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Hydrometry — Suspended sediment in streams and canals — Determination of concentration by surrogate techniques

Hydrométrie — Sédiments en suspension dans les cours d'eau et dans les canaux — Détermination de la concentration par des techniques de substitution

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Foreword

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

The committee responsible for this document is ISO/TC 113, *Hydrometry*, Subcommittee SC 6, *Sediment transport*.

Introduction

Sedimentation and sediment transport in streams, rivers, reservoirs and estuaries are key parameters in many scientific, environmental, engineering, and agricultural problems. Success in managing and solving sedimentation problems requires comprehensive knowledge of sediment movement. This requires reliable methods of estimation of sediment load with high-quality data. The amount of sediment transport data being collected, however, has steadily declined in recent decades largely due to difficulty and costs associated with field methods used for data collection. High temporal resolution data of high quality are needed to better understand and more adequately describe many sedimentation processes.

The bed load and suspended load broadly constitute total sediment load. However, the scope of this International Standard is confined to the measurement of suspended sediment. Conventional methods for measurement of suspended sediment concentrations in streams rely on the principle of collecting samples of water-sediment mixture at various points in time and space using suitable sampling equipment and deployment methods and analysing the samples in laboratory for estimating the sediment concentration. These methods are labour intensive, expensive and can be hazardous. Moreover, the accuracy of these methods in estimating the sediment concentration of rivers and streams over a period of time may not be dependable due to the large spatial and temporal variability associated with the transport of suspended sediment.

Continuous and accurate estimation of suspended sediment concentration is essential in certain situations such as:

a) in hydropower projects for the safety of the turbines and other machinery, reservoir silting and flushing;

b) water-supply projects for monitoring water quality;

c) storm water run-off from urban areas;

d) silting of wetlands; and

e) long-term monitoring of sediment transport in rivers and streams, in order to obtain reliable base lines that can be used for decision making.

In such situations, automatic and cost-effective techniques are essential to collect high-quality data on suspended sediment concentrations and particle sizes.

Recent technological advances in the fields of optics and acoustics have provided new sediment-surrogate technologies and methods to determine suspended sediment fluxes and characteristics. Some of these methods can be used to measure suspended sediment concentration at higher resolution, with greater automation and potentially lower cost than traditional methods. These methods involve surrogate technologies that derive the suspended sediment concentration from measurements of optical backscatter, laser diffraction and acoustic backscatter.

The measurement of suspended sediment concentration (SSC) in the water samples can be carried out with the help of nephelometry, transmission, laser diffraction and acoustic back scatter techniques. The working principles, applications, advantages and disadvantages, limitations and usable instruments of the above techniques are elaborated in this International Standard. The optical backscatter technique is readily available and relatively inexpensive. Optical backscatter sensor sensitivity depends on grain size, colour and composition. The advantages are small size and small sample volume, linear and high frequency response, insensitive to ambient light, large measuring range and low cost. The laser diffraction (LD) technique is also readily available and cost effective. The acoustic backscatter is another technique for measurement of SSC in the aquatic ecosystems. Measurements are possible for a range of sediment sizes that is dependent on the acoustic frequency. The available maximum sampling depth will be limited at high concentrations.

Hydrometry — Suspended sediment in streams and canals — Determination of concentration by surrogate techniques

1 Scope

This International Standard specifies methods for determination of the concentrations and particle-size distributions of suspended sediment in streams and canals by surrogate techniques. Methods based on bulk-optical principle of water such as transmission and nephelometry are the most commonly used surrogates for determining suspended sediment concentrations (SSC). Instruments and techniques based on acoustic attenuation and/or acoustic backscatter principles are also in use for measurement of suspended sediment concentration. Instrumentation based on the laser diffraction principle is also used for the measurement of particle size distribution. This International Standard covers brief description of the operating principle of each method and details of some of the instruments available.

The detailed method and principle of optical and acoustical transmission, nephelometry, and optical back scatter (OBS), laser diffraction technique (LD) and acoustic back scatter technique (ABS) with their limitations are described in Annex A, Annex B and Annex C respectively.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

ISO 4363, *Measurement of liquid flow in open channels — Methods for measurement of characteristics of suspended sediment*

ISO 13320, *Particle size analysis — Laser diffraction methods*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772, ISO 4363 and ISO 13320 and the following apply.

3.1
surrogate technique
indirect method in which a substitute object or property is used for measurement in place of the original object or property

Note 1 to entry: Optical and acoustic properties of water-sediment mixture such as optical transmission, acoustic scattering and laser diffraction are some of the surrogates for measurement of suspended sediment concentration.

3.2
nephelometry
any method for estimating the concentration of particles in suspension by measuring the intensity of scattered light

Note 1 to entry: Light scattering depends upon number, size distribution, colour, composition (as manifested in the complex index of refraction) and shape characteristics of the particles.

4 Measuring principles

Optical and acoustical methods can be used for continuous measurement of sediment concentration. The measuring principles for the above surrogate techniques are similar and can be classified in three categories as described in 4.1 to 4.4 (see Figure 1).

4.1 Transmission

The source and detector are placed opposite to each other at a distance l as shown in Figure 1 A. The source emits a collimated light beam with intensity I_o. The sediment particles in the measuring volume reduce the beam intensity by absorption and scattering resulting in a reduced detector signal. The relationship between the detector signal (I_t) and the sediment concentration (c) is described by Beer's Law[43] and is given by Formula (1):

$$I_t = I_o e^{-kcl} \quad (1)$$

where

I_t is the transmitted light through a sample of length l in water of sediment concentration c;

I_o is the incident intensity of the emitter source;

k is a constant depending on the sediment, water, and instrument characteristics.

4.2 Scattering

The source and detector are placed at an angle φ relative to each other shown in Figure 1 B. The detector receives a part of the radiation scattered by the sediment particles in the measuring volume. The relationship between detector signal (I_s) and sediment concentration (c) is given by Formula (2):

$$I_s = k_3 I_o c e^{-k_2 c} \quad (2)$$

where

I_o is the incident intensity of the emitter source;

k_2 is a constant depending on the sediment, water, and instrument characteristics;

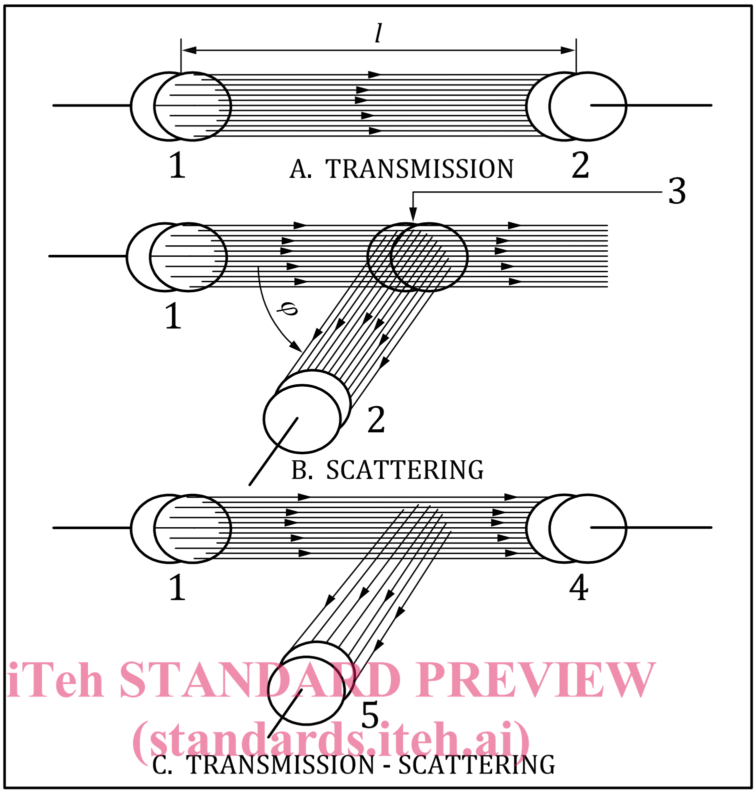
k_3 is a calibration coefficient depending on instrument geometry, particle properties (size distribution, shape, index of refraction or composition), optical /acoustic wave length and travel distance (l).

NOTE Often, the distance l cannot be defined in optical backscatter type systems.

An important limitation of the scattering method is the strong nonlinearity of the relation between the detector signal and sediment concentration for large concentrations. Even in low concentrations where the response is linear, the output depends strongly on grain size and colour. For instance, colour alone may change the calibration by a factor of 10 for higher concentration[37] and the grain size may cause an additional change in calibration. For example, the calibration is shown to change by a factor of 20 between a white 5 µm sediment and a grey 10 µm sediment. As such, changes in sediment properties are not uncommon in nature, which are generally not known during the course of monitoring. Spot calibration from samples is likely to be contaminated by unknown errors when sediment properties change in space/time. The errors can reach several hundred percent and greater. However, the use of laser sensors is able to overcome these errors to great extent.

4.3 Transmission — Scattering

This method is based on the combination of transmission and scattering, as shown in Figure 1 C.



Key

1 source
2 detector
3 measuring volume
4 detector
5 detector

Figure 1 — Basic principles of optical and acoustic methods

4.4 Diffraction

The phenomenon of bending of light from its straight line path around the corners of an obstacle or slit is known as diffraction. Diffracted light can produce fringes of light, dark or coloured bands. This property is used for measuring suspended sediment concentration in laser diffraction instruments.

Laser diffraction measures suspended sediment concentration by measuring the angular variation in intensity of light scattered as a laser beam passes through a dispersed particulate sample. Large particles scatter light at small angles relative to the laser beam and small particles scatter light at large angles. The angular scattering intensity data are then analysed to calculate the size of the particles responsible for creating the scattering pattern, using the Mie theory of light scattering.

5 Properties of sediment of importance for sediment surrogate techniques

5.1 General

The transport of sediment is based on hydraulic characteristics and physical properties of the sediment. Some of these properties are of importance for evaluating the accuracy and precision with which the sediment surrogate technologies described in this International Standard can determine SSC.

5.2 Particle size

Suspended sediment size is of importance for bulk optical and acoustical methods as these fundamentally respond to the surface area of the particles. If the surface area changes but the concentration remains constant these sensors will report a change in concentration that is proportional to the change in surface area[37]. The concentration output from LD sensors does not change with particle size.

5.3 Particle colour

The output of single-parameter bulk optical sensors depends strongly on particle colour. Sediment colour changes alone may change the calibration by a factor of 10 for higher concentration.[37] Combined with changes in grain size this may cause an additional change in calibration. For example, the calibration can be shown to change by a factor of 20 between a white 5 µm sediment and black 10 µm sediment[37]. The concentration output from LD or acoustical sensors is not influenced by particle colour.

6 Methods for determination of suspended sediment concentration by surrogate techniques

6.1 General

The surrogate methods employ *in situ* measurement using sensors that measure either

a) the bulk optical properties of the water-sediment mixture, including transmission, nephelometry and optical backscatter (OBS) sensors, or

b) laser diffraction (LD) sensors.

The methods also include sensors that measure the acoustical properties of the water-sediment mixture such as acoustic backscatter (ABS).

6.2 Bulk optics

Measurements of the bulk-optical properties of water-sediment mixture are the most common means for determining turbidity (water clarity) and estimating SSC in rivers. A number of optical instruments are commercially available. Bulk-optic instruments can be categorized as follows.

a) Transmissometers, which employ a light source beamed directly at the sensor. The instrument measures the light transmission, i.e. the part of the light not scattered by the suspended particles.

b) Nephelometers, which measure light scattered by suspended particles (rather than light transmission). The light reaching the detector is directly proportional to the amount of sediment particles scattering the source beam if their size, shape, colour and composition do not change. Nephelometers can be divided into two general categories:

   1) Turbidity meters generally measure 90° or forward scattering. Nephelometric measurements typically are expressed in turbidity units defined by the light source, detection angle, and whether the sensor has single or multiple detectors. The units of turbidity from a calibrated nephelometer are called nephelometric turbidity units (NTU).

   2) Optical backscatter (OBS) instruments measure backscattered infrared light, usually at 165° from the emitter, in a small (concentration dependent) volume.

These instruments provide an estimate of the suspended sediment concentration from a single point. Both transmission and scattering are functions of the number, size, colour, index of refraction, and shape of suspended particles. Particles of all sizes can be measured in this way. However, the sensitivity of these bulk optics methods depends on bulk particle area concentration, i.e. C/d, or $\Sigma_I\ Ci/di$ where C is volume concentration [when particles are smaller than the wavelength of light λ, the summation includes a weight factor corresponding to the scattering efficiency of particles, which for such small particles is other than 2 (the value for particles > λ)] and d is particle size. In other words, the method is progressively less sensitive to increasing particle size. It also follows that the maximum working concentration depends linearly on particle size. The details of the method are given in Annex A.

These bulk-optical instruments are generally inexpensive, do not have moving parts unless a wiper for the optical window is used, and provide rapid sampling capability. The instruments rely on empirical calibrations to convert measurements to estimates of SSC. No generic calibration that can be used to calibrate the output from a transmissometer or nephelometer to SSC is possible.

There are several drawbacks associated with use of bulk-optic instruments that include:

a) lack of consistency in instrument measurement characteristics;

b) variable instrument response to grain size, composition, colour, shape, and coating;

c) biological fouling or damage to optical windows;

d) nonlinear and censored responses of sensors at high sediment concentration; and

e) variable response with dissolved constituents causing colour.

Maximum concentration limits for these instruments depend in part on particle-size distributions. An optical backscatter (OBS) sensor has a generally linear response at concentrations less than about 2 g/l for clay and silt, and 10 g/l for sand although the exact concentrations at which the response becomes nonlinear is size dependent. The upper concentration limit for transmissometers additionally depends on the optical path length [see Formula (1)].

Transmissometers are more sensitive at low concentrations but nephelometers and OBS sensors have a broader operating range of concentrations. Because of the relation between calibration to particle size and particle colour, nephelometers and OBS sensors are best suited for application at sites with relatively stable particle-size distributions and colour.

6.3 Laser diffraction (LD)

The LD principle is described briefly in this subclause (for details see ISO 13320).

A laser beam is directed into the sample volume where particles in suspension scatter, absorb, and reflect light. Scattered laser light is received by an array of detectors that allow measurement of the scattering at multiple angles from the original direction of the beam. This yields a vector of light scattering intensities with one numerical value for each detector. Using a suitable mathematical procedure and optical model the scattering intensities are converted into a volumetric size distribution in discrete size classes defined by the scattering angles covered by the detectors. By summing the individual elements of the particle size distribution the total volume concentration for the size range covered by the instrument is obtained.

The name laser diffraction derives from the original application of this method where light scattering at multiple very small forward angles was measured. At these small forward angles (about $< 10°$), the scattering is dominated by diffraction, rendering particle composition (i.e. refractive index) of only secondary importance.

The LD method offers a fundamentally different basis for *in situ* measurement of the concentration (as well as sizes) of suspended sediment particles at a point in the water column. Unlike bulk optical or acoustic methods, the LD method does not suffer from a significant change in calibration with changing sediment colour, composition or size for sediment sizes within the instrument measurement limits and it does not require any calibration by the user. This property has led to the broad acceptance of the method in applications ranging from measurements of biological specimens to ceramics and particles of all types.

6.4 Acoustic back scatter (ABS)

Characterization of SSC using backscatter and attenuation of acoustic signals in water has been described and developed for several decades. The basic principles are that acoustic waves passing through a

