Real-time measurements of suspended sediment concentration and particle size using five techniques

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Abstract. Fine sediments are important in the design and operation of hydropower plants (HPPs), in particular with respect to sediment management and hydro-abrasive erosion in hydraulic machines. Therefore, there is a need for reliable real-time measurements of suspended sediment mass concentration ($SSC$) and particle size distribution (PSD). The following instruments for $SSC$ measurements were investigated in a field study during several years at the HPP Fieschertal in the Swiss Alps: (1) turbidimeters, (2) a Laser In-Situ Scattering and Transmissometry instrument (LISST), (3) a Coriolis Flow and Density Meter (CFDM), (4) acoustic transducers, and (5) pressure sensors. LISST provided PSDs in addition to concentrations. Reference $SSC$s were obtained by gravimetrical analysis of automatically taken water samples. In contrast to widely used turbidimeters and the single-frequency acoustic method, $SSC$s obtained from LISST, the CFDM or the pressure sensors were less or not affected by particle size variations. The CFDM and the pressure sensors allowed measuring higher $SSC$s than the optical or the acoustic techniques (without dilution). The CFDM and the pressure sensors were found to be suitable to measure $SSC \geq 2 \text{ g/l}$. In this paper, the measuring techniques, instruments, setup, methods for data treatment, and selected results are presented and discussed.

1. Introduction

In the design and operation of hydropower plants (HPPs), fine sediments are important with respect to reservoir sedimentation, hydro-abrasive erosion of hydraulic machines (pumps and turbines) and related countermeasures. The management of fine sediments, which make up the major part of the sediment yield, has economic and ecological implications. For a better understanding and management of sediment-related processes, in-situ measurements of suspended sediment mass concentration ($SSC$) and particle size distribution (PSD) with high temporal resolution are required. For many applications, continuous real-time measurements are an advantage or even a requirement to support short-term decision making, e.g. for temporary shut-downs of turbines during floods or the control of bottom outlet gates during reservoir flushing operations.

Many techniques for suspended sediment monitoring (SSM) in various application cases are available and described in literature [1] [2]. However, there are specific requirements for SSM systems at HPPs. For turbine erosion mitigation, reliable measurements of higher $SSC$s (up to e.g. 100 g/l), especially of coarser particles, are important – preferably with information in particle sizes.
This paper reports on the investigation of various measuring techniques for continuous SSM in a recent field study at the high-head HPP Fieschertal in the Canton of Valais, Switzerland. The study was conducted in the frame of a research project on hydro-abrasive erosion on Pelton turbines [3]. Other parts of the project are treated in companion papers, e.g. [4] and [5]. The HPP is situated downstream of a highly glaciated catchment. The water in the power waterway contains mainly silt particles with an average SSC of 0.5 g/l, rising several times a year above 5 g/l.

The following instruments have been used to continuously measure SSC: (1) turbidimeters, (2) a ‘Laser In-Situ Scattering and Transmissometry’ instrument (LISST) without dilution chamber, (3) a Coriolis Flow and Density Meter (CFDM), (4) acoustic transducers, and (5) pressure sensors. Reference SSCs were obtained by gravimetrical analysis of automatically taken bottled water samples. In addition, PSDs were obtained from LISST. The performance of the first four measuring techniques has been briefly discussed in [6]. To the knowledge of the authors, the LISST, the CFDM and the pressure-based technique have not been used in parallel for SSM at HPPs so far.

In the first part of this paper the measuring techniques are reviewed. Then the instruments, setup and methods for data treatment are described. Finally, selected results are presented and discussed with respect to the performance of the measuring techniques.

2. Measuring techniques

2.1. Turbidimeters
Turbidimeters are easy to handle, inexpensive and so far most popular for SSM. They measure either scattering or attenuation of emitted light. Measured turbidities are usually converted to SSCs based on the results of gravimetrical analysis of bottle samples (e.g. [7]). Turbidity does not only depend on SSC, but also on particle size, shape and color [8]. Hence, biases in SSCs obtained from turbidimeters are to be expected if these particle properties change over time and are not correlated with SSC.

2.2. Laser diffraction and LISST
Besides sieving, hydrometer and image analysis, laser diffraction is widely used for PSD analysis in laboratories. Portable laser diffraction instruments for in-situ PSD and SSC measurements have become available under the trademark ‘LISST’ since about 15 years [9]. In LISST instruments, the scattering (diffraction) of a laser beam at small angles (< 9°) and its attenuation, caused by suspended particles, are measured. From these light intensities, the particle volume concentrations in 32 logarithmically spaced size classes (also called size bins) are computed with the software provided by the manufacturer. From the volume concentrations of each size bin, the PSD and the total volume concentration (TVC) are determined. In a last step, the TVC is converted to SSC (concentration by mass).

LISST instruments allow measuring SSCs up to a limit which is given by a minimum optical transmittance. At high turbidity, SSCs in rivers and HPPs may temporarily exceed the measuring range of most LISST models. To measure also higher SSCs, a special type of LISST device with a dilution chamber is available [10].

2.3. Vibrating tube densimetry and CFDMs
Higher SSCs can be measured via the density of the water-particle mixture. In the process industry, continuous in-line density measurements are commonly done with ‘Vibrating Tube Density Meters’ (also called ‘oscillating U-tubes’) or ‘Coriolis Flow and Density Meters’ (CFDMs). In the first type of instruments, the density is measured based on the measuring tubes’ natural frequency, which is reduced as the mass of the fluid in the tubes increases. In CFDMs, the Coriolis effect is exploited to measure the mass flow rate; the density measurement is also based on the tubes’ natural frequency [11]. So far, CFDMs have been rarely used for SSM [12].

CFDMs overestimate the density and thus SSC if debris, sediment or biofilms accumulate inside the measuring tubes. The density and SSC may be underestimated if the measuring tubes are eroded or if so-called phase decoupling occurs in particulate fluids [13]. In the latter case, particles do not...
strictly follow the motion of the fluid in the oscillating tubes. This effect on the density measurement is known to be more important with larger particles.

2.4. Acoustic techniques
Ultrasonic signals are used for SSM in many ways, mostly with Acoustic Doppler Current Profilers (ADCPs). SSCs are estimated from acoustic backscatter intensities and reference SSCs (in-situ calibration) [14]. Acoustic discharge measurement installations (ADM), as existing in many larger HPPs, can also be used for SSM. This type of single-frequency acoustic attenuation technique and other acoustic approaches are treated more in detail in [4].

2.5. Differential pressure
Differential pressure is another SSM technique. The estimation of SSC is based on pressure measurements of two sensors installed at a fluid column at two levels with a known difference in elevation. In the application of this technique at the penstock of a HPP, the headwater level and the static pressure at the downstream end of the penstock (upstream of the turbines) are measured. If the water in the penstock contains suspended sediment, the pressure difference between the upper and the lower sensor is higher than in clear water conditions. Knowing the densities of the clear water and the particles, these pressure deviations are converted to SSCs in quasi-steady state conditions.

2.6. Automatic water sampling
Gravimetric analysis of bottled water samples in the laboratory is the reference for the indirect SSC measuring techniques described above. In field studies with manual bottle sampling, higher SSCs are likely to be missed because they rarely occur. This problem can be mitigated by using an automatic water sampler triggered by SSC (or indicators for high SSC).

3. Instruments and setup

3.1. Instruments
The instruments for SSM used in this study are listed in Table 1. Further information on tested turbidimeter models are given in [15]. Prior to the field study, the measuring capabilities of the instruments (1), (2) and (4) were systematically investigated in a mixing tank in the laboratory [16] [17]. From this investigation, for instance, a good agreement between PSDs obtained from LISST and from image analysis was found for spherical and rounded particles [17].

| Item no. | Measuring technique | Instrument description | Instrument model | Instrument manufacturer | Derived parameters |
|----------|---------------------|------------------------|------------------|------------------------|-------------------|
| (1)      | Turbidity           | In-line turbidimeter, at free falling jet | AquaScat         | Sigrist Photometer     | SSC               |
| (2)      | Laser diffraction (LISST) | Type C, with 90% path reduction module | LISST-100X       | Sequoia Scientific     | SSC, PSD          |
| (3)      | Vibrating-tube densimetry | Coriolis Flow- and Density Meter (CFDM) | Promass 83F DN15 | Endress+Hauser         | SSC               |
| (4)      | Acoustic attenuation | Based on ADM (1 MHz, 2.27 m path length) | Risonic          | Rittmeyer              | SSC               |
| (5)      | Differential pressure | Pressure transmitters (u/s and d/s of penstock) | 2088, 1151       | Rosemount              | SSC               |
| (6)      | Gravimetric         | Bottle sampler with 24 bottles of 1 litre | Isco 3700        | Teledyne Isco          | SSC               |
The selected turbidimeter model (1) measures turbidity at a free-falling jet. No cleaning is required because its optical parts are not in contact with the sediment-laden water. This turbidimeter model has been mainly used for quality control in drinking water supply systems so far. Turbidity up to 4000 FNU (Formazine Nephelometric Units) is measured by light scattered at 90°.

With respect to LISST (2), a submersible all-round model without dilution chamber was used. With the inversion mode for so-called 'random shaped' particles [18], the instrument’s nominal PSD range is 2 to 380 μm. Its optical path length was reduced from 50 to 5 mm by inserting the strongest available path reduction module (glass cylinder) to increase the upper limit of measurable SSCs.

The CFDM (3) contains two bent tubes with 8 mm inner diameter. The temperature is also measured and used in the internal data processing to compensate thermal expansion. The CFDM is factory-calibrated with respect to mass flow, density and temperature. The specified accuracy of the density measurement is ±0.5 g/l, which is a common specification [11].

3.2. Setup

The instruments (1), (2) and (6) of table 1 were installed in the valve chamber of HPP Fieschertal in June 2012. The valve chamber is located at the top of the penstock, downstream of a 2 km-long free-surface-flow storage tunnel (figure 1). In June 2013, the CFDM (3) was added. The ADM installation (4) and the pressure transmitters (5) have already been in place before the research project. The turbine water should contain only particles with less than 0.3 mm diameter because upstream gravel and sand traps are designed to exclude larger particles.

![Figure 1](image-url). Schematic longitudinal profile of the HPP Fieschertal with the instrumentation for SSM; numbers refer to table 1.

The instruments (1) to (3) were fed with water from the penstock by a sampling pipe arrangement (figure 2). The discharges in the sampling pipes were regulated by ball valves at their outlets. The turbidimeter (1) requires a flow rate of only 0.06 to 0.12 l/s. In the main pipe, a minimum discharge of 0.15 l/s corresponding to a flow velocity ≥ 0.5 m/s was selected to prevent settling of particles in the ascending pipe. The discharge in the main pipe was up to 0.25 l/s at high water level in the tunnel.

At the measurement location, no air bubbles which would bias the measurements were observed in the water. No provision to prevent clogging of the CFDM was required because the sediment particles at the measuring location (≤ 0.3 mm) were much smaller than the internal diameter of the CFDM’s measuring tubes (8 mm) and there was practically no floating debris. The CFDM was mounted vertically to reduce deposition of particles inside its measuring tubes.

The automatic bottle sampler (6) was controlled from a measurement computer in the valve chamber using an auxiliary software developed at VAW/ETH Zürich. Water samples of 0.5 l were...
pumped from the bucket (figure 2) every three days, or more frequently if the trigger signal exceeded certain threshold values. In 2012, turbidity was used as trigger signal. Since the installation of the CFDM in 2013, the mixture density has been used instead (generally better indicator for high SSC).

4. Methods

4.1. Data acquisition and laboratory work
The outputs of the turbidimeter (turbidity), of the CFDM (density, flow rate and temperature) and of the ADM (amplitudes of the forward scattered signals), as well as the head water level, the discharge in the penstock, the pressures upstream of the turbines and the electric outputs of the generators were recorded every second. The LISST was set to execute one burst per minute (10 measurements at 1 Hz followed by a break of 50 s). The optical parts of the LISST in contact with the water were manually cleaned every month on average. In the power house, the pipes between the penstock and the pressure sensors upstream of the turbines were flushed periodically. The instruments were used with their factory calibrations. From the 1 Hz data, minute-by-minute averages were calculated.

From the water samples, the SSCs were determined in the laboratory by gravimetric analysis which included the following steps: weighing of sample, evaporation of water, weighing of dried residue, and calculation of SSC by accounting for the concentration of dissolved minerals (≤ 0.08 g/l). These SSCs served as a basis to convert the instruments’ outputs to SSC time series. These conversions can also be called ‘field calibrations’ in the wider sense of the word. In the following, these conversions are described for each measuring technique.

4.2. Conversion of turbidity and acoustic damping to SSC
In figure 3a, the gravimetric SSCs from 46 bottle samples in 2013 (< 3 g/l) and the turbidity values measured at corresponding times are compared. Turbidity values were not always available because the small hose leading to the turbidimeter was sometimes clogged, especially at higher SSCs. The
scatter of the points is attributed to mainly temporal PSD variations. A linear fit through the origin was selected because the turbidimeter was not affected by fouling which would result in a turbidity offset. The relation in figure 3a was used to convert the measured turbidity time series to SSC. The time series of acoustic damping was converted to SSC in the same way [4].

4.3. Conversion of LISST’s volume concentrations to SSC
As a first step of LISST data treatment, the volume concentrations in the 32 size bins were plotted as a function of time and checked for plausibility. Besides the concentrations in size bins well within the LISST’s size measuring range, there were also relatively high concentrations in size bins (i) close to the lower end of the size measuring range and (ii) sometimes towards its upper end. Generally there were relatively high concentrations in bins no. 1 to 3 (1.9 to 3.1 µm) decreasing towards a local minimum in bin no. 4 (3.1 to 3.7 µm). Relatively high concentrations at the fine end of PSDs were also reported by [17] and [18]. These may be due to effects of small out-of-range particles or highly non-spherical particles. The concentrations in bins no. 1 to 3 were judged to be implausible and were thus discarded [17].

At the coarse end of the PSDs, the concentrations in the range of bins 25 to 32 (100 to 380 µm) gradually increased during some periods in late summer and autumn. Such concentrations were attributed to fouling and were also discarded [20]. By summing up the remaining plausible volume concentrations in all size bins at each time step, the time series of the total volume concentrations (TVC) was calculated.

The average solid density of the particle material \( \rho_s = 2.73 \, \text{g/cm}^3 \) was measured in the laboratory by a helium pycnometer at dried residues of twelve bottle samples. TVCs were multiplied by \( \rho_s \) to convert from volume to mass concentrations (SSCs). The resulting time series was denoted as SSC\(_{L0}\).

In Figure 3b, the gravimetrical SSCs below 3 g/l obtained from 96 bottle samples in 2013 are compared to SSC\(_{L0}\) at corresponding times. With the assumptions that the measuring uncertainty of the gravimetrical SSCs and of the pycnometer density are negligible, it was concluded that the SSCs obtained from LISST with \( \rho_s \) are on average 71% higher than these from the bottle samples (linear fit). In the laboratory investigation with angular feldspar or flaky mica particles, considerable LISST concentration overestimations by factors of 1.38 or 8, respectively were quantified [17]. These were attributed to mainly effects of highly non-spherical particle shapes and to possibly flocculation of fine particles. The SSC\(_{L0}\) values were divided by 1.71 to compensate the overestimation.

Figure 3. a) Turbidity, and b) SSC\(_{L0}\) obtained from LISST and the solid density of the particle material, both compared to gravimetrically determined reference SSCs (SSC\(_{G}\), < 3 g/l) measured at the waterway of HPP Fieschertal in 2013.
Another way to obtain corrected SSCs from LISST, but without the need of pycnometer measurements, consists of the following steps: plot TVCs against gravimetrical SSCs at corresponding times, find a conversion factor by linear fitting through the origin and apply the factor to the TVCs. This factor has units of a density and was called ‘apparent density’ in [19]. In the present study, the apparent density is 1.60 g/cm$^3$ ($= 2.73$ g/cm$^3$ / 1.71). In [19], an average apparent density of 1.24 g/cm$^3$ was found for sediment particles in river waters, which was also considerably lower than $\rho_s$.

4.4. Conversion of CFDM’s mixture density to SSC

The SSCs from the CFDM, denoted as $SSC_C$, were calculated from both measured time series of the mixture density $\rho_m(t)$ and the water temperature $T(t)$ using equation (1) [20]:

$$SSC_C = \frac{\rho_m(t) - \rho_w(T(t))}{1 - \frac{\rho_w(T(t))}{\rho_s}} + K(t) \approx 1.6 \left[ \rho_m(t) - \rho_w(T(t)) \right] + K(t)$$

The clear water density $\rho_w$ was calculated as a function of the temperature $T(t)$. From the pycnometer measurements, $\rho_s$ was taken as a constant. A site-specific and seasonally variable minor offset $K(t)$ was determined by comparing the SSCs from CFDM with the gravimetrical SSCs. This corresponds to a periodic in-situ calibration. $K(t)$ compensates density offsets due to (i) dissolved chemical elements, (ii) variable biofilm and/or particle deposits inside the measuring tubes, and other factors [20]. The approximation shown on the right-hand side of equation (1) is based on $\rho_s = 2.73$ g/cm$^3$.

The water temperatures varied between 0.1 and 6 °C, leading to a variation of $\rho_w < 0.13$ g/l. According to equation 1, this corresponds to a SSC-variation < 0.21 g/l. In autumns 2013 and 2014 a gradual slight increase of the mixture density was measured, while $SSC$ was expected to decline to zero towards the winter. This increase was attributed to the growth of a biofilm inside the measuring tubes [20] and corresponded to an SSC offset of ≤0.6 g/l. The density signal was de-trended based on the gravimetrical SSCs. With the periodic in-situ calibration, the expanded SSC measuring uncertainty (at 95% confidence level) was quantified as ±0.35 g/l based on measurements from 2014 [20].

4.5. Determination of SSCs by the pressure-based technique

SSCs were determined from pressure and further measurements according to the following steps:
- Discarding of temporarily implausible pressure measurements (e.g. due to complete or partial clogging of pipes between the penstock and the pressure transmitters or of the transmitters);
- Comparison of pressure and head water level measurements in periods of no flow and clear water, and minor correction of pressure data by applying a scaling factor close to 1;
- Determination of the head losses in the penstock as a function of the discharge and the operation mode (one or two turbines running), based on measurements (quadratic fits);
- Identification of quasi-steady state periods by checking for changes in the discharge;
- Calculation of the density of the sediment-water mixture in the penstock at every time step in quasi-steady state periods, based on head water level, discharge and pressure measurements and considering the head losses;
- Conversion of the mixture densities to SSCs as described in section 4.4.

5. Results

The performances of the measuring techniques and instruments were assessed by evaluating the SSC and PSD time series from the measurements during three years. Figure 4 shows an example of these time series with SSC results from the five techniques for continuous measurements and the discontinuous reference technique (bottle samples). The particle size $d_x$, obtained from LISST, stands for the diameter of graded particles, of which $x$ % by mass are smaller. The following observations and interpretations are made:
• The CFDM measured SSCs up to 13 g/l. It is expected that also higher SSCs can be measured as long as the measuring tubes are not clogged. With the particles mainly in the size range of silt, no considerable underestimation of SSCs due to phase decoupling was observed in the field measurements.
• The corrected SSCs from LISST matched generally well with those from the CFDM. However, no LISST results were available above 4 to 5 g/l at \(d_{50} = 30\) to 35 \(\mu m\) (\(d_{50}\) in the size range of coarse silt).
• The SSCs calculated from the turbidimeter and the single-frequency attenuation measurements were considerably lower than the SSCs from the other techniques mainly in periods of elevated SSCs and often after SSC peaks [15], when the particles were coarser than usual. The temporary underestimations are explained as follows: The SSCs from these techniques were determined using linear conversions based on \(SSC_G < 3\) g/l. These conversions are correct for the usually prevailing relatively fine particles, but lead to SSC underestimation if the particles are coarser.
• The pressure-based technique yielded similar SSCs as the CFDM and a bottle sample (figure 4). The SSC from pressure was considered only above 2 g/l, because the measuring uncertainty was judged to be too high at lower SSCs. The deviations between the SSCs from pressure and from CFDM are mainly attributed to the different measurement volumes: while the CFDM measured SSCs in a small sampling pipe at the top of the penstock (point measurement), the SSC from pressure refers to the volume of the whole penstock, i.e. is averaged over 3500 m\(^3\).

Further results on the SSC and PSD measurements at HPP Fieschertal in the years 2012 to 2014 are presented in [5].

![Figure 4](image.jpg)

**Figure 4.** Examples of time series of a) particle sizes obtained from LISST and of b) SSCs from six techniques, measured in the valve chamber of HPP Fieschertal (modified from [6]).

6. Conclusions and Outlook
A turbidimeter, an all-round LISST instrument without dilution chamber, a CFDM, a single-frequency acoustic technique based on ADM, and pressure sensors were used to measure SSC at the waterway of an alpine HPP. In addition, PSDs were obtained from LISST. The SSC measuring performances of these instruments and techniques were assessed by comparison to also the gravimetric technique.

With the CFDM, SSCs up to 13 g/l were measured without reaching the upper limit of the measuring range. Accounting for temperature variations and the seasonally variable density offset (by periodic field calibration based on gravimetric SSCs) contributed to reduce the SSC measuring uncertainty to \(\pm 0.35\) g/l. Accepting a relative measuring uncertainty of approximately 20\%, the CFDM
technique is thus suitable for \( SSCs \geq 2 \) g/l. To further investigate the CFDM technique, systematic laboratory tests also with particles up to the size range of sand and at high \( SSCs \) are recommended.

Similarly, the pressure-based technique is suitable to measure \( SSCs \geq 2 \) g/l at high- or medium head HPPs. This technique yields spatially well-averaged \( SSC \) measured directly in the penstock and has the advantage of using sensors which are already in place in many HPPs. The pressure technique has the drawbacks of (i) yielding no results during hydraulic transients (change of turbine flow rate leading to water hammer) and (ii) offering only a short pre-warning time for turbine switch-offs, because the sediment-laden water is already in the penstock if high \( SSCs \) are detected.

The \( SSCs \) obtained from the LISST’s plausible volume concentrations and the solid density of the particle material were on average 71 % higher than the gravimetric \( SSCs \) from bottle samples. With the LISST technique, an average particle shape has to be assumed in the calculation of the volume concentrations. In environments with highly non-spherical particles, as typically in mountainous regions, it is recommended to take bottle samples and to convert LISST volume concentrations to \( SSCs \) based on gravimetric reference \( SSCs \). Applying this method, effects of particle shapes and of particle density (including potential flocculation) on \( SSCs \) are compensated. The LISST with an optical path length of 5 mm and without dilution allowed measuring \( SSCs \) up to 5 g/l with \( d_{50} \) in the size range of coarse silt and with the shapes of the prevailing particles. Apart from the limited \( SSC \) measuring range, LISST offered the advantage of providing PSDs.

With the PSD results, temporary biases of \( SSCs \) obtained from turbidimeters and the single-frequency acoustic attenuation technique were explained as consequences of particle size variations. To reduce such \( SSC \) biases, the use of non-linear conversion functions is recommended, which consider (i) a potential correlation between \( d_{50} \) and \( SSC \), and (ii) the potentially non-linear behavior of measuring systems at high \( SSCs \). The practical advantages of the acoustic technique for sediment monitoring in HPPs based on ADM installations are highlighted in [4]. In contrast to turbidimeters and the single-frequency acoustic technique, the LISST, the CFDM and the pressure-based technique provided \( SSCs \) which were less or not affected by PSD variations.

The mentioned type of turbidimeter provided drift-free measurements without cleaning. For the LISST, manual cleaning every month was not frequent enough. Options to avoid fouling are to either use an auxiliary device to protect and clean the measuring window (a so-called ‘bioblock’) or another type of LISST instrument with automatic cleaning. In the CFDM, fouling caused a gradual shift of \( SSCs \) by up to 0.6 g/l. Because frequent and rigorous cleaning inside the CFDM’s measuring tubes is not practical in SSM applications, a correction based on gravimetric \( SSCs \) is recommended instead, if a high accuracy in \( SSC \) is required, e.g. to determine annual sediment loads. If a CFDM is solely used to warn of high turbine erosion potential, say above 5 or 10 g/l, no bottle sampling, laboratory analyses and field calibration are required, since small density offsets due to fouling are not relevant.

Based on these findings, a combination of a LISST instrument without a dilution chamber and a CFDM appears to be an economic option for SSM at HPPs, if \( SSC \) from a few mg/l to several 10 g/l of mainly silt is to be measured, and the lack of PSD data at high \( SSCs \) is accepted. In addition, automatic bottle sampling is highly recommended for calibration and validation of continuous indirect \( SSC \) measurements. The parallel use of several independent instruments based on different measuring techniques is seen as an advantage with respect to (i) the data coverage in environments with wide \( SSC \) and PSD ranges as well as (ii) the reliability of the measured values.

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