverine SSM monitoring techniques and serves as a valuable scientific reference for soil erosion and conservation.

3.2. Field Comparative Measurements

Using conversion coefficients obtained from laboratory tests as a reference, we aimed to improve their accuracy under real-world conditions. Field comparison tests were conducted at three hydrological stations to establish a stable and reliable model, ensuring precise and consistent measurements. Although the one-year data set is limited, initial implementation at these stations highlights the instrument’s effectiveness and value. This serves as a foundation for broader, long-term monitoring of suspended solids in key river systems.

3.2.1. Xiaolangdi Hydrological Station

Xiaolangdi Hydrological Station is located in Jitai Mountain Village, Henan Province, China (latitude $34^{\circ}55'16.1''$ N, longitude $112^{\circ}24'19.3''$ E), covering a watershed area of $694,221 \text{ km}^2$ [31]. As the outflow station of Xiaolangdi Reservoir, it is the second-largest water conservancy project in China and the last integrated hub in the mainstream of the Yellow River, playing a crucial role in flood control, soil and water conservation, and water resource management of the Yellow River [31].

Between autumn and spring of each year, Xiaolangdi Hydrological Station records relatively clear river water. However, during the June to September period, there are significant fluctuations in SSM content, which are mainly attributed to heterogeneous flow discharge from Xiaolangdi Reservoir at this time [32]. Given this background, we chose the summer month of July from 2020 to 2021 to conduct a comparison test with the following procedures: (1) Instrument installation: A trestle bridge was provided at Xiaolangdi Hydrological Station on the left bank 50 m downstream of the stream meter flow section, with a starting distance of 80 m near the single-SSM gauging station. The trestle bridge is equipped with a 100 kg leadfish winch, which is used to carry the instrument. During the test, we used a leadfish to suspend the photoelectric sand meter and placed the instrument at a depth of 0.50 m below the water surface. The leadfish winch and suspended photoelectric sediment gauge should be maintained in relatively stable positions, with the layout taking into account the flow conditions of the river and potential fluctuations.

During periods of high SSM content, it was ensured that the instrument was able to work continuously (Figure 3). (2) Manual sampling: The SSM content measured by a horizontal sampler (1000 mL) was used as the standard value. We sampled by suspending the sampler at the depth of the photoelectric SSM detector probe using the displacement method. The method involves determining the quality of concentrated muddy water samples and calculating sediment mass using specific formulas derived from computational methods. The main procedure entails weighing the concentrated muddy water sample in a specific-gravity bottle, measuring the temperature of the water inside the bottle, and calculating the sediment mass based on the known weight of the bottle with added clean water at the same temperature, along with the displacement factor obtained from preliminary experiments.

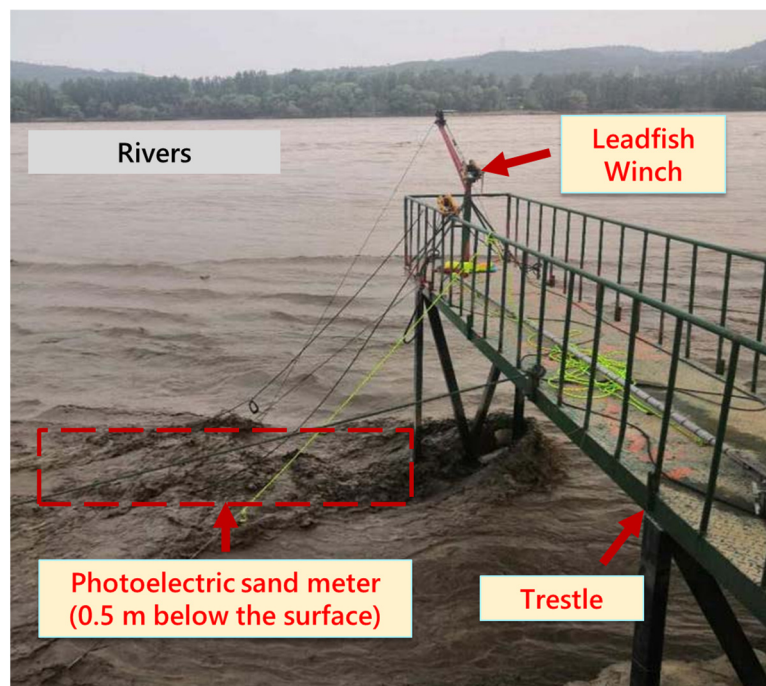


Figure 3. Trestle working platform at Xiaolangdi Hydrological Station.

Due to the periodic pulsating motion of sediment in rivers or water bodies during flow, which may be caused by fluid dynamic effects or terrain features, particularly under stable water flow conditions, the sediment concentration at a point within a cross-section fluctuates over time. It is not only influenced by flow rate pulsations, but is also related to sediment characteristics. The sediment concentration measured by the lateral sampler used in this study is instantaneous, with maximum pulsations. Typically, sediment pulsations are greater than flow rate pulsations because sediment movement depends on flow rate. Sediment movement requires reaching a critical flow rate to be initiated, and when the flow rate is below a certain threshold, sediment settles. Therefore, sediment movement relies on intervals of relatively high flow rate, resulting in higher frequencies of initiation and settling compared to flow rate pulsations. In order to minimize the effect of SSM pulsation, no less than two samples were taken at a time, and the sampling volume error did not exceed 10.00%. An electronic balance of 0.001 g sensitivity and specific-gravity bottles of different volumes were used for this comparison test.

Figure 4 illustrates the flow rate and SSM content comparison process, along with the distribution of comparison points, at Xiaolangdi Hydrological Station in July 2020. From 4 to 20 July, flow rates varied between approximately 1400 and 4600 m³/s, while SSM content measured by the photoelectric sand meter ranged from 0.002 to 348.00 kg/m³, with the lowest value recorded at 1:18 on 4 July and the highest at 9:48 on 7 July, indicating a trend of

rapid increase followed by a decrease. A total of 38 samples were collected between 8 July, 16:45, and 19 July, 8:00. The maximum SSM content from manual sampling was 65.80 kg/m^3 , with a minimum of 6.98 kg/m^3 . Notably, the maximum flow rate corresponding to the highest SSM content was $3460.00 \text{ m}^3/\text{s}$, exceeding the maximum flow rate of $3600.00 \text{ m}^3/\text{s}$ during the measurement period. To accurately assess the SSM measuring instrument's precision, it is crucial to conduct a comparative analysis of SSM values obtained from manual sampling at the same depth points. Mixing measurement points in relation to the average SSM content could obscure whether the instrument's accuracy is lacking or if the points are poorly representative, complicating the timely application of the SSM meter in practical settings. In addition, SSM samples require a minimum of 24 h for settling and processing, resulting in data that lags behind real-time sediment content in rivers by at least 24 h. This delay compromises the timeliness of hydrological SSM monitoring data, which is insufficient for flood control decision-making. While various real-time SSM meters have been tested at hydrological stations, their high production costs and inefficacy in highly SSM-laden rivers limit their application. In contrast, the photoelectric sand meter (HHSW·NUG-1), equipped with photonic sensors designed for high SSM content and flow rates, effectively addresses these technical challenges.

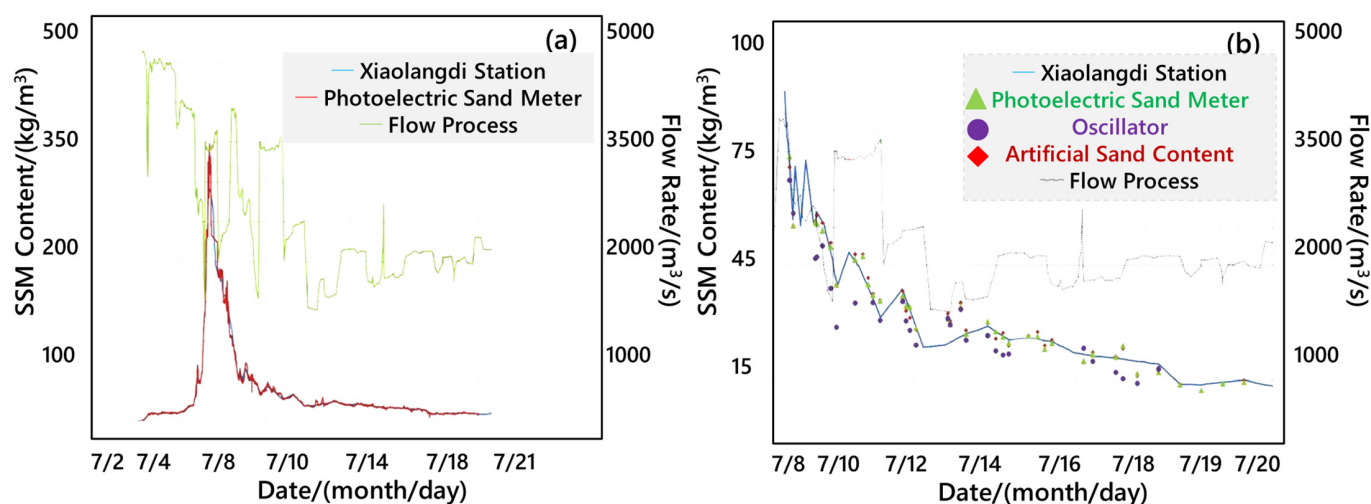


Figure 4. Comparison of sand content (a) and flow (b) at Xiaolangdi Hydrological Station and distribution of comparison points in July 2020. The white dotted line in (b) is the flow rate.

In July 2021, 38 comparative measurements were conducted at Xiaolangdi Hydrological Station from 12:45 on 4 July to 14:00 on 8 July. During this period, the maximum SSM content monitored by the photoelectric sand detector was 375.00 kg/m^3 , and the maximum flow rate was $2980.00 \text{ m}^3/\text{s}$, with the flow rate at the measurement point remaining at 2.00 to 3.00 m/s (Figure 5). Considering the slight difference in sampling time between manual and photoelectric sand meters, it may lead to a large difference between the two. There were more periods with smooth SSM content changes than gauging points, while there were fewer periods with drastic SSM content changes than gauging points. It should be noted that during floods, significant variations in flow velocity and water level lead to substantial fluctuations in sediment suspension and deposition, causing rapid changes in SSM concentrations. In conditions of high flow and high SSM load, the long-term stability of the instrument faces challenges. To address this, we optimized the instrument parameters, set a 6 min recording interval during floods, and implemented real-time calibration. Especially under high flow conditions, we regularly adjusted the instrument's measurement parameters (e.g., sensitivity, sampling frequency) to adapt to varying hydrological conditions. Additionally, the wide measurement range allows the instrument to handle broader

SSM concentration changes, enhancing its stability during floods. Comparisons between manual and instrument measurements showed highly consistent results, demonstrating the reliability of the instrument's stability during floods.

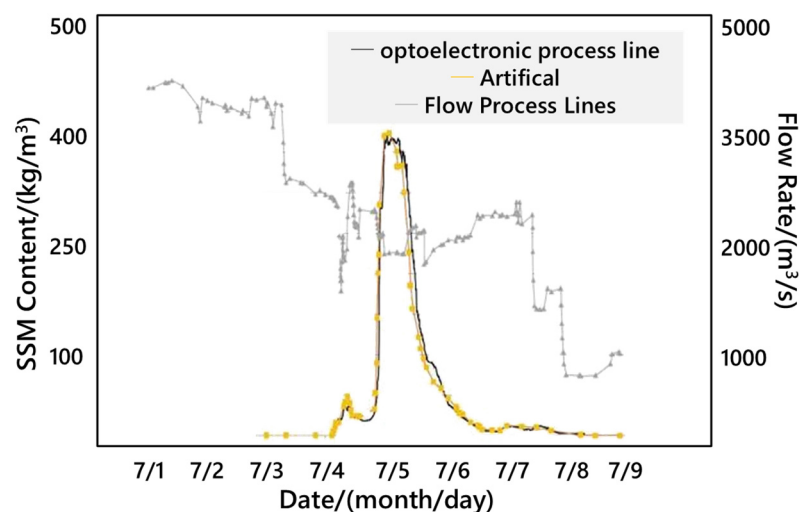


Figure 5. SSM content at Xiaolangdi Hydrological Station and distribution of comparison points in July 2021.

Subsequently, we performed a point-to-point linear correlation with polynomial relationships for the full ratio data (Figure 6).

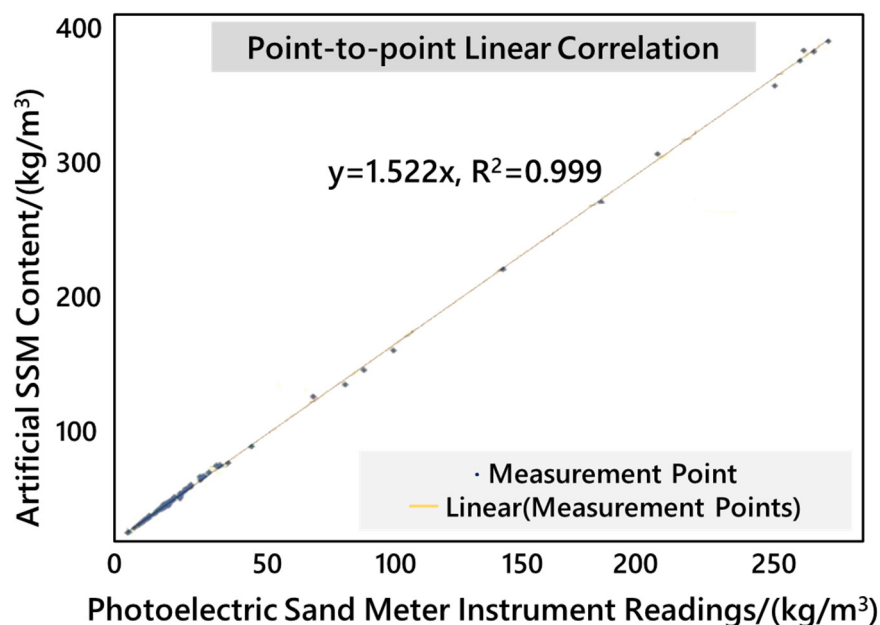


Figure 6. Correlation diagram of all comparative measurements at Xiaolangdi Station (linear).

The results indicated that the three tests failed with a transformation coefficient k_k of 1.52. After optimization, the tests passed with k_k set to 1.55, resulting in a systematic error of -1.37% , a standard deviation of 4.40% , and random uncertainty of 8.90% . A systematic deviation was observed when the SSM content exceeded 50.00 kg/m^3 , being small for the range of $50.00\text{--}100.00 \text{ kg/m}^3$ and large for values greater than 100.00 kg/m^3 . Polynomial correlation analysis yielded a systematic error of -1.77% , a standard deviation of 0.50% , and random uncertainty of 1.10% . The significant difference in SSM content around 50.00 kg/m^3 necessitates separate analysis. Based on the historical data from Xiaolangdi Hydrological

Station and the stability of the photoelectric sand meter, we categorized the SSM content into two groups: below and above 50.00 kg/m^3 , establishing distinct correlations for each.

The choice of 50.00 kg/m^3 as the threshold for SSM content is based on five key aspects: (1) Significant variation in systematic deviation; experiments show that when SSM content exceeds 50.00 kg/m^3 , systematic deviation changes markedly—small between 50.00 and 100.00 kg/m^3 and large beyond 100.00 kg/m^3 —indicating this is a critical threshold impacting measurement accuracy. (2) Data distribution characteristics; statistical analysis reveals that 50.00 kg/m^3 serves as a boundary, illustrating distinct response characteristics and measurement precision of the photoelectric sand meter in different concentration ranges. (3) Facilitation of correlation establishment; categorizing SSM content into two groups simplifies the development of correlation models, enhancing model fit and clarity in data analysis by reducing confusion. (4) Relevance to practical applications; considering the changing characteristics of SSM content under various hydrological conditions at Xiaolangdi, this threshold aids in hydrological monitoring and management, providing insights into photoelectric sand meter performance. (5) Improved result reliability; grouping enhances the reliability of results, accounting for potential differences in sediment behavior within the distinct concentration ranges below and above 50.00 kg/m^3 , thereby reducing uncertainty in the analysis. In summary, the selection of 50.00 kg/m^3 as the threshold for SSM content is supported by experimental statistical analysis and practical application considerations. However, the research community should adjust this threshold based on specific experimental and survey conditions.

(1) Analysis of coefficients with SSM content less than 50.00 kg/m^3 : There were 59 measurements with SSM content less than 50.00 kg/m^3 , including 33 times in 2020 and 26 times in 2021. Through the line fitting relationship, it was determined that the conversion coefficient k was 1.59 for 2020 and 1.60 for 2021, and the relative error between the two was 0.25%, which was by the Specification for River SSM Tests. The conversion coefficient obtained by fitting the two years of data together was 1.59, with an R^2 of 0.99 (Figure 7). Using this coefficient could not pass the three tests, and after optimization analysis, the test was passed when 1.59 was used for k . The test procedure and results are detailed in Tables S1 and 2.

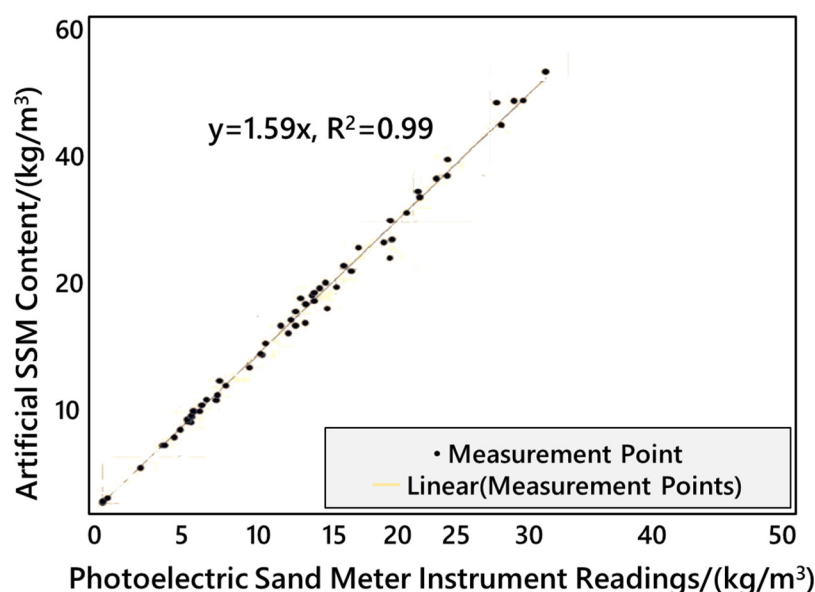


Figure 7. Conversion factor rate plot of photoelectric sand meter at Xiaolangdi Station (SSM content less than 50.00 kg/m^3).

Table 2. Relational test and statistical indicators of error at Xiaolangdi Station (sand content < 50 kg/m³).

Items	Calculated Value	Permissible Value	Qualified or Not
Symbol test	0.00	1.96	Yes
Fairness test	−2.232	1.64	Yes
Deviation from numerical test t	0.65	2.02	Yes
Systematic error	0.4%	±2%	Yes
Standard deviation Se	4.3%	9%	Yes
Random uncertainty	8.7%	18%	Yes

(2) Analysis of the coefficient of SSM content greater than 50.00 kg/m³: There were 17 measuring points with SSM content greater than 50.00 kg/m³, including 5 times in 2020 and 12 times in 2021. Among them, the SSM content was more than 300.00 kg/m³ 5 times, and the maximum value was 375.00 kg/m³. The SSM meter coefficient was 1.52 and R² was 0.99, which passed the test. The specific test process and results are shown in Tables S2 and 3.

Table 3. Relational test and statistical indicators of error at Xiaolangdi Station (sand content > 50 kg/m³).

Items	Calculated Value	Permissible Value	Qualified or Not
Symbol test	0.97	1.96	Yes
Fairness test	0.25	1.64	Yes
Deviation from numerical test t	0.00	2.11	Yes
Systematic error	−0.50%	±2.00%	Yes
Standard deviation Se	2.90%	9.00%	Yes
Random uncertainty	5.80%	18.00%	Yes

3.2.2. Xixian Hydrological Station

Xixian Hydrological Station is located on the left bank of the mainstream of Huaihe River in Qiaolou Street, Xixian County, Henan Province, China, with geographic coordinates of 32°19′26.6″ N latitude and 114°44′20.9″ E longitude, and a basin area of 101,900 km². As one of the national key hydrological stations, it has important monitoring and control duties in the upper reaches of the main stream of Huaihe River. The average annual runoff is about 3.690 billion cubic meters, the average annual SSM transport is 2.20 million tonnes, and the average SSM content is 0.60 kg/m³. The geographic location of the station and its strategic importance in the upper reaches of the mainstream of the Huaihe River has made it an important object of study in the fields of hydrological research and water resource management.

The experiment was carried out in November 2020, using the same instrumentation installation method as at the Xiaolangdi hydrographic station. At this station, we used the one-point method at the water surface as a single-sample artificial sampling method, and a total of 30 comparative measurements were made. Specifically, the method involves manually collecting individual samples for analysis to obtain sample data for specific time periods or locations. The artificial maximum SSM content was 0.03 kg/m³ and the minimum artificial SSM content was 0.01 kg/m³. The rate-setting diagram of the conversion factor of the photoelectric sand meter is shown in Figure 8, where k is 1.47, but it does not satisfy the test criteria. In order to optimize the adjustment, we carried out a similar procedure. Specifically, the optimization of conversion coefficients is presented in Table S3. The procedure is identical to the optimization previously performed at Xiaolangdi Hydrological Station. The detailed steps include data collection, parameter calibration, and validation of the model results. The test results are shown in Table 4, and finally all three tests were passed when k was 1.45, with a systematic error of 0.10%, a standard deviation of 8.00%, and a random uncertainty of 15.90%. It is important to note that we

conducted large-scale experiments at the major hydrological station (Xiaolangdi), but the number of comparative measurements at Xixian Station was relatively limited, which may impact the results. We recommend addressing this limitation in future investigations by conducting more extensive studies to validate and optimize the application potential of the photoelectric sand meter.

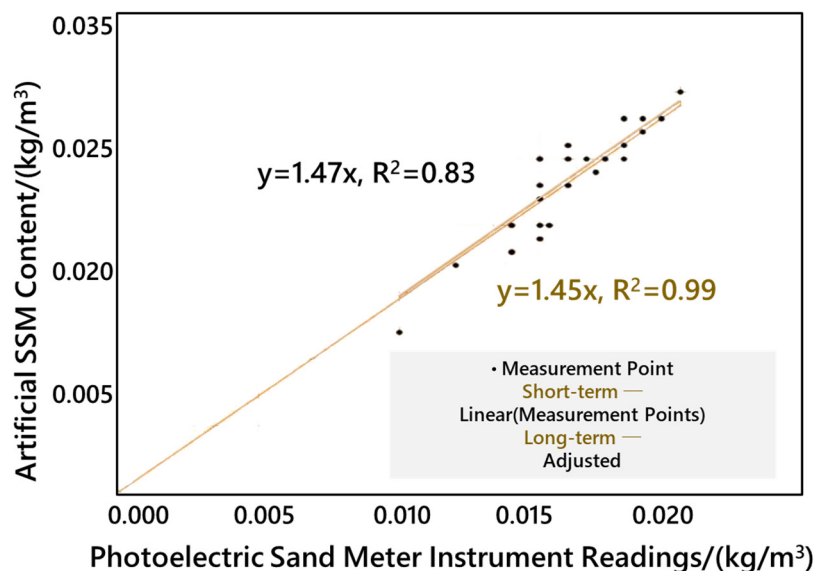


Figure 8. The rate-setting diagram of the conversion factor of the photoelectric sand meter.

Table 4. Relational test and statistical indicators of error at Xixian Station.

Items	Calculated Value	Permissible Value	Qualified or Not
Symbol test	0.55	1.96	Yes
Fairness test	0.37	1.64	Yes
Deviation from numerical test t	0.00	2.11	Yes
Systematic error	0.10%	±2.00%	Yes
Standard deviation Se	8.00%	9.00%	Yes
Random uncertainty	15.90%	18.00%	Yes

It is worth noting that the maximum error is only 0.003 kg/m³ due to the small SSM content at this station, but the maximum relative error is 21.00%. This may be due to the large influence of fluctuations in dissolved matter in the water, balance sensibility, balance level status, sampling errors, and incidental errors such as filter paper. In future studies, we will further optimize the experimental design to reduce the effects of these errors and ensure the accuracy and reliability of the data.

3.2.3. Huayuankou Hydrological Station

Huayuankou Hydrological Station is located in Huayuankou Village, Zhengzhou City, Henan Province, China, with geographic coordinates of 34°54′20″ N latitude and 113°40′49″ E longitude, and a controlled catchment area of 730,036 km². As a national basic hydrological station, a national important hydrological station, and one of the important control stations of the Great River, the station adopts the single-sample sampling method of the mainstream three-line plumb line mixing (2:1:1). The photoelectric sand meter was installed on the test platform at the Lixi River cross-section in the second half of 2019 to provide uninterrupted monitoring of the station's suspended mass SSM content.

The downstream flow of the Yellow River is a wandering trough with a large oscillation, resulting in unstable representativeness of the monitored SSM content at the test platform of Huayuankou Station. Periodic oscillations or fluctuations occur in river

channels or waterways, typically caused by interactions between fluid flow and terrain features. The river channels are characterized by wide and shallow cross-sections, chaotic water flow, rapid movement and deformation of sandbars, and unpredictable shifts in the main channel position. Rivers of this meandering type are often in a state of intense sediment deposition, leading to continuous elevation of the riverbed. The main reasons for the formation of meandering rivers include loose bank sediments prone to erosion and widening, high sediment loads leading to bed aggradation, and significant fluctuations in flow rates due to sudden floods and drops in water levels. During the high-water period, the representativeness is better, but during the low-water period, the representativeness is lower and even maybe off-stream. By comparing the artificial and photoelectric sand meter-monitored SSM content process lines during the 2020 and 2021 floods, the artificial SSM content in the figure is based on the data compiled from several single-break SSM coefficients, which have been converted into section-averaged SSM content. In contrast, there is only one photoelectric sand meter coefficient.

In the figure, the trends of the two SSM content monitoring values are similar, but the photoelectric sand meter values are larger at the SSM peaks and smaller than the manual monitoring values before and after the SSM peaks. This may reflect the effect of channel oscillations on SSM content monitoring and needs to be taken into account in data analysis and interpretation to ensure the accuracy and reliability of the results. Additionally, for hydrological stations using the plumb line mixing method for single-sample collection, the conversion coefficients should first be analyzed based on the plumb line average SSM content at relative water depths of 0.00, 0.20, or 0.60. The probe of the SSM meter should then be positioned accordingly. Within the SSM meter, the integrated coefficient K can be preset as $K = k \cdot K1$, where k is the conversion coefficient of the photoelectric sand meter and $K1$ is the coefficient of the converted plumb line average SSM content at the measurement point. For hydrological stations without SSM analysis tasks, the instrument can be positioned at a predetermined relative depth during SSM transport rate tests. The average SSM content along the vertical line is then calculated according to the “Specification for SSM Test of Suspended Matter in Rivers (National standards issued in 2015)”, allowing for the determination of the SSM transport rate and average SSM content of the section. In contrast, gauging stations with SSM analysis tasks should conduct the transport rate test following the original program, with manual sampling performed during single-sample surveys to ensure SSM analysis requirements are met.

3.2.4. Other Description

In the comparative analysis conducted at the Xiaolangdi Station, sediment samples were not subjected to particle analysis individually; rather, they were evaluated based on the particle gradation of the single sand present at the station. Throughout the comparison test, the sediment exhibited a grain size distribution spanning from 0.00 to 1.00 mm, with median grain sizes ranging from 0.01 to 0.08 mm and average grain sizes ranging from 0.01 to 0.09 mm. Additionally, the water temperature during testing varied between 25.80 and 27.80 °C. Furthermore, our observations revealed a positive correlation between sediment grain size and sand content, with the average grain size of sediment ranging from 0.02 to 0.03 mm when the SSM content reached 50.00 kg/m³. In our experimental investigation at the Huaihe River Xixian Hydrological Station, we determined the coefficient k to be 1.46, with measurements conducted specifically during November. The maximum observed SSM content was 0.03 kg/m³, indicating relatively fine sediment particles. These findings suggest that variations in sediment particle size significantly influence the conversion factor k .

Laboratory experiments are characterized by strong control and fewer variables, whereas field hydrological stations are subject to complex and variable river conditions

(e.g., flow velocity, sediment characteristics, and interference factors). As a result, the measurement error in the laboratory (1%) is lower than that observed in field surveys (5%). The comparative error between the two scenarios ranges from 1% to 5%, which is within a controllable range. It is imperative to acknowledge that the limited scope of water level fluctuations observed during the testing period precludes definitive conclusions regarding the influence of water temperature on the conversion factor k . To elucidate this matter, future investigations must encompass a broader spectrum of environmental variables. By incorporating a more comprehensive range of factors, including water temperature, we can better discern any potential impact on the conversion factor k . Furthermore, the size of suspended particulate matter is a crucial parameter in instrument calibration and utilization, offering insight into the potential capabilities of the instrument. This study primarily presents the range of grain size, median grain size, and average grain size of sediment at hydrological stations. Future research endeavors should comprehensively showcase the complete results of grain size distribution, thereby providing vital references for its application in other hydrological stations or regions. We have diligently obtained the standard deviations of particle size distributions from laboratory experiments and Xiaolangdi Hydrological Station, which are 1.70% and 3.60%, respectively. These findings are important for the accurate interpretation of experimental results and their application in hydrological studies. Furthermore, this preliminary evaluation of the optical sediment monitoring instrument still has several aspects that require improvement, such as the influence of environmental variables, diversification of experimental conditions, and data analysis methods. For instance, the effect of environmental factors (e.g., humidity) under varying meteorological conditions on measurement accuracy, and the instrument's performance across a broader range of hydrological stations and diverse geographical settings, need to be further explored. The accuracy and stability of data processing algorithms also play a crucial role in ensuring reliable measurements, requiring appropriate algorithms to process sensor data effectively. Consequently, the current study is limited in scope, with relatively uniform experimental conditions. Future research should expand the scope to include more hydrological stations and river sections with varying characteristics, and increase the diversity of experimental conditions, such as different seasons, meteorological conditions, and water levels, to enhance the generalizability and reliability of the results. In addition, addressing the impact of sediment characteristics (e.g., size and gradation) on measurement results is crucial. This requires in-depth standardized calibration experiments, the incorporation of auxiliary parameters, and the optimization of measurement settings, all of which are actively being pursued by our team. Therefore, the photoelectric sand meter (HHSW·NUG-1), successfully developed in 2020, is the only instrument in China featuring an ultra-wide measurement range. It received a utility model patent in 2021 and has been applied in SSM transport monitoring in the Yellow River for three consecutive years. This instrument not only ensures safety, stability, and ease of installation, but also represents a significant innovation in SSM measurement.

4. Conclusions

The HHSW·NUG-1 photoelectric sand meter quantifies SSM in water samples using scattered light principles. It is designed for high SSM levels and flow rates, featuring specially developed core photoelectric components, a sampling control module, and optimized algorithms to ensure reliability in extreme conditions.

- (1) Laboratory tests show a measurement range of 0.00–730.00 kg/m³, while this pilot study focused on 0.00–375.00 kg/m³, meeting hydrological station testing and online monitoring requirements.

- (2) Analysis of two years of data from Xiaolangdi Hydrological Station revealed that for SSM content $\leq 50.00 \text{ kg/m}^3$, the relationship between manual measurements and meter readings is as follows: manual value = $1.59 \cdot \text{SSM meter value}$. For SSM levels $> 50.00 \text{ kg/m}^3$, this adjusts to the following: manual value = $1.52 \cdot \text{SSM meter value}$. Comparisons across three hydrological stations indicated a systematic error of less than 1.00%, meeting the “Basic Parameters and General Technical Conditions of Hydrological Instruments (2017 version)” and the “Specification for Suspended Matter SSM Tests in Rivers (National standards issued in 2015)”.
- (3) The instrument’s standard deviation is within 5.00%, and random uncertainty is below 10.00%, aligning with the “Hydrological Data Compilation Specification [33]” for high-precision stations regarding water level flow and single-SSM break relationships. Reliability and accuracy are further validated through goodness-of-fit tests, sign tests, and numerical deviation tests.

Overall, the application of this photoelectric sand meter model at Xiaolangdi and two other hydrological stations is stable and reliable, showing considerable potential for wider use in hydrological research and applications.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w17010026/s1>, Table S1: Xiaolangdi Station photoelectric sand meter conversion factor test (sand content less than 50 kg/m^3); Table S2: Xiaolangdi Station photoelectric sand meter conversion factor test (sand content greater than 50 kg/m^3); Table S3: Xixian Station photoelectric sand meter conversion factor test; Figure S1: The HHSW-NUG-1 photoelectric sand meter features a data collection interface (a), parameter settings (b), and sediment concentration display interface (c).

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