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A review of methods and instruments to monitor turbidity and suspended sediment concentration

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ABSTRACT

Turbidity and suspended sediment concentration are crucial parameters indicative of water quality, playing pivotal roles in evaluating the well-being of aquatic ecosystems and the effectiveness of water treatment processes. This manuscript provides an in-depth review of various methods and instruments in use for *in situ* and in-line applications. The exploration of optical instrumentation is central to this review, examining its widespread use and current challenges within standard methods, commercial instruments and scientific research. The study also delves into alternative techniques, such as acoustic and capacitive methods, elucidating their applications, calibration intricacies, and practical considerations. Furthermore, the paper scrutinizes the emerging importance of satellite and aerial imaging processing as a supplementary tool for turbidity monitoring, underscoring its potential to offer comprehensive insights on a larger scale. The review emphasizes the key accomplishments and challenges of the state-of-the-art technologies, providing a comprehensive overview of the current stage of the field and its prospects. and aims to provide valuable insights for researchers, practitioners, and decision-makers involved in environmental monitoring and water facility management, enabling a deeper comprehension of the significance of turbidity and suspended sediment concentration in safeguarding water quality and ecosystem health.

1. Introduction

Water quality assessment is a critical aspect of environmental science, with far-reaching implications for ecological health and human well-being [1]. Among the myriad parameters influencing water quality, turbidity and suspended sediment concentration (SSC) stand out as indicators of the physical and chemical characteristics of aquatic systems. Accurately measuring these parameters is fundamental to understanding and managing water resources effectively. While turbidity and SSC are occasionally used interchangeably, their differences must be acknowledged [2].

Turbidity is a physical property of fluids that translates into their reduced optical transparency, cloudiness, or haziness due to the presence of suspended material that blocks the transmission of light. The sources of turbidity are diverse, ranging from natural processes such as erosion, particle transport and sedimentation to anthropogenic activities like urban runoff, industrial discharges, pesticides and microplastics [3–6]. Turbidity measurement is an essential diagnostic tool, revealing the degree to which suspended particles interfere with light transmission through water. Beyond its aesthetic implications, it is pivotal in shaping aquatic ecosystems and in water treatment assessment. Turbidity levels profoundly affect light penetration, a critical factor for photosynthetic organisms. Excessive turbidity hinders the photosynthetic processes of aquatic plants and algae, disrupting the delicate balance of the ecosystem [7,8]. Water with high turbidity may appear cloudy, murky, or discoloured. While not necessarily harmful on its own, high turbidity can indicate the presence of other contaminants that may affect taste, odour, and appearance, and can serve as an indicator of potential microbial contamination in water [9,10]. Consequently, understanding and quantifying this parameter is imperative for comprehending the potential ecological consequences and devising effective management strategies.

Complementary to turbidity, suspended sediment concentration delves into quantifying solid particles that resist settling and remain

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suspended in water. These particles encompass a spectrum of materials, including fine sand, silt, clay, and organic matter [5,11,12]. SSC is a direct reflection of erosion processes, sediment transport, and the overall sediment dynamics within aquatic systems. While turbidity refers explicitly to the cloudiness caused by these particles, SSC quantifies the actual concentration of suspended solids in the water. Sediment can serve as a carrier for various contaminants, including heavy metals, nutrients, pesticides, microplastics and organic pollutants, and provide a medium for microorganisms to attach and thrive, including bacteria, viruses, and protozoa, some of which may be pathogenic and cause waterborne diseases such as diarrhoea, cholera, and giardiasis. These contaminants can attach to sediment particles and be transported in water bodies, potentially contaminating drinking water sources [13–15]. Suspended sediment concentration is intricately linked to the health of water bodies considering their ecological role, influencing nutrient cycling, habitat structure, predatory dynamics and the distribution of aquatic organisms. Moreover, elevated SSC levels can have cascading effects, ranging from increased turbidity and reduced light penetration to the smothering of benthic habitats. While much attention is often given to the negative impacts of high SSC levels, low SSC can also pose challenges to aquatic ecosystems. The sensitive balance of sediment dynamics plays a crucial role in maintaining the health and functionality of water bodies. As such, an accurate understanding of SSC is indispensable for comprehending the mechanisms driving sediment-related processes and their ramifications for aquatic ecosystems [16,17].

The impact of turbidity and suspended sediment concentration extends beyond environmental considerations and encompasses a critical role in the realm of water facilities (*e.g.*, Wastewater Treatment Plants, Water Treatment Plants, Industrial Water Treatment Systems, Aquaculture and Fisheries, *etc.*). The effective operation of many water facilities relies heavily on the precise management of these parameters and its importance cannot be overstated [18–21]. Water treatment processes, including coagulation, flocculation, and sedimentation, are finely tuned to remove suspended particles from raw water. Elevated turbidity levels can challenge these processes, inducing higher chemical dosages and treatment strategy adjustments. Filtration is a pivotal step in water treatment, and the performance of filtration systems is directly influenced by the levels of suspended solids. Excessive turbidity can lead to clogging and reduced filtration efficiency. Additionally, pipes, pumps, and valves are susceptible to damage caused by abrasive particles in raw water. Water quality regulations often stipulate maximum allowable turbidity and suspended sediment concentration levels in treated water. According to the World Health Organization's standards, the turbidity of drinking water should be below 1 NTU before disinfection, otherwise, the effectiveness of chlorination significantly decreases. In areas where fewer resources are available, the turbidity should be below 5 NTU. Compliance with these standards is paramount for water facilities to ensure the delivery of safe drinking water to the public. Both turbidity and SSC serve as critical indicators for optimizing water treatment processes, ensuring regulatory compliance, protecting infrastructure, minimizing downtime and maintenance costs, and fortifying the resilience of operations in the face of dynamic environmental conditions. As water resources face increasing pressures, integrating advanced monitoring and management practices becomes crucial for sustaining the reliability and safety of water supplies.

The most effective method to measure SSC, in this case referred to as total suspended solids (TSS), is by gravimetric analysis. In this methodology, a water sample is filtered and dried, and the collected solids are weighed. This is the most accurate technique for measuring total suspended solids. However, it is also more time-consuming, needs qualified human operators and is impractical for *in situ* and in-line monitoring [22]. Since the gravimetric methodology is only suited for laboratory analysis, new approaches had to be invented for other branches of applications. These advancements have primarily been driven by technological innovation and the increasing demand for accurate and efficient water quality monitoring. These technologies can employ different sensing and offer real-time or near real-time data collection, enabling continuous monitoring of water quality. Advances in miniaturization and cost reduction have made turbidity and SSC monitoring instruments more accessible and affordable. Portable and handheld devices are now available for field-based measurements, allowing for rapid assessment of water quality in remote or resource-limited areas. Additionally, remote sensing and integration of autonomous platforms like underwater and surface vehicles allow for high-resolution data collection in challenging environments.

Despite these advancements, several challenges and limitations persist in monitoring turbidity and SSC. Calibration procedures, standards and turbidity units' comparisons are not yet fully established to ensure consistency and comparability of data collected from different sensor platforms. Turbidity and SSC measurements can be influenced by various environmental factors such as water temperature, salinity, and organic matter content. Understanding and mitigating these sources of interference is essential for obtaining accurate and representative data. At the same time, effective interpretation and integration of turbidity and SSC data with these water quality parameters are critical for assessing ecosystem health and identifying potential impacts on aquatic biota and human activities. Also, Turbidity and SSC exhibit significant spatial and temporal variability in natural water bodies, posing challenges for monitoring efforts. Achieving adequate spatial coverage and temporal resolution in monitoring programs requires careful planning and resource allocation.

This review embarks on an exploration of the diverse methods, techniques, and instruments to measure turbidity and suspended sediment concentration. Tracing the historical evolution of measurement methodologies and critically examining contemporary practices, it aims to provide a comprehensive overview of the state-of-the-art approaches in this field. From traditional field measurements to sophisticated sensing technologies, the review will traverse the spectrum of techniques, shedding light on the strengths, limitations, and emerging trends in turbidity and SSC assessments. In essence, the review seeks not only to deepen our understanding of these fundamental water quality parameters but also to foster a dialogue on the broader implications of their measurement. As global water challenges intensify, an enhanced grasp of turbidity and suspended sediment concentration becomes a cornerstone for sustainable water resource management, offering a nuanced perspective on the dynamic interplay between water, sediment, and life.

2. Light and particulate matter interaction

Prevailing methodologies for assessing turbidity and suspended sediment concentration predominantly rely on optical instrumentation. This approach aligns with the conceptualization of turbidity as the optical transparency of a fluid, thereby positioning turbidity as an indirect indicator of suspended sediment concentration. Given the prevalent reliance on optical measurement instruments, a comprehensive examination of the physical interaction between light and particle matter becomes imperative.

2.1. Light absorption and light scattering

The measurement of turbidity and SSC by optical methods relies on the attenuation of light in the medium and exploits the changes in light intensity caused by the light and suspended particle interactions. The attenuation of light itself is the combined effect of light scattering and light absorption. The particulate matter refers to a broad category of solids suspended in the medium that can vary significantly in size, ranging from ultrafine particles (<0.1 μm) to coarse particles, and have both natural and anthropogenic origins.

Light absorption is a phenomenon where light is taken up and converted into other forms of energy, typically heat, within a material. Light absorption occurs when photons, particles of light, interact with electrons in atoms or molecules. The energy carried by the photons is transferred to the electrons, causing them to move to a higher energy state or even be removed entirely from their original atomical orbit. In other words, the particles suspended in water exhibit light-absorbing properties, particularly in certain wavelength ranges. As light passes through a turbid medium, the particulate matter can absorb photons, reducing the intensity of the transmitted light. The extent of light absorption depends on the nature of the particles, their size, and the specific wavelengths of light involved. Different types of solids absorb light at distinct wavelengths, and this specificity is exploited in turbidity measurement instruments. By using light sources with specific wavelengths, measurements to target the absorption characteristics of the suspended particulate matter can be tailored. Beer-Lambert Law describes the relationship between the absorbance of light by a substance and its concentration in a solution and is expressed mathematically as:

$$A = \varepsilon \cdot c \cdot l \quad (1)$$

A = absorbance of the sample [dimensionless]
ε = molar absorptivity [L/mol/cm]
c = concentration of the absorbing substance in the solution [mol/L],
l = path length of the light through the solution [cm].

$$\varepsilon = \frac{4\pi^* k}{\lambda} \quad (2)$$

k = empirical constant or coefficient associated with the material [dimensionless]
λ = wavelength of the incident light [cm]

The law states that the absorbance of light by a substance in a solution is directly proportional to both the concentration of the absorbing substance and the path length of the light through the solution. Mathematically, it can also be expressed in terms of transmittance (T, dimensionless) as:

$$A = -log_{10}(T) \quad (3)$$

In practical terms, the transmittance can be analyzed as the proportion between the incident (I_0) and transmitted light (I_1):

$$T = \frac{I_1}{I_0} \quad (4)$$

The Beer-Lambert Law demonstrates an exponential relationship between the light transmission through a substance and its concentration, as well as the correlation between transmission and the distance travelled by the light through the material. The coefficient of absorption (ε) value varies depending on the absorbing material properties and the wavelength for each specific material. Thus, light absorption increases with rising concentration, greater suspended particulate matter content, and shorter incident wavelength.

In turn, light scattering is a phenomenon that occurs when light interacts with particles or irregularities in a medium, causing the light to change its direction. The scattering of light can be divided into regular and diffuse scattering. Its interaction with different particulate sizes can also be divided into two phenomena: Rayleigh scattering and Mie scattering. Regular scattering refers to the predictable and organized dispersion of waves, often characterized by specific angles or wavelengths. A classic example is Bragg scattering, which is observed in crystals when light waves interact with a regular array of atoms or the scattering of light on a smooth and mirrored surface. Diffuse scattering involves the random dispersion of waves in various directions, lacking a specific pattern. This occurs in materials with disordered structures or imperfections, such as liquids or amorphous solids. The absence of a regular arrangement of particles or atoms leads to scattering in multiple directions. Rayleigh scattering occurs when the size of the scattering particles is much smaller than the wavelength of the incident light and is predominant with samples with colloidal particles. The intensity of Rayleigh scattering is inversely proportional to the fourth power of the wavelength of light. This means shorter wavelengths (blue and violet) are scattered more strongly than longer wavelengths (red and orange). Mie scattering occurs when the size of the scattering solids is comparable to or larger than the wavelength of light. Mie scattering is less dependent on the wavelength of light compared to Rayleigh scattering and is more prominent for larger particles as typical suspended sediment from the watersheds. Both light-scattering interactions have practical applications in various fields and are extensively used for determining the size distribution of particles in colloids, aerosols, and biological samples. Light scattering is a crucial principle behind turbidity measurements, where the amount of scattered light is proportional to the concentration of particulate matter in a fluid.

2.2. Nephelometry, backscattering and turbidimetry

Based on the concepts of light scattering and absorption, different methodologies are applied to gauge the interaction between light and suspended particulate matter within a fluid. These methods encompass nephelometry, backscattering, and turbidimetry (Fig. 1).

Nephelometry is a pivotal technique in analytical chemistry and environmental monitoring, employed for precisely quantifying suspended particulate matter in liquid samples. The method involves measuring light scattered at a specific angle (typically 90°) from a suspension of particles in a liquid medium. This scattered light is detected orthogonally to the incident light, allowing for accurate determination of particle concentration based on the intensity of the scattered light. For distilled water, the absence of optical obstacles results in a null optical value, which will increase with the increase of suspended particles. However, for high turbidity values, the reflected light is absorbed by the materials and the output decreases. The nephelometric detection is particularly accurate for low turbidity and depends mainly on the size and number of particles in suspension [23].

Backscattering focuses on the measurement of light scattered directly backwards, opposite to the direction of the incident light. Often employed at an angle close to 135°, backscattering provides valuable insights into the properties of scattered particles in various media. For distilled water, this type of detection has a zero-optical sensing value (there are no obstacles reflecting the light). With the increase of turbidity and consequent increase of suspended sediments and reflections, the detected light output increases. The advantage of this type of detection is the wide measuring range and accuracy for high turbidity values. On the other hand, for low turbidity values, backscattering is less accurate than nephelometric detection. The backscatter detection strongly depends on the size, composition and shape of the suspended particles [24].

Turbidimetry, often referred to as transmitted light detection or

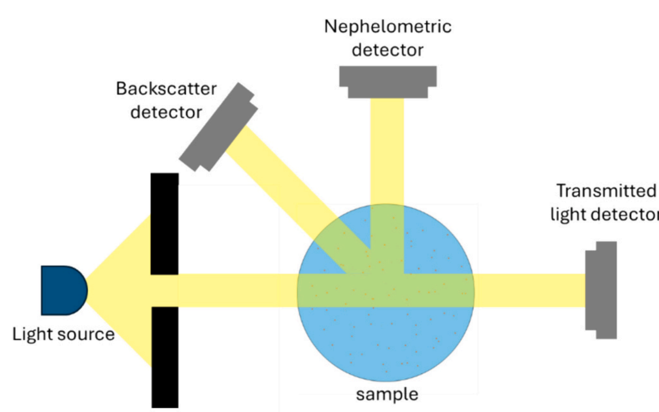

Fig. 1. Illustration of the three predominant optical methods for quantifying light scattering and absorption.

transmissometry, is an analytical method widely utilized for assessing the concentration of suspended particles in liquid samples based on the reduction in transmitted light intensity. As light passes through a turbid medium containing dispersed particulate matter, it undergoes scattering and absorption, decreasing the measured transmitted light intensity. This decrease is directly correlated with the concentration of particles present in the sample. For distilled water, the light detection has a maximum output value, that decreases with the increase of turbidity (particles will absorb and scatter the light on its path). This technique presents higher sensibility, offering a wide dynamic range. However, it is vulnerable to colouration, particle transparency, and particle size, which results in lower precision [25].

The central components of optical instrumentation utilized for the measurement of turbidity and suspended sediment are the techniques of nephelometry, backscattering, and turbidimetry. These methods play a foundational role in providing quantitative insights into the concentration and characteristics of suspended particles within a fluid medium. Together, these optical techniques form an integral part of analytical methodologies, contributing essential data for environmental monitoring, water quality assessment, and diverse scientific investigations involving suspended sediments.

3. Optical methods and techniques

3.1. Visual empirical methods

The first practical attempt to measure turbidity in the laboratory was through the Jackson candle method. The instrument consists of a lighted candle, placed under a glass tube with a flat bottom. The fluid, in which the turbidity is to be measured, is slowly poured into the tube until the flame image is no longer visible from a top point of view (the light does not disappear completely, just the image of the flame). This phenomenon occurs when the light is completely dispersed by the suspended particles in the liquid. The tube contains a graduation that allows relating the volume of the liquid to its transparency and consequent turbidity. To standardize the instrument, the initial grading used was ppm (parts per million) of silicon dioxide (SiO2, or commonly silica), called Jackson Turbidity Units (JTU). After the invention of Formazin in 1926, a new degree was adopted: Formazin Turbidity Units (FTU). Formazin is currently the most popular turbidity standard solution for calibrating turbidity devices. Other techniques, often called turbidity tubes, were improved based on the Jackson candle method. Turbidity tubes are transparent tubes filled with water samples. The operator visually compares the turbidity of the sample against a standard disk or pattern at the bottom of the tube and estimates turbidity based on the water clarity. Commonly, turbidity tubes are used in the field to provide a quick visual assessment of water turbidity. Even with some improvements over time, these methods have limitations. The Jackson Candle has a limited dynamic range, and samples below 25 JTU are impossible to read. Also, the readings are subjective as they are based on human observation.

A well-known method to measure turbidity *in situ* is the Secchi Disk, created in 1865 by Pietro Angelo Secchi. Due to its simplicity, low cost, portability and ease of handling, it is still used in naval instrumentation. The Secchi disk consists of a flat circular disk with a diameter between 16 cm and 40 cm, usually divided into four equivalent parts, with the contrasts of black and white or, in some cases, completely black or completely white. The disk, attached by a rope, is slowly submerged in the water until it is no longer visible, finding the Secchi depth. The readings using this instrument depend on the attenuation of light in water, which is, the ability of light to penetrate the medium. When the disk is underwater and the light is reflected from it, the disk is visible to the observer. When the disk is obscured by suspended sediment, the light is scattered and diffused through the medium. High depths are related to increased water clarity and low turbidity levels. On the opposite, low depths indicate high levels of turbidity. As for the Jackson Candle Method, this technique is also unreliable. Readings are affected by changes in sunlight conditions, water shaking, time of day and human error [26]. Currently, these types of light-extinction methods are considered obsolete, in favour of electronic instruments that offer greater dynamic range and accuracy.

3.2. Standard methods

The optical turbidimeters have solved the problem of susceptibility to human error presented by previous methods while increasing their dynamic range and precision. These electronic devices use a light source and one or more optical receivers. When the light passes through the medium it is scattered and absorbed by the existing suspended particles, varying the electrical signal of the light detectors. This electrical value is correlated to a turbidity or suspended sediment concentration value.

There are several standardized methods for measuring turbidity, yet each employs distinct units. The introduction of multiple turbidity units is attributed to variations in instrument design, light source type, detector specifications, and measuring angles, all of which can influence instrument readings. Consequently, different turbidity instruments may yield distinct measurements when applied to the same sample. The U.S. Environmental Protection Agency (EPA) has approved eight methods for drinking water monitoring. Until 2009, only four methods were accepted: EPA Method 180.1, Standard Method 2130B, Great Lakes Instrument Method 2 (GLI 2) and Hach Method. In 2009, the EPA approved four new methods: Mitchell Methods M5271 and M5331, Orion AQ4500, and AMI Turbiwell. In addition, the United States Geological Survey (USGS) and the International Organization for Standardization (ISO) employ their techniques. Table 1 summarizes the most significant turbidity standard methods currently in use.

3.2.1. EPA 180.1

EPA 180.1 is a turbidity measurement method approved to monitor the quality of water for human consumption [27]. This method uses nephelometric technology with a photodetector positioned at 90° (±30°) from the light source. To minimize differences in light scattering measurements, the light path from the light source to the photodetector is constricted to 10 cm. Additional receivers are allowed if the 90° angle prevails the most relevant. The light source used is a tungsten lamp with a colour temperature between 2200 and 3000 Kelvin. This means that the output is polychromatic (broadband spectrum). The photodetector receives light with a wavelength of 400 to 600 nm. The broadband spectrum allows the instrument to be sensitive to smaller particles. This sensitivity means that the tungsten lamp source provides a more accurate response than a monochromatic light source when measuring smaller suspended particles. However, it also makes the device more susceptible to coloured matter. If too much matter is absorbing different wavelengths, the accuracy of the sensor decreases. Also, the use of the tungsten lamp requires a daily calibration check and frequent recalibration due to the incandescent decomposition inherent to the lamp. As the lamp slowly burns, the light output decreases, producing errors in the readings.

EPA 180.1 Method uses nephelometric technology calibrated with a formazin standard. Thus, its units come in Nephelometric Turbidity Units (NTU). Instruments ruled by this standard are suitable for measuring turbidity levels between 0 and 40 NTU. At higher levels, the relationship between light scattering and turbidity becomes nonlinear. This means that the amount of stray light that can reach the photodetector decreases, limiting the capability of the instrument. The optimal condition for using this method is in samples without colour interference and low turbidity. If high turbidity samples need to be measured, the dilution of the sample is possible using the following equation:

$$T_o = \frac{T_d{*}(V_w + V_o)}{V_o} \tag{5}$$

T_o = turbidity value of the original sample [NTU]

Table 1
Turbidity standard methods in use for drinking water monitoring.

Method	Organization	Light source	Detector(s)	Light path	Range	Resolution
180.1	EPA	Tungsten lamp 2200–3000 K	400–600 nm 90 ± 30°	10 cm	0–40 NTU	0.02 NTU
2130B	Standard Methods	Tungsten lamp 2200–3000 K	400–600 nm 90 ± 30°	10 cm	0–40 NTU	0.02 NTU
7027	ISO	LED 860 ± 30 nm	860 ± 30 nm 90°	10 cm	0–1000 NTU	0.02 NTU
Method 2	Great Lake Instruments	Two LEDs 860 ± 30 nm	860 nm 90 ± 2.5°, and 0 ± 2.5°	Not defined	0–40 NTU	0.02 NTU
10,133	Hach	LASER 630–690 nm	630–690 nm 90 ± 2.5°	10 cm	0–5NTU	0.001 NTU
M5271	Leck Mitchell	LASER 620–680 nm	620–680 nm 90 ± 30°	10 cm	0–40 NTU	0.001 NTU
M5331	Leck Mitchell	LASER 510–540 nm	510–540 nm 90 ± 30°	10 cm	0–40 NTU	0.001 NTU
Orion AQ4500	Thermo Scientific	White LED, and IR LED	860 nm 90 ± 30°, and 0°	10 cm	0–40 NTU	0.02 NTU
AMI Turbiwell	Swan Analytische Instrumente AG	White LED	400–600 nm 90 ± 30°	10 cm	0–40 NTU	0.02 NTU

T_d = turbidity of the diluted sample [NTU]
V_w = volume of dilution water [mL]
V_o = volume of the original sample taken for dilution [mL]

3.2.2. Standard method 2130B

Standard Method 2130B was established by the American Public Health Association (APHA) for water and wastewater quality monitoring [28]. This method has only a few slight differences from EPA 180.1, so they are often mistaken. The components used and the design rules of the instrument are the same as EPA 180.1. The differences relate to the definition of the primary calibration standard and the measuring range of the methods.

According to Standard Methods for Examination of Water and Wastewater, the only acceptable primary calibration standard is formazin, made from scratch by the user, and following the specific instructions described. However, Method 2130B states that user-prepared formazin should be used as a last resource due to the use of carcinogenic compounds. Instead, they recommend the use of commercial or manufacturer-supplied calibration solutions, which are considered secondary standards. On the opposite, EPA 180.1 considers both user-prepared formazin and commercial formazin as primary standards and does not differentiate. The second difference is the dynamic measuring range of the devices. EPA 180.1 sets the maximum measurement limited at 40 NTU, and for higher value measurements the sample must be diluted. Standard Method 2130B claims that its range extends to 1000 NTU and sample dilution should be avoided whenever possible as the composition of the sample may change, resulting in less accurate measurements.

3.2.3. ISO 7027

The International Organization for Standardization has developed its nephelometric method known as ISO 7027 [29]. This standard attempts to ensure that turbidity devices have good repeatability and comparability. Although quite common throughout Europe, this method is not approved by EPA for drinking water regulations.

As with previous methods, turbidity is measured by diffuse light at 90°, and the difference relates to the spectral band of the light source. This method specifically requires a monochromatic light source, with a wavelength of 860 nm, and a spectral bandwidth of 60 nm. In most cases, instruments using this method use an 860 nm light-emitting diode (LED). For the light detector, a 90° primary angle is required. Additional detection angles are also allowed, but the nephelometric detector is the primary source of measurement. As for EPA 180.1, the light path distance is limited to 10 cm. For turbidity levels between 0 and 40 NTU, the recommended unit for this method is the Formazin Nephelometric Unit (FNU). The USGS suggests that this method can be used up to 1000 NTU with a single photodetector, or up to 4000 NTU if additional detectors are used. For the last case, the used unit is the Formazin Nephelometric Ratio Unit (FNRU).

Both EPA 180.1 and ISO 7027 use nephelometric technology calibrated with formazin standards. However, differences in the light source and slight differences in design create distinct measurement results. ISO 7027 has the advantage of using near-infrared light, which is less absorbed by coloured particles, thus reducing the error that a broadband light source has. In addition, LEDs are more stable over time than tungsten lamps. However, since longer wavelengths are less sensitive to small particle sizes, this method produces turbidity readings slightly lower than the EPA 180.1 method for low turbidity samples.

3.2.4. GLI Method 2

The GLI Method 2 doubles the number of light sources and photodetectors used in the previous methods, doubling the number of measurements and using them to cancel errors [30]. This method, also known as four-beam modulated turbidimetry, uses an emitting source and two receivers positioned at angles of 0° and 90° for each measurement. Alternating between active emitters changes the significance of each one in turn. The method uses two 860 nm LEDs that alternate the pulses of light every half second. The photodetectors take simultaneous readings providing an active signal and a reference signal. The detector placed directly in front of the active LED is considered the reference signal (transmission light technique) and the detector at a 90-degree angle is considered the active signal (nephelometric technique). The active and reference signals alternate every half second when the other LED pulses. Thus, GLI Method 2 provides two active and two reference measurements to determine each reading. Due to these differential measurements, errors that may appear are mathematically cancelled. The following expression calculates the turbidity measured:

$$Turb = Cal_0 * \sqrt{\frac{Ative_1 * Ative_2}{Reference_1 * Reference_2}} - Cal_1 \tag{6}$$

$Turb$ = turbidity value of the sample [NTU]
Cal_0 = calibration coefficient 0
Cal_1 = calibration coefficient 1
$Ative_1$ = 90 Degree Detector Current [mA] (Light Source 1 ON, Light Source 2 OFF)

$Ative_2$ = 90 Degree Detector Current [mA] (Light Source 1 OFF, Light Source 2 ON)
$Reference_1$ = Transmitted Detector Current [mA] (Light Source 1 ON, Light Source 2 OFF)
$Reference_2$ = Transmitted Detector Current [mA] (Light Source 1 OFF, Light Source 2 ON)

The GLI Method 2 allows higher sensitivity and error cancellation for turbidity levels between 0 and 100 NTU. However, its accuracy decreases as turbidity levels rise above 40 NTU due to the increase of scattered light. GLI 2 instruments are ideal for low turbidity ranges and are extremely accurate when used on samples with turbidity levels between 0 and 1 NTU. Due to the multibeam design, the USGS recommends using Formazin Nephelometric Multibeam Unit (FNMU) instead of NTU. Instruments with this design are still classified as nephelometric technology due to the use of photodetectors at 90° angles.

3.2.5. Hach 10133

Hach 10133 is a measurement method approved by the U.S. Environmental Protection Agency [31]. Based on nephelometric technology, this method uses light amplification by stimulated emission of radiation (LASER) as a light source, opposing to the tungsten lamp or infrared LED used by EPA 180.1 and ISO 7027, respectively. The LASER emits red light with a wavelength between 630 and 690 nm, and the light path is limited to 10 cm. The photodetector is placed at 90° from the light source and is connected to a photomultiplier tube (PMT) through a fibre optic cable. The PMT is used to increase the sensitivity of the photodetector. This configuration allows the detection of very low turbidity levels. Due to the high resolution, its units are commonly expressed in milli Nephelometric Turbidity Units (mNTU). Thus, the recommended range for the instruments is 0 to 5000 mNTU (0 to 5 NTU). Unlike previous methods, the Hach Method 101033 was designed for in-line or in-process monitoring. Instruments following this method are ideal for fluids with very low turbidity, such as drinking water or effluents in wastewater treatment plants. In 2016, the Hach 10258 method was also approved by EPA. The difference from the previous method is the use of 360° nephelometry detection.

3.2.6. Mitchell M5271 and M5331

Mitchell's methods are alternative testing procedures, approved by EPA in 2009, to measure drinking water turbidity [32]. The term alternative test procedure refers to using EPA-approved nephelometric techniques without resulting in a completely new method. Thus, Mitchell's methods produce comparable results to the EPA 180.1 method. As Hach 10133, these technologies aim to be used for in-line monitoring. For method M5271, the light source is a LASER with a wavelength between 620 and 680 nm. The M5331 uses an LED with a wavelength between 510 and 540 nm. For both, the photodetector is placed at 90° with a margin of 30°, and the light path is limited to 10 cm. The differences between these methods compared to the previous ones are the introduction of water bubble retention mechanisms and an anti-condensation window. Instruments conformed to these methods must be able to withstand up to 30 psi. Like the EPA 180.1 method, the measurement range is limited from 0 to 40 NTU.

3.2.7. Orion AQ4500

The Orion AQ4500 method, developed by Thermo Fisher Scientific, is based on using the Thermo Orion AQUAfast turbidimeter model AQ4500 and is also an alternative test procedure for EPA 180.1 [33]. The method operates on nephelometric and direct light transmission that allows turbidity measurement based on EPA 180.1, ISO 7027 and GLI 2. The instrument uses two light sources (white and infrared LEDs) to pulsate light at high frequencies, allowing synchronous detection. This way, scattered light and inducted electronic errors can be corrected. Two receivers sense the light: a nephelometric detector to measure turbidity, and a transmitted light detector, placed at 0° from the emitting source, used as a reference for colour compensation. The ratio between the two measurements results in the final turbidity value. Although the manual of this instrument claims that its measurement ranges from 0 to 4000 NTU, EPA only recognizes this method for measurements up to 40 NTU. For turbidity values above this value, the sample must be diluted.

3.2.8. AMI Turbiwell

AMI Turbiwell, developed by SWAN Analytic Instruments, is also an alternative EPA-approved test procedure for in-line continuous monitoring [34]. This turbidimeter has a unique property and does not have direct contact with the fluid to perform the measurement. Also known as surface scatter, this method uses a reservoir, through which the liquid flows, with a thin glass opening that is exposed to a light source placed outside the tube. The emitted light is reflected by the particles in the liquid and sensed by a nephelometric receiver. The light-emitting source used is a white LED (typically a blue LED coated with phosphor) placed at 45° to the surface of the liquid. The photodetector is placed at 90° to the emitter and has a wavelength sensibility of 400 to 600 nm. According to the method, the sensed light cannot travel more than 10 cm. Although the technique states that this system can be used for measurements up to 200 NTU, it is limited to 40 NTU by EPA.

3.3. In situ sensors

While standard methods are well established in water facilities, they present additional problems when considered for *in situ* monitoring. First, most of the methods are limited to 40 NTU. Rivers, coastal areas and estuaries can have high concentrations of suspended sediment in the water, so this range is insufficient. Also, the standard methods are expected to be used for laboratory analysis or in-line measurements, which means that they are dependent on the electric grid, need human operation, are not suited for submersion, and, in many cases, are large, heavy and expensive. Nevertheless, they are the technological base used in the available commercial optical turbidity sensors for continuous monitoring in the field. Due to the short dynamic range of the previous apparatus, a new light detection technique was introduced for *in situ* turbidimeters: the optical backscatter technology. In contrast to the commonly used nephelometric technique, backscattering detection allows for measuring high turbidity levels. Other capabilities were optimized to perform longstanding measurements in the field: internal batteries, internal storage, electronic watertight, and, in some cases, biofouling protection.

Seabirds Scientific, Valeport and Seapoint Sensors are some of the most popular brands for oceanographic instruments, including optical backscatters. Hach and Hanna Instruments, are also recognized brands in this market, but they primarily target wastewater treatment plants and other water treatment facilities. The commercial offer these brands provide is wide, with different series of *in situ* turbidimeters with measuring ranges up to 4000 NTU and precision of 0.01 NTU. Although these devices are technologically suitable for *in situ* monitoring, they present a problem regarding their cost. Depending on the extras desired (battery, wipers, complementary sensors, *etc.*) their prices typically range from 2000 € to 30.000 €, which can be unpractical for massive deployments. Besides the cost of these instruments, the difficulty of maintenance, installation, replacement, and calibrations are pointed out as some of the concerns of its users [35,36].

With the emergence of the Internet of Things (IoT) and smart sensors, the scientific community has gathered efforts to apply the available technology to develop low-cost instruments for environmental monitoring. These instruments usually measure turbidity using backscattering, nephelometric or transmitted light detections, are calibrated with standard formazin, and present their output in NTU [37–40]. Others, take a step forward in the measurement of SSC and do the calibrations with clay, feldspar, sand and even sediment collected from the deployment areas [41–43]. Although the calibration of suspended sediment is not easy due to the significant variability of matter that appears in natural waters, some works go even a step further, presenting proofs of concept to differentiate inorganic from organic matter compounds using light sources of different wavelengths [43–45]. New techniques have been introduced to avoid daylight interference based on light modulation or external light calibrations [43,46–48], optical fibre designs to increase sensitivity [49–51], and wireless capabilities to integrate the sensors in monitoring networks and platforms [52–55]. Also, although field studies with turbidity instruments often overlook this issue, the scientific community has directed attention toward biofouling as a comprehensive concern, leading to the emergence of new and innovative technologies [56–58]. The effectiveness of these emerging techniques holds the potential to enhance the prolonged application of *in situ* instruments in environmental deployments. The field of micro-electromechanical systems (MEMS) has also spurred the development of novel sensing devices applicable across various domains. Spectroscopy technology, notably, has found successful integration into miniature instruments [59,60], which may provide the base for a new generation of optical turbidimeters.

The limitations of the current literature's findings are that most of the showcased devices are still confined to the laboratory, without field results and, in many cases, without water tightness or energy consumption concerns. Additionally, there is a notable absence of comparative analyses between these low-cost devices and their commercial counterparts, along with a scarcity of ground-truth validation during field deployments.

4. Other methods and techniques

4.1. Acoustic backscatter sensors

One commonly utilized oceanographic instrument is the Acoustic Backscatter Sensor (ABS). The ABS technology is rooted in the Acoustic Doppler Current Profiler (ADCP), a widely employed technology in Autonomous Underwater Vehicles (AUV). However, they diverge in terms of the specific parameter designed to measure. Unlike its optical peers, the ABS does not intend to measure turbidity. The objective is to measure the amount and size of suspended sediment in the medium, this is, to measure the Total Suspended Solids (TSS) in the water. To do so, an emitter and an acoustic receiver are placed in the same plane and with the same orientation. The emitter generates acoustic waves that are reflected by the suspended particles in the water. The receiver transducer senses the reflected echoes. Acoustic turbidimeters process the power magnitude of the received echoes, estimating the amount and size of the particulate matter in the water. With the time of flight of the acoustic waves, it is also possible to determine the distance to which the sediments are, thus obtaining a stratified measurement in depth [61].

The ABS technology presents significant advantages compared with optical turbidimeters: it measures TSS instead of turbidity, which is a better estimation of suspended sediment concentration; it can differentiate sediment particulate size; and by measuring the time-of-flight of the echoes it is possible to estimate SSC at different depths. Also, using the principle of operation of ADCPs to measure the frequency shift of the echoes, it is possible to estimate water velocity, which can be correlated with sediment concentration measurements and provide information about sediment transport [62–65]. The main problem with this technology is that suspended sediment can take the most varied shapes, sizes and matter constitutions, resulting in different acoustic responses. The interpretation of the echoes becomes a difficult task, even with good calibrations. Because of their accuracy limitations, ABSs have lower acceptance when compared to optical technologies.

4.2. Capacitive sensors

Capacitive sensors have gained prominence in environmental monitoring due to their versatility and reliability in measuring various parameters. These kinds of devices measure changes in capacitance, which is the ability of a system to store an electric charge. In the context of turbidity and suspended sediment measurement, capacitive turbidity sensors operate based on changes in capacitance caused by the presence of suspended particles in water. The sensor typically consists of two electrodes and the capacitance between them is influenced by the dielectric constant of the medium. As water turbidity increases due to the introduction of particles, the dielectric constant changes, resulting in alterations in the capacitance. These changes are then translated into turbidity readings by the sensor.

Capacitive sensors are highly sensitive to changes in turbidity levels, allowing for the detection of low concentrations of suspended particles and are less affected by biofouling when compared to optical turbidimeters. However, these instruments may face challenges in providing accurate measurements in waters with high suspended sediment concentration and the calibration is rather complex. Any variation in the medium characteristics (pH, temperature, salinity, *etc.*) produces changes in the dielectric of the capacitive mechanism, which is an obstacle for environmental and most industrial processes. Henceforth, capacitive sensors for measuring turbidity have not garnered commercial availability or significant attention from the scientific community. While the literature does contain a limited number of proof-of-concept studies employing this methodology, these investigations were predominantly conducted within controlled laboratory settings [66,67]. A notable gap remains, as field demonstrations are requisite to validate capacitive sensors as a robust and viable option for measuring suspended sediment concentration.

4.3. Satellite and aerial imaging

Satellite and aerial imaging are powerful tools for remotely sensing turbidity in large bodies of water. These methods leverage the ability of specific sensors to capture and analyze the light properties of water, allowing them to estimate turbidity levels over extensive areas.

Satellites equipped with remote sensing instruments, such as multispectral or hyperspectral sensors, capture data in different spectral bands. Each band corresponds to a specific range of wavelengths of electromagnetic radiation. Some bands can penetrate water to varying depths, especially in the visible and near-infrared spectrum. Turbidity affects the ability of light to penetrate the water column, leading to changes in the reflected and absorbed light. Analyzing the reflectance patterns in these bands makes it possible to estimate the concentration of suspended particles in the water. Higher turbidity levels typically result in increased scattering and absorption of light, leading to distinctive spectral signatures.

Aerial imaging involves capturing photographs or data from aircraft flying over a specific area. This method offers higher spatial resolution, but less coverage area than many satellites, allowing for detailed observations of smaller water bodies or particular regions of interest. Like satellites, aircraft can carry multispectral or hyperspectral sensors to capture data in various bands. This enables the analysis of specific wavelengths related to water properties. Aerial imaging provides more flexibility regarding flight paths and can be used for targeted surveys or detailed studies in areas of interest. In some cases, aerial imaging may provide near real-time data, especially when deployed for specific research campaigns or environmental emergencies.

Both satellite and aerial imaging have been used in various applications, including environmental monitoring, water quality assessment, and disaster response [68–76]. These methods are particularly valuable for studying turbidity in large water bodies, coastal zones, and areas where access may be challenging. However, they depend on the validation and calibration of ground-truth instruments, can have limited spatial and temporal resolutions, and are dependent on atmospheric conditions. Acquiring and processing satellite or aerial imagery can be expensive, especially if high-resolution data is required. Additionally, the sensors on satellites and aerial platforms may have limitations in terms of spectral resolution. Different constituents often influence turbidity in water, and a narrow spectral range may not capture all relevant information. This can make it challenging to differentiate between various water quality parameters.

5. Conclusion

The measuring of turbidity has deep roots in monitoring the water quality of water facilities. Thus, the existence of rigorous and well-established methods to ensure public safety is not a surprise. The available instrumentation already offers the necessary measuring range and precision for proper operation. Even though different methods can produce slightly different readings to the same sample, the lack of standardization is deemed acceptable, as the primary focus remains on maintaining turbidity levels below predefined thresholds.

The recent technological advancements in measuring turbidity and SSC are evident in the domain of environmental monitoring, and they are expected to continue alongside the increasing prominence of IoT and smart sensing technologies. While the available commercial turbidimeters provide the required tools for *in situ* monitoring, the advent of cost-effective gadgets appearing in the literature suggests that their prices pose a hindrance to the widespread adoption of field studies. The demand for low-cost sensors has driven recent technological progress in this area, introducing new designs, alternative calibration methodologies, and a focus on particulate matter compounds. However, the overload of field studies and truth validation of these instruments is still a challenge to overcome. Furthermore, unlike monitoring in water facilities, ensuring comparability and interchangeability of turbidity measurements from different instruments is essential, yet standardization poses a forthcoming challenge. By tackling these challenges head-on, together with techniques for biofouling mitigation, we can enhance the reliability and effectiveness of turbidity monitoring in environmental applications.

Optical instrumentation remains the most widely adopted method for evaluating turbidity and SSC, it is expected that this trend will continue into the foreseeable future. While acoustic techniques hold allure with promises of measuring sediment size distribution, depth profiling, and potential correlation with water velocity, their calibration complexity surpasses that of optical sensors, affecting their accuracy. Still, the extensive utilization of ADCPs and other acoustic-based sensing technology in research vessels and underwater vehicles will maintain the relevance of acoustic backscatter sensors. Conversely, capacitive instrumentation is unlikely to gain prominence, as there is a lack of substantial fieldwork validating its applicability in real-world scenarios.

Finally, satellite and aerial imaging processing appears as a complementary technique for turbidity monitoring and the frequency of published remote-sensing works indicates an increasing importance of this field. While its effectiveness relies on field validation through traditional measuring techniques, its convenience and capacity to monitor expansive water bodies render it a compelling tool for the foreseeable future. The integration of machine learning and deep neuronal networks and their forecasting capabilities further enhances its potential applicability, extending its utility to both remote and *in situ* observations.

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CRediT authorship contribution statement

T. Matos: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **M.S. Martins:** Writing – review & editing, Validation, Supervision, Project administration. **R. Henriques:** Writing – review & editing, Validation, Supervision. **L.M. Goncalves:** Writing – review & editing, Validation, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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