Turbidity sensor choices: Backscatter is crucial to measure high suspended sediment concentrations

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Abstract

Suspended sediment monitoring is an important basis for river system and hydropower plant (HPP) management. To measure suspended sediment concentration (SSC) in real-time, turbidity sensors are widely used. However, the SSC in rivers due to intense rains or reservoir flushing may exceed the measuring range of most available turbidity sensors. Hence, Imhof cones are generally used to measure medium and high SSC so far. The upper limit of SSC which can be measured by a turbidity meter depends on its design and the properties of the sediment particles. We review the physical principles of turbidity measurement and distinguish four ranges of sensor response. Based on laboratory and field measurements we show that the range of measurable SSC is considerably extended if not only side-scatter but also backscatter intensity are sensed. Such turbidity sensors exploiting backscattered light may increasingly be used in situations where also high SSC need to be monitored, e.g. during reservoir flushing or the operation of HPP intakes, and solutions are sought to reduce efforts for manual measurements.

1 Introduction

Real-time suspended sediment monitoring plays nowadays an important role in river system monitoring and the operation of hydropower plants (HPPs). For such monitoring, the suspended sediment mass concentration (SSC) is the most variable and hence most important parameter to measure at high temporal resolution. Typical applications are:

- on main rivers: long-term SSC measurements by hydrographical services to quantify sediment loads and associated mass flows of e.g. pollutants, also in view of the effects of climate change (Grasso et al., 2021; Haimann et al., 2014; Spreafico et al., 2005).
- in high- and medium-head run-of-river HPPs and storage HPPs with intakes along the headrace tunnel: real-time SSC measurements to warn of temporarily high SSC, so that intakes can be closed during such events to avoid excessive sediment loads and hydro-abrasive erosion in HPP systems for economic optimization (Felix, 2017).
- at water reservoirs (lakes) of storage HPPs where sediment needs to be managed (e.g. by drawdown flushing or venting) to maintain the active storage volume for operational flexibility (Morris, 2020; Schleiss et al., 2016): SSC measurements in downstream river reaches to control sediment management activities for compliance with environmental regulations (Crosa et al., 2010; Hauer et al., 2020; Newcombe & Jensen, 1996). Usually, measured SSC time series must be submitted in the reporting to the responsible authorities.

Several techniques are used to measure SSC in river systems and HPPs. The primary method is to take a water sample, bring it to the laboratory and determine the SSC (in g/l) by the gravimetrical method: measure the sample volume, let the water pass through a filter (pore size e.g. 0.65 µm) and weigh the dried particle mass on the filter according to DIN EN 872:2005; (Felix, 2017; Grasso et al., 2021). The method is labor-intensive and results are not available in real time. For on-site measurements during e.g. reservoir flushing (Figures 1a, b), Imhoff cone measurements are common: a water sample is poured into a transparent cone of 1 liter (Fig. 1c). After a defined time, e.g. 15 or 30 minutes, the volume of settled particles (unconsolidated sediment, including pore water) is read from the gradation lines on the cone.

Figure 1: Example of suspended sediment concentration monitoring at a river reach (b), downstream of an alpine HPP reservoir (a), using Imhoff cones (c) during drawdown flushing (Stutz, 2024).

The Imhoff cone method yields an approximate volumetric suspended sediment concentration (in ml/l) on site with a delay of only the settling time. Hence this method can be used to control upstream sediment mobilization activities to comply with maximum admissible concentrations during the sediment management process. The unit of ml/l referring to the Imhoff cone method is commonly used by authorities in Switzerland and neighboring countries to formulate ecologically acceptable SSC during flushing events.

For continuous SSC measurements, various indirect techniques (Wren et al., 2000) are used in-situ, listed here by how often they are applied at rivers and in HPP schemes:

- Turbidity meters: attenuation, forward-, side- and/or backscatter of near infrared or visible light (Felix, 2017; Grasso et al., 2021; Haimann et al., 2014; Voichick et al., 2018),
- Acoustic instruments: backscatter and/or attenuation of ultrasonic pulses at one or several frequencies (Aleixo et al., 2020; Ehrbar et al., 2017; Felix et al., 2019),
- Vibrating tube density meters, e.g. Coriolis Flow– and Density Meter (Felix, 2017),
- Nuclear gauge (attenuation of gamma radiation), requires specially trained and certified staff,
- Laser in-situ scattering and transmissometry (Ehrbar et al., 2017), if also particle size distribution is of interest.

A drawback of these indirect techniques is that they require site-specific calibration. But in contrast to direct measurements, they offer the advantage of providing outputs continuously and in real-time. The site-specific calibration is usually obtained by comparing instrument outputs to reference SSC. These are ideally obtained by the gravimetric method, or from Imhof cone measurements if the gravimetric method is not affordable or not required at medium to high SSC.

The present paper focuses on turbidity measurement based on near-infrared scattering. Firstly, the relevant range of SSC and typical particle properties for suspended sediment monitoring are summarized. Secondly, a widely used turbidity meter type with one detector measuring perpendicular to the beam (at 90°, side-scatter) is reviewed and its response to increasing SSC is discussed. An application example of such a sensor reports its limited SSC-measuring range. Thirdly, the response of a two-channel turbidity meter with a second detector measuring backscattered light at 135° to the beam is presented and compared. An application during a sediment flushing operation confirmed a wider measurement range of such turbidity meters exploiting backscatter. Finally, the implications for SSC measurements at rivers and HPP are discussed.

2 Relevant parameter ranges for suspended sediment monitoring in rivers and HPPs

2.1 Particle properties

For turbidity meters, the conversion of their output signal to SSC and hence their SSC-measuring range depend on the particle properties, i.e. mainly size, shape and density (Friz et al., 2026). The suspended sediment particles in rivers and HPPs have typically diameters mainly in the size-range of silt (2 to 63 µm according to European geotechnical classification, Figure 2). During floods or reservoir flushing, a higher fraction of sand (diameter 63 µm to 2 mm), particularly fine sand (63 to 200 µm), may be transported in rivers because of the higher shear stress and turbulence of the increased flow.

Natural silt particles are usually angular. Depending on mineralogy, a part of them has platy shapes due to the layer structure of sheet silicates such as mica. Highly non-spherical particles cause higher scattering than spherical particles.

In mountain streams, the suspended sediment particles consist mainly of mineral particles in the described size range. Hence, aggregation or flocculation are less important than for finer and more organic particles typically found in slowlier flowing waters.

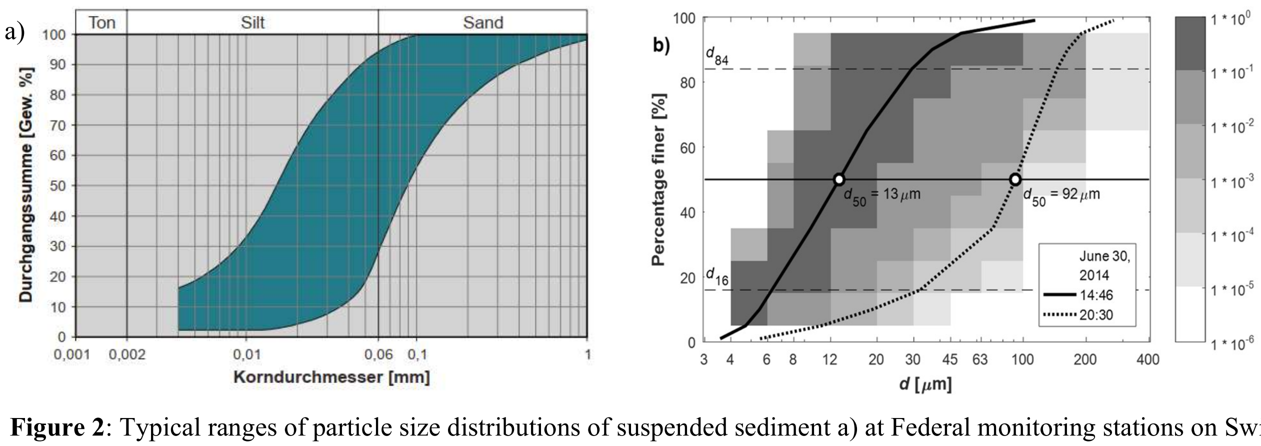

Figure 2: Typical ranges of particle size distributions of suspended sediment a) at Federal monitoring stations on Swiss rivers (GHO 1987, in Spreafico et al., 2005) and b) in the turbine water of HPP Fischertal 2012-2014 (Felix, 2017).

2.2 SSC ranges

For suspended sediment monitoring in rivers, also in connection with the operation of HPP intakes or flushing of reservoirs, the following numbers give an indication of which SSC-range is of interest:

- natural SSC in mountain rivers: on average and usually well below < 1 g/l, several g/l during intense rains as may occur every year, several 10 g/l up to about 100 g/l during intense and exceptional rains or floods, even higher in case of landslides or debris flows reaching the upstream river.
- threshold SSC, above which the operation of a HPP intake becomes unprofitable: 1 to 15 g/l (Abgottspon et al., 2025; Felix, 2017) depending on turbine and sediment properties, with average electricity prices.
- SSC during flushing of reservoirs: peaks similar to natural SSC due to floods; admissible values are lower for longer durations and depend on the ecological situation in the downstream river reach.

Hence, instruments for suspended sediment monitoring in rivers need to measure SSC at least up to several g/l. The ability of measuring up to 20, 50 or 100 g/l is an advantage or a requirement in some applications.

3 Turbidity measurement with a side-scatter detector (one channel)

3.1 Geometrical arrangement and calibration

Turbidity meters contain a light source and at least one detector which measures the incident light intensity after the passage through the potentially particle-laden fluid. To reduce the dependency on water color, near-infrared (NIR) with a wavelength >800 nm is used according to DIN EN ISO 7027-1:2016. Although NIR is not or hardly visible for the naked human eye, NIR is called light in this paper.
If the detector is placed in the direction of the emitted light beam, the attenuation is measured. The distance over which the light travels through the fluid is the optical path length. If it is shortened, higher SSC can be measured. Short optical path length may however disturb the flow and hinder the passage of sediment particles in suspended sediment monitoring applications.
In the present paper we focus on detectors placed not in the direction of the emitted beam. Such turbidity measuring techniques, in which scattered light is detected, are called "nephelometry" according to DIN EN ISO 7027-1:2016. Most commonly, the scattered light intensity is measured at an angle of 90° (Figure 4). Such one-channel side-scatter sensors are typically used for the quality monitoring of drinking water, where low turbidity is of interest.
An internationally widely used turbidity calibration standard is Formazine, i.e. a polymer forming colloidal particles (Riedener et al., 2016). This chemical substance is used because it allows to produce calibration standards and dilution series in a well-reproducible way. If manufacturer-calibrated with this substance, one-channel side-scatter sensors provide a turbidity signal in FNU (Formazine nephelometric units). For suspended sediment monitoring, the site-specific conversion to SSC in g/l has to be found by the user by comparison to reference SSC (ideally by the gravimetrical method or approximately by Imhoff cone). Alternatively, a conversion can be estimated based on similar application cases, if reference measurements are not affordable and a higher uncertainty is accepted.

3.2 Sensor response with four ranges

Figure 3 shows schematically the output signal of a one-channel side-scatter turbidity sensor as a function of SSC. The representation is based on laboratory measurements with natural fine sediment particles taken from deposits in a HPP reservoir in Switzerland. Units were omitted because the numerical values depend on particle properties and this paper focuses on the general behavior of turbidity sensors up to high SSC.

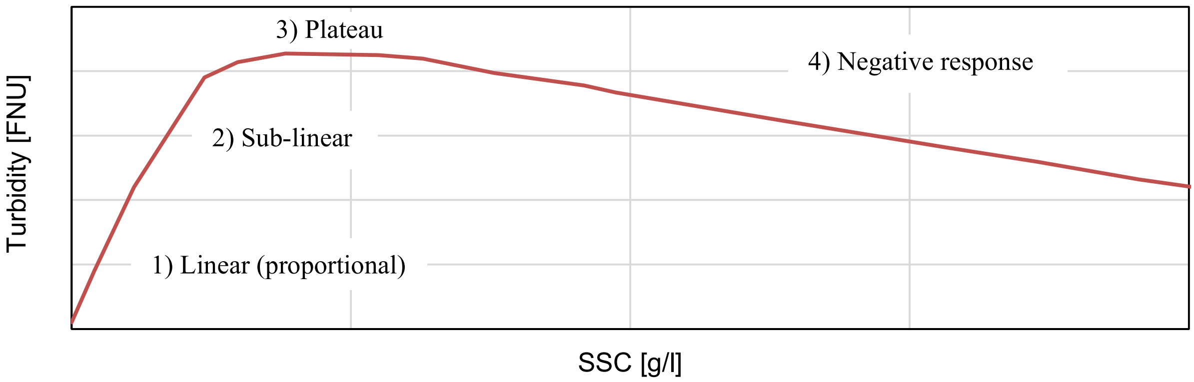

Figure 3: Schematic response of an one-channel side-scatter turbidity sensor: linear range at low SSC and deviating behavior due to multiple scattering at higher SSC (measurement data: Sigrist-Photometer AG).

On Figure 3, four ranges can be distinguished (Riedener et al., 2016):

1) Linear (proportional) range: The turbidity signal increases with SSC. This is the basic range, in which the output of a turbidity sensor can easily be converted to the SSC with a constant factor if particle properties do not vary systematically with SSC (Felix, 2017; Friz et al., 2026). This factor corresponds to the slope of a straight line (through the origin, no offset due to e.g. fouling) and is also called the "specific turbidity".
2) Sub-linear range: The turbidity signal increases less than in proportion to the SSC (approaching saturation). If the signal shall be used in this range too, a non-linear relation needs to be considered.

3) Plateau: The turbidity signal no longer increases or is "capped" by the upper limit of the measurement range. This range cannot be used to infer SSC from turbidity because there is no clear relation.
4) Negative response: The turbidity signal decreases whereas the SSC continues to increase: In suspended sediment monitoring this range cannot be used because there is no unique relation from turbidity to SSC, i.e. two different SSC-values are possible for a recorded output level. The application of turbidity meters at high turbidity can be misleading (Voichick et al. 2018, and Fig. 8 in Abgottspon et al., 2022) and should be avoided.

The reason why turbidity does not always increase proportionally to SSC is multiple scattering. At low concentrations, the light scattered by a particle has room to propagate freely (simple scatter in Figure 4a). At higher concentrations, however, two additional effects become important: the particles closer to the light source tend to screen off the incident light, and the scattered light can no longer propagate freely and is hindered from reaching the detector. As indicated by the thickness of the yellow arrows in Figure 4, the received scattered light intensity in a pronounced multiple-scattering regime is lower than in a simple-scatter regime. All in all, Figure 4 shows that the measurement of the side-scatter light intensity is suitable for rather low SSC.

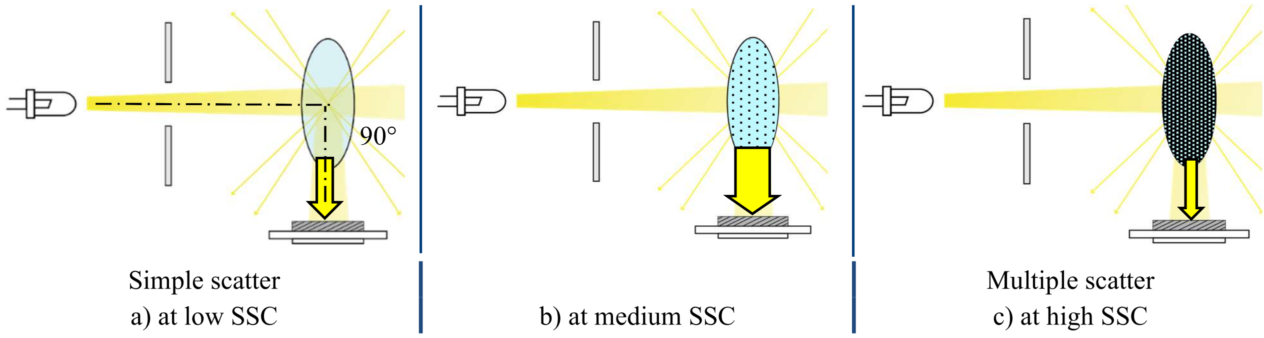

Figure 4: Schematic of turbidity measurement with an one-channel side-scatter sensor, which receives scattered light at 90° at increasing SSC. In the simple scatter regime at low SSC (a) light propagates freely, whereas it is increasingly hindered at high SSC (c) due to multiple scattering.

3.3 Application experience in a HPP on a glacier stream

Such a one-channel side-scatter turbidity meter was applied to measure SSC during several summers in the run-of-river HPP Fieschertal, Switzerland (Felix 2017). This HPP is located downstream of the second longest glacier in the European Alps. At the measurement location, in the valve chamber between the storage tunnel and the penstock, the transported sediment particles are mainly in the size range of silt. Further upstream, coarser sediment is excluded by gravel and sand traps and partly in the storage tunnel (depending on operation).

The turbidity meter was an AquaScat *WTM A* from Sigrist-Photometer AG which measures scattered light at an angle of 90° in a nominal range of 0.001 to 4000 FNU. The instrument, originally developed for quality control in water supply systems, measures turbidity on a free-falling water jet. Due to this arrangement, no cleaning of the optics is required to prevent fouling. Some 0.2 l/s of slightly pressurized water was conveyed by a hose from the beginning of the penstock to the instrument installed at the chamber wall. Turbidity was recorded every minute during the summer seasons. In parallel, SSC was measured with a Coriolis Flow and Density meter (SSC_C), and water samples were pumped occasionally to obtain gravimetrical SSC from laboratory analyses (SSC_G). In the following, the upper limit of the SSC measuring range of this one-channel side-scatter turbidity meter is evaluated for the particles transported at that site.

Figure 5a shows the measured turbidity as a function of the reference SSC obtained from 122 water samples. On average over the months, 594 FNU corresponded to 1 g/l. This slope of the line of the conversion function is the average specific turbidity for the prevailing sediment particles. With a nominal measuring range of 4000 FNU, this instrument allows measuring SSC up to 4000 / 594 ⇒ 6.7 g/l on temporal average.

Figure 5b shows again the measured turbidity, but here as a function of the SSC obtained from the density meter, which served as a secondary reference with much higher temporal resolution. The black line shows again the average conversion found in Figure 5a. The point colors indicate the median size (d_{50}) of the particles. As expected from theory and laboratory experiments, the specific turbidity was lower when coarser particles were transported. For the blue dots, corresponding to washed fine sand during resuspension of deposits in the storage tunnel, the specific turbidity was only about 120 FNU per g/l. For such fine sand particles, the instrument allows measuring SSC of up to 4000 / 120 ⇒ 33 g/l. But on average and during floods, not only sand but mainly silt was transported, leading to a much lower limit of measurable SSC.

When finer particles were transported than on temporal average, the specific turbidity rose to about 1000 FNU per g/l (grey dots in Figure 5b). For such mainly fine and medium silt particles, the instrument allows measuring SSC of up to 4000 / 1000 ⇒4 g/l only. This SSC measuring range is sufficient for most of the time, but not during floods or flushing events.

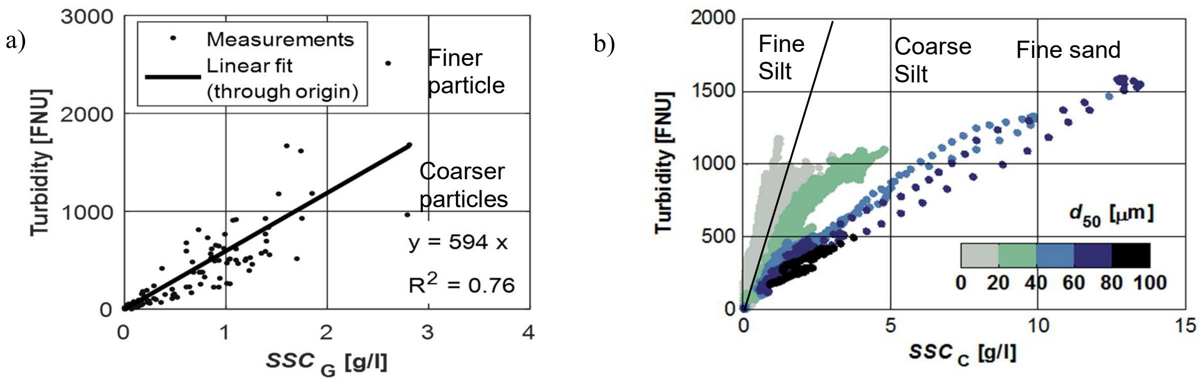

Figure 5: Turbidity measured with a one-channel side-scatter turbidity sensor (AquaScat *WTM A* by Sigrist-Photometer AG) in summers of 2013 and 2014 at HPP Fieschertal as a function of reference SSC: a) at times when water samples were taken and b) minute by minute with point colors indicating the median particle size d_{50} (Felix 2017).

4 Turbidity measurement with side- and backscatter detectors (two channels)

4.1 Geometrical arrangement

Some turbidity meters employ a second detector placed at a different angle than 90°. If the additional detector is placed at a large angle of about 135° from the beam direction, backward scatter is measured (Figure 6).

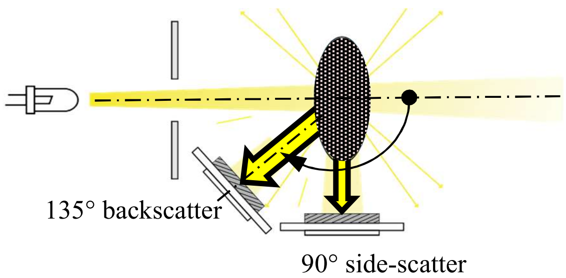

Figure 6: Schematic of turbidity measurement at high SSC with a two-channel turbidity sensor, which receives scattered light intensity at angles of 90° and 135°. In a multiple scatter regime, more light is received at 135° than at 90°

4.2 Response of the two detectors

Figure 7 shows schematically the two signals of such a two-channel turbidity sensor as a function of SSC. The response of the 90°-detector is identical as in Figure 3, but plotted over a 50 % higher SSC-range. The response of the 135°-detector, based on the laboratory measurements as in the previous section, is shown in addition (black line). At low SSC, few scattered light is received at 135°. With increasing SSC, more light is backscattered and in a pronounced multiple scatter regime, the detector at 135° receives a higher signal than the detector in the standard position at 90°. Hence, the signals of the two detectors complement each other and are used to extend the SSC-measuring range of such a two-channel sensor.

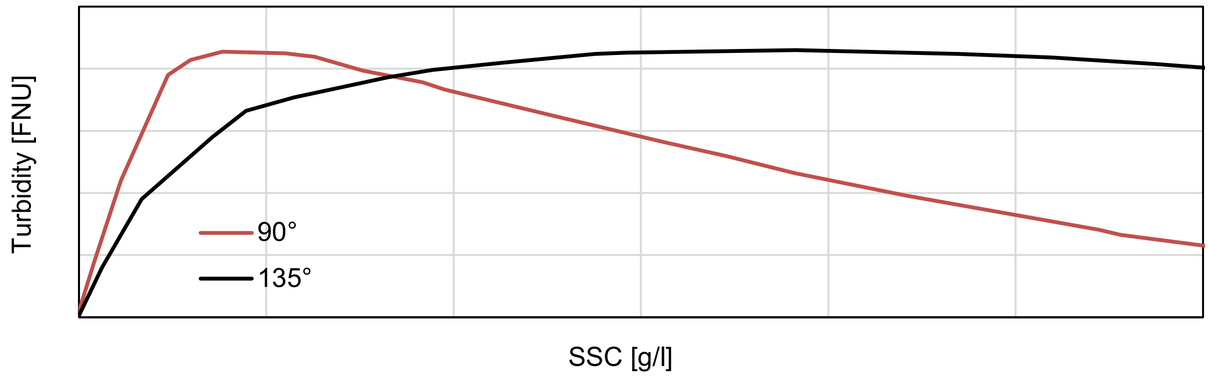

Figure 7: Schematic responses of a two-channel turbidity sensor with receivers at 90° and 135°: In a simple scatter regime, the responses are linear to SSC. At higher SSC, the 90°-signal reaches a plateau whereas the 135°-signal still increases. In a multiple scatter regime, more scattered light is received at 135° than at 90° (data: Sigrist-Photometer AG).

4.3 Application experience from a sediment flushing operation

Such a two-channel side- and backscatter turbidity meter was recently applied to measure SSC in a mountain river during a recent sediment flushing operation. The turbidity meter was installed on the residual flow reach downstream of a HPP reservoir in the Swiss Alps. The submersible probe was installed at a fixed position in the riverbed, roughly 900 m downstream of the reservoir's bottom outlet. The turbidity meter was an AquaScat S HT (under development) from Sigrist-Photometer AG which measures scattered light at angles of 90° and 135°. The signals of each channel are available as separate outputs. Turbidity was recorded every 5 seconds. Since the turbidity was fluctuating due to highly turbulent flow conditions, the intermittent nature of suspended sediment transport (Parsons et al., 2015) and varying discharge (wave propagation due to outlet opening), mean values over 3 minutes were calculated. In parallel, water samples were taken every 15 minutes to obtain gravimetrical SSC (SSC_G).

Figure 8 shows the measured turbidity as a function of the reference SSC obtained from 14 water samples ranging from 1.5 to 57 g/l. The side-scatter turbidity signal (at 90°) began to deviate from a linear response already below 5 g/l. Turbidity at 90° saturated towards 2000 FNU ("plateau") at 8 g/l to 18 g/l, whereas turbidity at 135°-backscatter still increased. When the peak of the propagating suspended sediment wave passed the measurement site, an SSC_G of 57 g/l was observed. At this high SSC, multiple scattering occurs: the side scatter sensor yields a negative response, whereas the 135° backscatter signal still increased. Although the backscatter sensor response is not linear, it allows measuring also high SSC beyond 20 g/l. This can be done with either the combined sensor signal of the AquaScat S HT or with a site-specific rating curve based on both measuring channels.

The deviation of some points from the overall trends in Figure 8 is attributed to potential variations of particle properties over time or local effects during the sampling process. Because the particle properties may vary from site to site, no globally valid rating curve nor SSC-measuring range can be retrieved from this case study. Nonetheless, the application shows a considerable extension of the SSC-measuring range in comparison to using a conventional one-channel side-scatter turbidimeter.

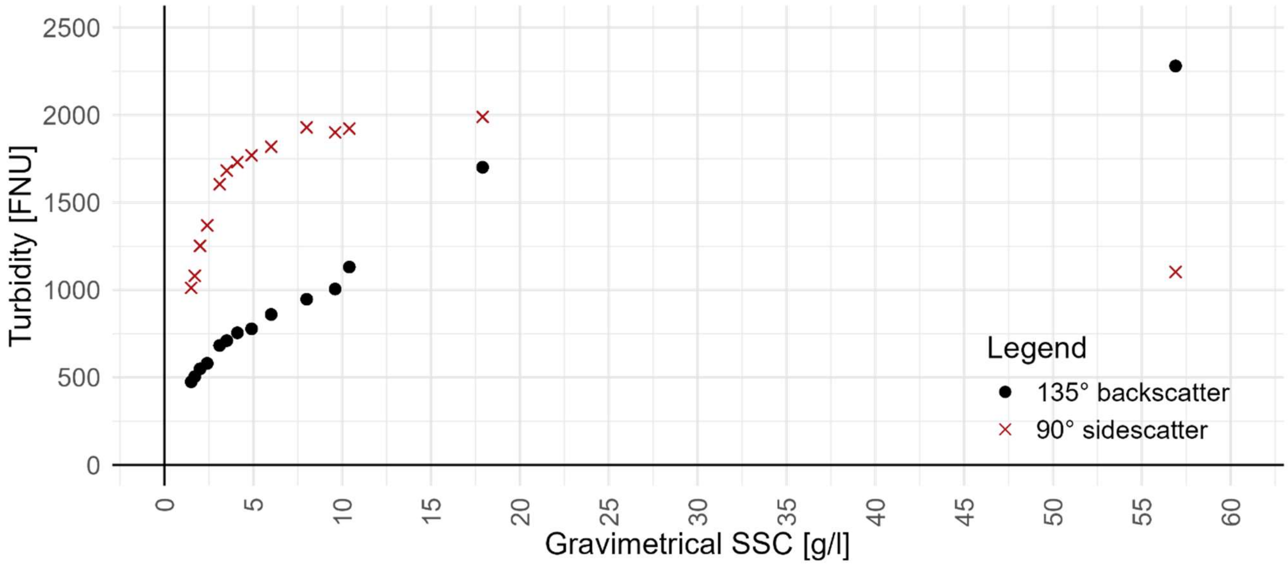

Figure 8: Responses of a two-channel turbidity sensor with receivers at 90° and 135° measured during a sediment flushing operation Turbidity at 90° (side-scatter) saturated towards 2000 FNU at 8 to 18 g/l, whereas turbidity at 135° (backscatter) still increased, which allowed to measure SSC beyond 20 g/l (data: Sigrist-Photometer AG and Kraftwerke Oberhasli AG, 2025).

5 Conclusion

For suspended sediment monitoring in river systems and HPPs, continuous and real-time SSC-measurements from indirectly measuring sensors are an attractive alternative compared to manual sampling with the gravimetric method or the Imhoff cone, particularly for longer or repeated monitoring. Turbidity measurements are widely used, but often limited by the SSC-measurement range, depending on the turbidity meter design and particle properties. This is especially relevant if the particles are fine (silt rather than sand) and the SSC shall be monitored not only in usual weather conditions including moderate rain, but also during floods or occasional sediment management actions such as reservoir flushing.

Due to multiple scattering occurring at increasing SSC, the response of a turbidity meter is not always proportional to the SSC. After a deviation from the linear range, the signal saturates or is capped and then even decreases. Such responses can be misleading in practical applications. Hence, only the range with increasing response can be used for suspended sediment monitoring. The linear range is most practical, because sensor readings can be converted to SSC using a constant factor. Above the non-linear range, either a combined sensor signal or a non-linear rating curve can be used.

Turbidity meters with one detector measuring perpendicularly (90°) to the light beam are common but show a limited SSC measurement range of up to 4 or 7 g/l of finer or coarser silt, which is typically present in mountain streams. However, a turbidity meter with an additional detector at a large angle of about 135° to the light beam (AquaScat S HT, by Sigrist-Photometer AG, under development) allowed measuring SSC up to at about 50 g/l in a river downstream of a HPP reservoir during sediment flushing. Hence, using backscattered light in addition to side-scattered light considerably extends the SSC-measuring range of turbidity meters and reduces the risk of misleading sensor readings at high SSC. Such two-channel turbidity sensors may increasingly be used on sites where occasionally high SSC, e.g. exceeding 20 g/l, are to be measured in real-time.

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