National Environmental Monitoring Standard

Turbidity Recording

Continuous in situ measurement of turbidity data

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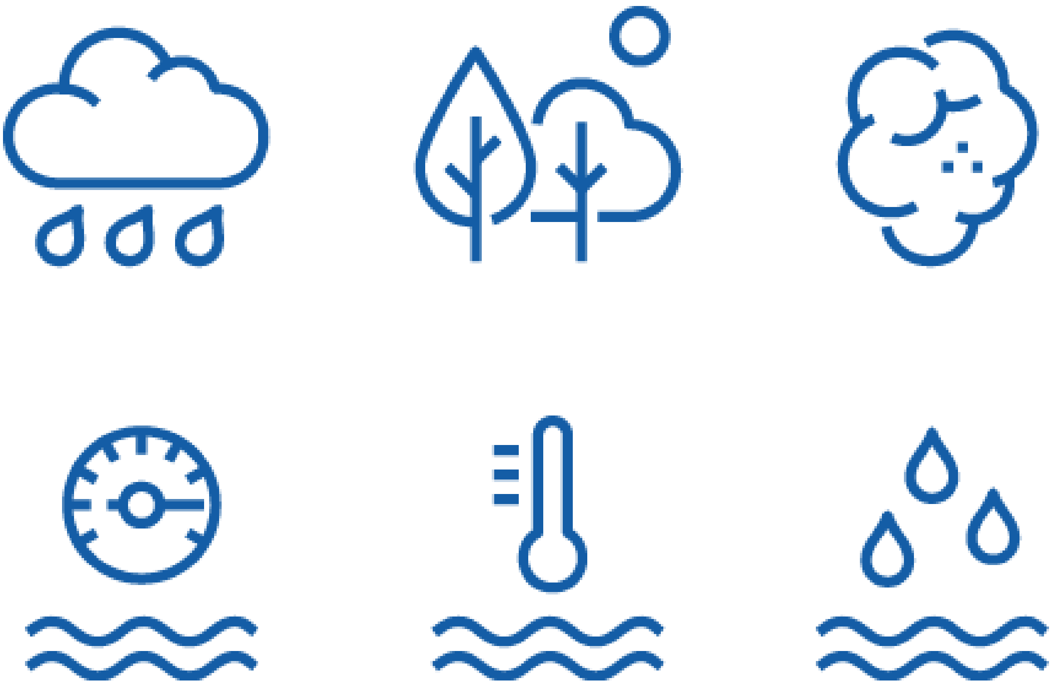

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Change register

Version Number	Date	Section	Revision Summary
1.0	May 2013		Initial release.
1.2	July 2017		Minor edits to document.
2.0.0	February 2025	Normative references	References added for: NEMS *Suspended Sediment* NEMS *Processing of Environmental Time-Series Data* NEMS *Water Quality: Part 2 of 4: Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data*
		Entire document	Terminology – 'turbidity sensor' changed to 'turbidity instrument' unless explicitly referring to the sensing device within the instrument.
		Entire document	Minor edits and grammatical changes.
		About this Standard: Introduction	Introduction has been expanded to discuss issues relating to standardisation amongst ISO 7027–compliant instruments. Absolute turbidity data type, related to a reference instrument, is introduced to ensure space-time standardisation of instruments where needed.
		About this Standard: The standard	The Standard requirements have been restructured and updated, including incorporating ISO 7027-1:2016 and distinguishing standard turbidity data and absolute turbidity data.
		Quality Codes	QC assignment flowchart now includes QC 0 (Non-verified data) and matrices to resolve between QC 400, QC 500 and QC 600 for standard and absolute turbidity data. Quality coding rules altered as necessary to align with NEMS *Processing of Environmental Time-Series Data.*
		Stationarity of record	Updated, noting requirement for absolute turbidity to ensure space/time stationarity.
		Purpose of turbidity instruments	Updated.

		Standard for Field Turbidity Instruments	Substantial revision to align with ISO 7027-1:2016. Allows use of turbidimeters and nephelometers.
		Calibration	Substantial revision to align with ISO 7027-1:2016, including allowing use of formazin alternatives as primary and secondary standards.
		Pre-deployment validation	Section revised. Use of 'validation' now aligns with NEMS glossary. Procedures clarified. Figure 2 replaced with a more relevant plot.
		Instrument swapping	New section added.
		Data collection specifications	Moderate revision.
		Management of fouling	Retitled "Environmental factors degrading data quality", and expanded to cover fouling, exposure, and burial. Updated to address ratio-metric multi-path instruments.
		Field verification measurements	'Validation' replaced throughout with 'verification' to align with NEMS glossary. Moderate-major revision throughout. New subsection added on normalised differences to deal with possible differences among ISO 7027–compliant instruments. 'Three-reading' strategy for verification status modified by increasing frequency of checking if tolerance is exceeded. New, more relevant, Figure 3 added.
		Clear-water, zero-point validation	Requirement for annual zero-point checks relaxed if instrument remains in tolerance after first year.
		Data Processing and Preservation	Section focuses on field data preservation. Guidance and standards for processing and archiving turbidity data are now covered in Annex E of the NEMS *Processing of Environmental Time-Series Data*.
		Absolute Turbidity	New major section on absolute turbidity added.
		Using Turbidity as a Proxy for Suspended Sediment Concentration	Rewritten. Now directs to annexes or other NEMS for details.

		or Visual Clarity	
		Annex A	List of Referenced Documents updated, including web-links to key documents.
		Annex B	This is now a new annex about developing absolute turbidity calibration functions.
		Annex C	Is the previous Annex B, covering at-site turbidity to at-site suspended sediment concentration (moderately revised). Figure 6 added to demonstrate residuals run-plot. Old Annex C (At-site SSC to cross-section mean SSC conversion) removed; readers now directed to NEMS Suspended Sediment for this.
		Annex D	Developing Calibration Functions between Turbidity and Suspended Sediment Concentration.
		Annex E	A new annex providing advice on using turbidity for compliance monitoring at earthworks sites and as a surrogate for visual clarity to meet NPS-FM (2020) monitoring obligations.

Table of Contents

The National Environmental Monitoring Standards

The National Environmental Monitoring Standards (NEMS), and associated codes of practice, Glossary, and National Quality Code Schema can be found at www.nems.org.nz.

Development

The strategy that led to the development of these Standards and associated documents was established by Jeff Watson (Chair) and Rob Christie (Project Director) of the initial National Environmental Monitoring Standards (NEMS) Steering Group, in 2014.

The NEMS initiative is supported by the Environmental Data Special Interest Group (ED SIG) (formerly the Local Authority Environmental Monitoring Group (LAEMG)), who contribute members to the NEMS Steering Group.

Implementation of the strategy is overseen by the NEMS Steering Group, which currently comprises Glenn Ellery (Chair), Jeff Watson (Technical Advisor), Phillip Downes, Rachel Herbert, Jon Marks, Charles Pearson, Jochen Schmidt, Clare Barton, Abi Loughnan, Sonja Miller, and Raelene Mercer (Project Manager).

The NEMS Steering Group directs preparation of NEMS documents on authority from the Chief Executives of the regional and unitary councils and the Ministry for the Environment (MfE).

The development of these documents involves consultation with regional and unitary councils across New Zealand, major electricity generation industry representatives, research institutes, and organisations providing supporting services such as laboratory processing. These agencies together are responsible for the majority of environmental monitoring in New Zealand.

This document has been prepared by Murray Hicks with support from Jeff Watson and Michaela Rose of Horizons Regional Council and Marianne Watson of Hydronet. The NEMS Steering Group's oversight of the development of this document, and subsequent review and alignment with a revised standard NEMS document format is gratefully acknowledged.

Implementation

Stationarity

NEMS Standards are intended for long-term monitoring programmes. Stationarity of record, whereby changes to methods and instruments do not introduce bias over the lifetime of the record, is an essential property (see also NEMS *Glossary*), without which a record cannot be confidently analysed for temporal trends.

Because the methods of collecting and processing environmental data do change over time, the Standards include provisions for identifying and mitigating potential loss of stationarity.

Data fit for purpose

To facilitate data sharing, the NEMS Steering Group recommend that NEMS Standards are adopted throughout New Zealand and all data collected be processed and quality coded in accordance with the methodologies described in the Standards.

The quality code is determined from the Standard adopted and applied at the time of data acquisition. The degree of rigour with which requirements of the Standards are applied may depend on the quality of data sought. The highest quality code (QC 600) may be assigned to data that meet the stated requirements for good data.

Data of lesser quality are accommodated but are assigned a lower quality code (i.e. less than QC 600). They may be fit for the current intended monitoring purpose but restricted in their use for a range of other current and future purposes.

Measured data coded as QC 500 (fair), or QC 400 (compromised) may be the best practicably achievable due to site limitations and/or transient lapses in data quality.

Health and safety

When implementing the Standards, current legislation relating to health and safety in New Zealand and subsequent amendments shall be complied with.

NEMS Codes of Practice (COP) provide additional guidance on health and safety issues and structural design. Use only the most recent published version of any NEMS COP.

Limitations

It is assumed that, as a minimum, the reader of these documents has an understanding of environmental monitoring and data processing techniques, and some competency in their application.

The documents do not relieve the user (or a person on whose behalf they are used) of any obligation or duty that might arise under any legislation, and any regulations and rules under those Acts, covering the activities to which these documents have been or are to be applied.

Instructions for manufacturer-specific instrumentation and methodologies are not included in NEMS documents.

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Funding

The primary funders of the NEMS project are Ministry for the Environment and New Zealand regional councils and unitary authorities.

Other financial and in-kind support to the overall NEMS project has been provided by the following organisations:

- National Institute of Water and Atmospheric Research Ltd (NIWA)
- Ministry of Business, Innovation and Employment – Science and Innovation Group
- GNS Science
- Genesis Energy
- StatisticsNZ
- Contact Energy
- Meridian Energy
- Mercury New Zealand Limited

Review

This document will be assessed for review within one year of its initial release and thereafter will be assessed for review approximately once every two years. Document status and proposed review dates can be found at www.nems.org.nz.

Feedback

If you wish to provide feedback regarding this version of the document, please provide it to https://www.nems.org.nz/feedback/.

About this Standard

Introduction

Turbidity measurement

It is important to understand the range of uses to which the data can be put, and to ensure that data collected for one purpose can be used as widely as possible in the future. Key to compiling a useful long-term record of turbidity measurements is the understanding of, and catering for, stationarity.

Turbidity is a measure of the optical properties of water that cause light to be scattered and absorbed. It is commonly appreciated as water “cloudiness” or “haziness”. Turbid water results from suspended material, for example sediment and organic matter, and dissolved constituents such as organic acids and dyes.

Turbidity is often used as an inverse measure of water clarity or as a surrogate for visual clarity. It is also a popular surrogate for continuously monitoring suspended sediment concentration because of its dependence on the concentration of sediment particles suspended in the water and because it is relatively simple to measure with *in situ* instruments (within limits).

The instrument types vary from transmission-type instruments (turbidimeters), which measure the attenuation of a light beam along a path between the light source and receiver, and backscattering instruments (nephelometers), which measure the intensity of diffuse light scattered back towards the source.

Instrument response in a given suspension depends on the suspension properties (composition and concentration), sensor type, and specific aspects of the sensor design (e.g., light source, angle between light source and detector). Therefore, instruments are designed and calibrated to provide a linear response to a specified concentration range of a reference suspension. The conventional suspension standard used to calibrate turbidity is formazin.

The operational range chosen for turbidity instruments depends on the application. Water clarity–related applications require high precision over relatively low turbidity ranges, while suspended sediment load determination of flood waters requires instruments with a relatively high turbidity range that do not saturate or over-range.

Standardisation issues

Even when calibrated to the same stock formazin solutions, instruments of different type and design can return significantly different results when measuring the turbidity of natural suspensions (e.g., suspended mud in a river). Consequently, turbidity records from different instruments are not necessarily comparable, resulting in a need for standardisation of instrument type, technical design, and calibration standard.

Since field-deployed *in situ* instrument turbidity measurements are typically verified off laboratory bench or portable instruments, the standardisation process needs to encompass both field and laboratory instruments.

This situation has led to the development of Turbidity Standards such as ISO 7027:1999 (ISO, 1999) and its update ISO 7027-1:2016 (ISO, 2016). These specify key features including the light source wavelength, measurement angle, operational range, and calibration standard. Data collected under a given Turbidity Standard are reported in units that are unique to and identify that standard and instrument type (e.g., ISO 7027:1999–compliant data are reported in Formazin Nephelometric Units, or FNU).

Earlier versions of this NEMS *Turbidity Recording* adopted the ISO 7027:1999 Turbidity Standard and assumed that all instruments considered to be compliant with that standard would provide consistent results across natural suspensions, thereby providing record temporal stationarity at-site and spatial stationarity between sites. In turn, this would enable compliance monitoring to unambiguously detect temporal change (e.g., from a baseline turbidity), spatial change (e.g., between upstream and downstream sites), or exceedance of a threshold value (e.g., a turbidity limit value consistent with the Turbidity Standard). Moreover, it would also mean that when using turbidity as a surrogate for suspended sediment concentration (SSC), data from any ISO 7027–compliant instrument could be used with an at-site turbidity–SSC relationship developed with any other ISO 7027–compliant instrument.

However, this assumption was found wanting in a recent NIWA study (Davies-Colley et al., 2021). The study compared measurements over a range of concentrations of three natural suspensions using six different ISO 7027–compliant nephelometers (two laboratory instruments and four *in situ* field instruments in triplicate) all calibrated to the same formazin standard solutions.

While reasonable agreement was observed among identical instruments of the same brand, the NIWA study results from the natural suspensions diverged across the instrument brands, with high-range turbidity values varying by a factor of two. This divergence was thought to be due to small differences in design features combined with different optical properties of natural suspensions compared to the formazin stock.

The conclusion was that, while the turbidity instruments could all be used after individual field calibration to provide surrogate records such as for suspended sediment concentration or visual clarity, their absolute turbidity readings were instrument-specific, which compromised the sought-after spatial stationarity and their use for compliance monitoring.

Key changes with this NEMS update

To accommodate these standardisation issues, this NEMS *Turbidity Recording* update includes three key changes:

- distinguishing a new “absolute” kind of turbidity data from standard, as measured turbidity data, with the choice of which kind of turbidity data being dependent on the application of the turbidity record
- constraints are advised on the use of turbidity for compliance monitoring, and

- the instrument standard is expanded to align with the latest ISO 7027 version (ISO 7027-1:2016).

Standard and absolute turbidity data and their applications

Turbidity data can now include:

- standard turbidity data – as measured from any *in situ* ISO 7027-1:2016−compliant instrument standardised to factory specification and consistent with previous versions of this NEMS, and
- absolute turbidity data (or instrument-specific turbidity data) – standard turbidity data collected directly with or calibrated to a primary reference ISO 7027-1:2016−compliant instrument.

Note: Absolute turbidity data may be generated from standard turbidity data collected with an instrument that is not equivalent to the primary reference instrument by applying a conversion relationship, such is done when standard turbidity is used as a surrogate for suspended sediment concentration.

Note: Absolute turbidity data are filed as records of "Absolute turbidity" and the primary reference instrument must be identified in metadata. Standard turbidity data are filed as records of "Turbidity".

Note: In this document, an in situ instrument is one installed (semi-) permanently at site and collecting a continuous turbidity record.

The anticipated applications of turbidity data are:

- To provide a surrogate record of suspended sediment concentration or visual clarity, requiring site-specific calibration of standard turbidity data to the suspended sediment concentration of water samples collected at the monitoring site or of visual clarity measured at the monitoring site, e.g., for National Policy Statement for Freshwater Management (NPS-FM) attribute state assessment requirements.
- To provide a record of absolute turbidity for regionally and/or nationally consistent datasets, where the *in situ* instrument is either a primary reference instrument or is calibrated to a primary reference instrument.
- To provide a record of relative turbidity, where the standard (or absolute) turbidity record of the *in situ* instrument is compared to either (a) a baseline period of reference record from the same (or equivalent) instrument at the same site, or (b) an equivalent instrument deployed at a related baseline site (e.g., where turbidity records are compared upstream and downstream of a sediment source such as an earthworks project).
- To provide a record of standard turbidity to be used only for the purpose of identifying the phasing of elevated turbidity events, often as a trigger for further investigations.
- A combination of the above, eg, a surrogate turbidity record for suspended sediment concentration is also calibrated to absolute turbidity.

Using turbidity for compliance monitoring

It is advised that while the first three applications above can be used for compliance purposes, consent conditions should not be based directly on turbidity values (either standard or absolute). Rather, consent conditions should be set in terms of suspended sediment concentration, visual clarity, or turbidity ratios.

Moreover, when turbidity is used to monitor consent compliance, compliance assessment should pay regard to the uncertainty associated with the calibration relationships between turbidity and sediment concentration or visual clarity. For example, if a consent condition requires that a suspended sediment concentration statistic (e.g., median) does not exceed a threshold value, then the associated limit on turbidity-generated suspended sediment concentration shall make allowance for the uncertainty associated with suspended sediment concentration predictions from turbidity.

Alignment with ISO 7027-1:2016

Previous versions of this NEMS *Turbidity Recording* adopted the ISO 7027:1999 Turbidity Standard, which specified only a nephelometry method using sensors with a measurement angle at 90^{o} to the light source beam and with Formazin Nephelometric Units (FNU).

The subsequent ISO 7027-1:2016 Standard includes both this nephelometry method, typically directed more at measuring low turbidity ranges, and a turbidimetry method, directed more at measuring relatively high turbidity ranges with Formazin Attenuation Units (FAU). Note that while both methods require formazin calibration, their results will diverge in natural suspensions, and no general equivalence should be expected between FNU and FAU.

Most New Zealand experience to date involves nephelometers, and the tolerance specifications included in this NEMS reflect that experience. Until further experience is accumulated with turbidimeters, it is assumed that the tolerance specifications provided herein apply to both instrument types. Different tolerance values for turbidimeters may appear in future revisions.

This document

This document is made up of two parts: the first part is the Standard, and the second part contains supporting information that practitioners are required to implement in order to achieve the Standard.

Objective

The objective of this Standard is to ensure that turbidity measurements in water bodies are obtained, quality assured, and preserved in a verifiable, consistent, and documented manner to a known standard over time throughout New Zealand, and are therefore suitable for:

- their current intended applications
- at-site analysis over time

- regional and national comparative analysis over space and time, and
- conceivable future applications.

Scope

The Standard covers all requirements and processes associated with the deployment of continuously recording *in situ* turbidity instruments for ambient turbidity monitoring and as a surrogate for suspended sediment concentrations and visual clarity in rivers, streams, and estuaries. While not otherwise specifically identified within this Standard, the same principles apply to the acquisition of turbidity data within lakes. The Standard includes:

- site selection
- instrument deployment
- instrument type
- calibration
- pre-deployment validation
- the acquisition of turbidity data
- *in situ* verification
- absolute turbidity
- metadata, including assigning initial quality codes
- preservation of record, and
- using turbidity as a surrogate (proxy) for suspended sediment.

Note: Guidance and standards for processing and archiving turbidity data are covered in Annex E of the NEMS Processing of Environmental Time-Series Data*.*

Using turbidity as a surrogate indicator

Procedures for relating turbidity to at-site suspended sediment concentration beside the turbidity instrument are covered in Annex C of this document. Procedures for relating at-site suspended sediment concentration to the cross-section mean suspended sediment concentration are detailed in the NEMS *Suspended Sediment*.

Exclusions

This Standard does not apply to the acquisition and analysis of turbidity data for:

- potable water supplies, or
- wastewater treatment.

Note: This Standard may not be applicable in a marine environment because in a marine environment other considerations are required that are not addressed in this Standard.

Terms, definitions, and symbols

Relevant definitions and descriptions of symbols used in this Standard are contained within the NEMS *Glossary* available at www.nems.org.nz.

Normative references

This Standard should be read in conjunction with the current versions of the following references:

- ASTM: D-3977-97 Standard test methods for determining sediment concentration in water samples: Standard procedure
- NEMS *Water Quality – Part 2 of 4: Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data*
- NEMS *Safe Acquisition of Field Data in and Around Fresh Water – Code of Practice*
- NEMS *Glossary – Terms, Definitions and Symbols*
- NEMS *Quality Code Schema*
- NEMS *Suspended Sediment – Measurement of Fluvial Suspended Sediment Load and its Composition (version 2.0.0)*
- NEMS *Data Processing – Processing of Environmental Time-Series Data*

The Standard – Turbidity

Data

Standard Turbidity and Absolute Turbidity data shall be archived as two distinct turbidity variables:

Standard Turbidity (See "About this Standard" "- Page xiii)	Data from any formazin-calibrated, ISO 7027-1:2016–compliant instrument.
Absolute Turbidity (See "About this Standard" - Page xiii)	Turbidity data adjusted as need be to align with a reference ISO 7027-1:2016–compliant instrument.

Minimum requirements for the application of all Standards

Table 1 – Minimum requirements for the application of all Standards.

Health and safety *(Page xi)*		Scope	All current legislation, including relevant amendments, shall be complied with.
Stationarity *(Sections 1.1, 2.3.1, 2.6, 5.3.3.2, 5.6, Annex B, Annex E)*			• Maintained wherever possible. • Documented in metadata if change occurs or is likely to occur. • If significant change (as defined in site requirements), create a new site.
Units of measurement *(Pages xiv, xv1, Sections 2.2.2, 2.2.2.3, 2.2.2.4, 5.5, Annex C)*			• Metric system. • SI units, unless stated otherwise (in the relevant Standard).
Timing of measurements *(Section 3.1)*		Time zone	Use New Zealand Standard Time (NZST), or Chatham Is. Standard Time (CHAST) as applicable. Do not use Daylight Time (NZDT or CHADT).

Metadata		Scope (Page xxxv1, Sections 3, 4.1, 4.2, 5.3.5, 5.5)	• Recorded for all sites and measurements. • Permanently archived and discoverable.
		Identification of Standards (Page xxxvi)	Standards and versions applied shall be tracked over time in time-stamped Stationarity Comments.
		Identification of data (Section 5.5. 4.2.1,)	All data shall be identified by a minimum of: • a unique site name and/or identifier • the variable's name and units (as defined in its relevant NEMS), and • date and time of the measurement or record.
		Quality coding Pages xxix, xxxvi, Section 5.3.5)	All data shall be quality coded using the NEMS *National Quality Code Schema*.
Archiving		Original and final records (Section 4.2.5, 5.5, also *see* - NEMS:- Processing of Environmental Time-Series Data*)*	Store, retain indefinitely, and if electronic, back up regularly: • Original data (as defined by the recording agency). • Final data (as verified). • Supplementary measurements. • All required metadata (including all calibration, validation, verification and editing information). • Additional time series and/or metadata used and/or generated during data processing. *(For further detail see:* - NEMS Data Processing – Processing of Environmental Time-Series Data – *Annex E).*

Requirements for turbidity data irrespective of quality

The following requirements apply to Standard Turbidity and Absolute Turbidity data.

Table 2 – Requirements for turbidity data irrespective of quality.

Units of Measurement	Units *(Section 2.2.2)*	Formazin Nephelometric Units (FNU) for nephelometers, or Formazin Attenuation Units (FAU) for turbidimeters.
Calibration	Method *(Sections 2.3, 2.4, 2.5, 2.6)*	Using formazin or substitute primary or secondary reference stock as approved by manufacturer and as specified in ISO 7027-1:2016.
Pre-deployment Validation	Instrument test *(Sections 2.5.1, 2.5.2)*	Comparison against a calibrated ISO 7027-1:2016–compliant laboratory instrument in reference stock solutions of formazin or a formazin substitute approved by manufacturer.
Field Verification	Instrument test *(Section 3.4)*	Comparison against a primary, ISO 7027-1:2016–compliant laboratory or portable reference instrument.
	Frequency *(Section 3.3.5)*	Monthly verification measurements, increasing to weekly if data quality is "suspect". Yearly verification measurements during one runoff event in which turbidity exceeds 100 FNU/FAU.
	Verification failure *(Section 3.4)*	Any verification failure of *in situ* instrument requires laboratory validation check using reference stock and recalibration if required.
Validation	*(Section 3.6)*	Annual zero-point validations, at least for first year of deployment at site.
Stationarity	*(Section 1.1)*	Absolute turbidity data shall be collected if spatial (i.e., inter-site) stationarity is required.

Metadata	Site records *(Section 4.2)*	• All stations shall have a unique identifier. • A Station History (or site file) shall be established and maintained, including a bore log at groundwater stations. • Remote telemetry station configuration changes shall be controlled and recorded. • All maintenance activities shall be logged. Records of those activities with bearing on data quality shall be retained indefinitely.
	Site visit records *(Section 4.2.1)*	A record of every site visit shall be made and retained indefinitely as original data.
	Sampling method *(Section 4.2.1)*	Any algorithm used to obtain point samples from a measurement burst shall be described and justified.
	Instrument records *(Section 4.2.1)*	• All specification, configuration, calibration, and validation records shall be collated and retained indefinitely. *Note: Include timing method used if part of instrument specification.* • Logger software history (version and code) shall be maintained and preserved.
	Change of method *(Section 4.2.1)*	Every method change shall be: • Noted in the site visit records at the time. • Added to the relevant history. • Summarised in a filed comment, and in a Stationarity Comment if significant change.
	Processing of data *(Sections 3.2, 3.4, 4.1, 5.5, 5.6)*	• Incoming data shall be tracked, and records of quality checks maintained and available. • All changes from raw data shall be documented. • Automated facilities shall be controlled, documented, and regularly evaluated. • Time-series comments shall be timestamped at the start of the applicable record period or gap.

	Supplementary measurements *(Sections 2.5.2, 2.5.3, 4.2, 5.2)*		All supplementary data shall be identified and described and stored indefinitely.
	Derived values	Statistics *(Annex B, Annex D)*	Shall be identified and labelled, catalogued in the metadata, kept separate from measured data, and used appropriately.
		Transformations *(Section 5.3.2 Annex B)*	Shall be fully traceable back to sensor output and summarised in the time-series metadata.

Additional Table 2 requirements only for absolute turbidity:

Table 3 – Requirements for absolute turbidity data irrespective of quality.

Conversion to absolute turbidity	Reference instrument *(Section 5.2)*	Reference instrument shall be an ISO 7027: 2016–compliant nephelometer.
	Conversion of recorded data to equivalent values on reference instrument (if reference and recording instruments are different) *(Sections 5, Annex B)*	Requires: • measurements/samples collected beside recording instrument during runoff events and base-flows for turbidity determination on reference instrument • calibration relationship between the 'in situ instrument and reference instrument developed from field samples/measurements (if not the same make and model) • relationship used to convert standard turbidity record to absolute turbidity record • statistics of accuracy of conversion relationship recorded (r^2, standard error of estimate, standard error of slope coefficient) • relationship updated and checked for temporal non-stationarity annually.
Metadata	*(Section 4.2)*	Metadata shall include the make and model of both recording and reference instruments.
Quality Coding	*(Sections 5.4)*	All data segments shall be assigned quality codes based on the lesser of quality codes associated with: • source standard turbidity data, and • the quality of the calibration relationship between the recording and reference instruments.

Additional requirements for turbidity data of good quality

As a means of achieving QC 600 under this Standard, the following requirements apply in addition to the requirements for the application of all Standards and the requirements for turbidity data irrespective of quality:

Table 4 – Additional requirements for turbidity data of good quality.

Resolution	Turbidity units *(Not specified elsewhere)*	0.1 FNU/FAU
Precision	Turbidity units *(Not specified elsewhere)*	0.1 FNU/FAU for values less than 20 FNU/FAU, or 1.0 FNU/FAU for values greater than or equal to 20 FNU/FAU.
Timing of Measurements	Sampling method *(Section 4.2.1)*	Point sample stored as an instantaneous value. *Note: A representative value (e.g., average or minimum) of a burst of measurements may be used but must result in a point sample.*
	Maximum recording interval *(Section 3.1)*	Record time-series turbidity at time intervals: ≤ 15 minutes for catchments greater than 25 km^2, or ≤ 5 minutes for catchments 25 km^2 or smaller.
	Time – Resolution *(Section 3.1)*	1 second
	Time – Accuracy *(Section 3.1)*	± 90 s/month
	Sampling method *(Section 3.1)*	A point sample. Recorded value shall be represented by a central statistic (e.g., average, median, mode) of a burst of measurements spanning a period of at least 10 seconds but no greater than 20 seconds.
Calibration	In-situ sensor *(Sections 2.2.2, 2.4.2)*	Sensor calibration shall be maintained using formazin or a manufacturer approved secondary standard such as AMCO CLEAR.
		Sensor calibration shall be undertaken whenever three or more laboratory-analysed samples show a consistent departure from the value measured by the sensor.

Supplementary Measurements	If turbidity data is to be used as a surrogate for suspended sediment concentration *(Sections 1.2.1, 3.3.4, 3.3.6, Annex C)*	• Stream/river flow records, and • water samples for analysis of suspended sediment concentration.
	Metadata *(Section 4.2)*	Any supplementary data streams are to be defined in the metadata.
Verification	Inspection of recording installations *(Section 1.2.3.1)*	A minimum of once every two months, but of sufficient frequency to ensure the data collected are free from error and bias, both in turbidity and time.

Other requirements, guidelines, and recommendations

The following table summarises other requirements and guidelines (e.g., for quality assurance or lower quality codes), and additional recommended practices that are either not relevant to or not required for QC 600 but if implemented will enhance work practices and data quality.

Table 5 – Other requirements, guidelines, and recommendations.

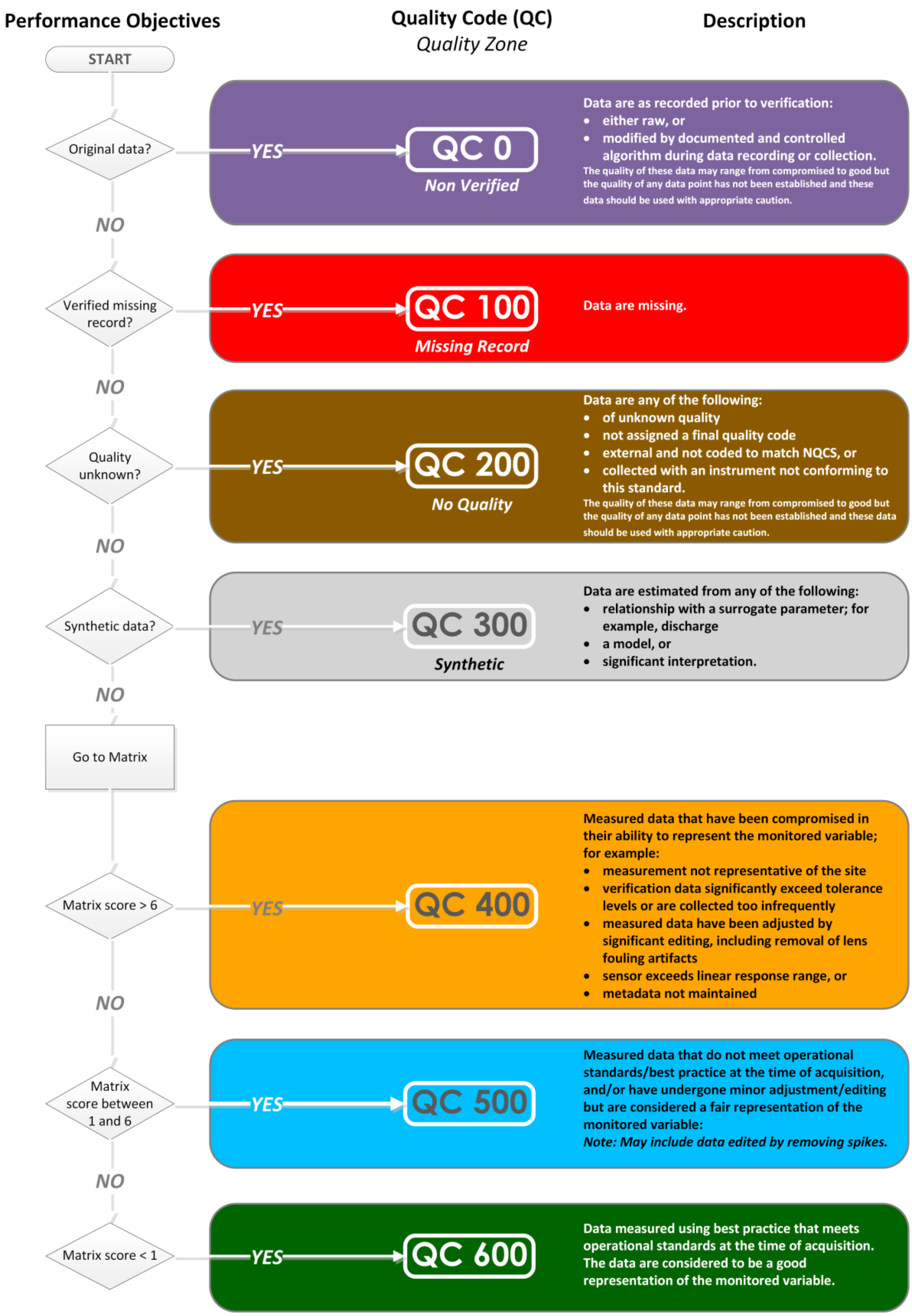
Risk management	Scope *(Sections 1.2.3.1, 1.2.3.2, 1.3.2, 1.3.3, 2.5.3)*		• Secure and safe access. • Hazards identified (initial and ongoing),
	Site access and security *(Sections 1.3.2, 1.3.3)*		• Permission required for all access. • Long-term access agreement recommended. • Signage and security systems required.
Site selection	When turbidity is used as a surrogate for suspended sediment *(Sections 1.2.1, 1.2.4.2)*		• Locate sensor in gauging reach if possible. • Ensure that the sensor is capable of measuring the full range of turbidity that will occur at the site.
Station design, construction, and installation *(Section 1.2)*			Conforms to requirements and guidance.
Measurement	Range *(Section 2.2.2.1)*		0–4000 FNU
	Missing data *(Section 5.4)*		• Operational target of < 30 days total missing from one year of any two consecutive years. • Backup sensor recommended.
Verification *(Section 3.3)*	Recording Installation	Frequency *(Section 3.5.1.3)*	Recheck agreement within 7 days if the difference between the sensor and the reference value exceeds the expected verification tolerance.

Audit	Field site and data audit *(Section 5.6)*	Agencies shall document and implement a standard methodology for audit and review. Audits should incorporate review of: • site and instrument metadata • data summaries and statistics • comments • missing and over-ranged data • data plots, including deviation with time plots of verification results • absolute turbidity calibrations and deviation with time • metadata • quality coding

Quality Codes – Turbidity data

All turbidity data shall be quality coded in accordance with the NEMS *Quality Coding Schema*. The schema permits valid comparisons within and across multiple data series.

Use the following flowchart to assign quality codes to all turbidity data, whether standard or absolute.


Performance Objectives
Quality Code (QC)
Quality Zone
Description
START
Original data?
YES
QC 0
Non Verified
Data are as recorded prior to verification:
• either raw, or
• modified by documented and controlled algorithm during data recording or collection.
The quality of these data may range from compromised to good but the quality of any data point has not been established and these data should be used with appropriate caution.
NO
Verified missing record?
YES
QC 100
Missing Record
Data are missing.
NO
Quality unknown?
YES
QC 200
No Quality
Data are any of the following:
• of unknown quality
• not assigned a final quality code
• external and not coded to match NQCS, or
• collected with an instrument not conforming to this standard.
The quality of these data may range from compromised to good but the quality of any data point has not been established and these data should be used with appropriate caution.
NO
Synthetic data?
YES
QC 300
Synthetic
Data are estimated from any of the following:
• relationship with a surrogate parameter; for example, discharge
• a model, or
• significant interpretation.
NO
Go to Matrix
Matrix score > 6
YES
QC 400
Measured data that have been compromised in their ability to represent the monitored variable; for example:
• measurement not representative of the site
• verification data significantly exceed tolerance levels or are collected too infrequently
• measured data have been adjusted by significant editing, including removal of lens fouling artifacts
• sensor exceeds linear response range, or
• metadata not maintained
NO
Matrix score between 1 and 6
YES
QC 500
Measured data that do not meet operational standards/best practice at the time of acquisition, and/or have undergone minor adjustment/editing but are considered a fair representation of the monitored variable:
Note: May include data edited by removing spikes.
NO
Matrix score < 1
YES
QC 600
Data measured using best practice that meets operational standards at the time of acquisition. The data are considered to be a good representation of the monitored variable.

Note: Data quality codes are typically assigned in two steps:

An initial assignment is made immediately after data acquisition to inform on data state or provenance. This covers data that are raw and are as yet unverified or edited (QC 0), have no quality information or have been collected with an instrument that does not conform to this standard (QC 200), or no data was collected by the instrument (QC 100).

This initial QC assignment is typically re-graded during data processing, with the quality codes QC 400, QC 500, and QC 600 indicating data reliability. These codes consider factors that influence the data acquisition, verification results, and data modifications undertaken during data editing.

Note also:

Data modifications can include:

- *corrections that carry no uncertainty and so have no effect on quality code*
- *'minor' adjustments (quality code can be no higher than QC 500)*
- *'significant' adjustments (quality code can be no higher than QC 400)*
- *data replacement with backup, secondary, or synthetic data (using quality code of replacement data), or*
- *data removal (QC 100).*

The NEMS Processing of Environmental Time-Series Data *(subsection 6.2.3) regards 'minor' adjustments as those involving:*

- *a period no more than a few recording intervals*
- *a small change to values relative to tolerance, and/or*
- *a small change to timesteps relative to the recording interval, and*
- *applied over no longer than the course of a single event or cycle.*

Adjustments beyond these extents are regarded as 'significant'.
Missing data (initially assigned QC 100) or compromised data (initially assigned QC 200) may be replaced with synthetic data during data processing and assigned to QC 300.
Over-ranged or saturated turbidity data, and false data caused by sensor exposure, if retained and stored as censored data are assigned QC 400.
Data that do not conform to this NEMS standard will remain QC 200 after data processing.

The following two matrices shall be used to resolve between QC 400, QC 500 and QC 600 during data processing:

- Standard Turbidity Data matrix, and
- Absolute Turbidity Data matrix (if absolute turbidity is required).

For standard turbidity, add-up the total score of the Standard Turbidity Data matrix. This is the standard turbidity score.

For absolute turbidity, take the greater of the standard turbidity score and the total score of the Absolute Turbidity Data matrix. This is the absolute turbidity score.

As appropriate, use the standard turbidity score or the absolute turbidity score to assign the quality code as per the table below.

Quality Code	Standard turbidity or absolute turbidity score
QC 600	0 points
QC 500	1-6 points
QC 400	>6 points

Note: The first column of each matrix includes references to the evaluation criteria. These references are either to sections of this document (T-) or sections of the NEMS Processing of Environmental Time-series Data *(DP-) or its Annex E (DP-E-), which covers turbidity data. For example, T-1.2.3 refers to subsection 1.2.3 of this document.*

The quality code assigned to absolute turbidity data can never exceed that assigned to the source standard turbidity data.

Standard turbidity data matrix

Criteria	7 Points	1 Point	0 Points	Score
		Field data acquisition		
Spatial representativeness of measurements *(T-1.2.3, T-1.2.4)*	Turbidity observed to be non-uniform over stream cross-section (e.g., instrument located in a partially mixed turbidity plume from nearby tributary or eroding bank)		No evidence that turbidity is non-uniform over stream cross-section	
Stationarity (temporal) *(T-1.1, DP-3.7)*	• Instrument recently moved to a new location, or • Instrument swapped with a non-equivalent instrument and relationship with verification instrument not established		No evidence of temporal non-stationarity	
Data logging interval *(T-3.1)*	Logging interval > 15 minutes	Logging interval > 5 minutes and ≤ 15 minutes for catchments < 25 km^2	Logging interval ≤ 5 minutes for catchments < 25 km^2 or ≤ 15 minutes for catchments > 25 km^2	
Metadata *(T-4.2, DP-E-2.1)*	Metadata on turbidity instrument and site is not up to date or archived		Metadata on turbidity instrument and site is up to date and archived	
		Validation and verification		
Pre-deployment validation *(T-2.4)*	Pre-deployment validation not undertaken		Pre-deployment validation undertaken	
Field verification tolerances *(T-3.4.2.4)*	• For turbidity values < 20 FNU/FAU, the normalised verification difference is > ±6 FNU/FAU, or • for turbidity values ≥ 20 FNU/FAU, the relative normalised verification difference is > 30%.	• For turbidity values < 20 FNU/FAU, the normalised verification difference is > ± 3 FNU/FAU and ≤ ± 6 FNU/FAU, or • for turbidity values ≥ 20 FNU/FAU, the relative normalised verification difference is > ±15% and ≤ ±30%.	• For turbidity values < 20 FNU/FAU, the normalised verification difference is ≤ ±3 FNU/FAU, or • for turbidity values ≥ 20 FNU/FAU, the relative normalised verification difference is ≤ 15%	

Field verification frequency *(T-3.3.5)*	No 'monthly' field verification measurements made within 6 weeks of data record	No verification measurements made during a high-turbidity event over year of preceding data record	All field verification frequency targets achieved	
Data editing				
Unintended or incorrect offset *(DP-E-3.2)* or Incorrect scaling *(DP-E-3.9)* or Time faults *(DP-E-3.10)* or Steps *(DP-E-3.3)*	Adjustment is significant	Adjustment is minor	Correction is fully traceable and involves no additional uncertainty	
Drift (baseline and calibration) *(DP-E-3.4)*	Adjustment is significant	Adjustment is minor	Drift not observed	
Spikes *(DP-E-3.5)*		Spikes removed	Spikes not observed	
Noisy data *(DP-E-3.6)*	Data resampled or smoothed		Data are not noisy	
Sensor over-ranging and saturation *(DP-E-3.7)*	Over-ranged/saturated data are removed and stored as 'censored'			
Missing data (in raw record or removed during editing) *(DP-E-3.11)*			Missing data period is 'brief', and missing data infilled by interpolation	
Total				

Absolute turbidity data matrix

Criteria	15 Points	6 Points	2 Points	0 Points	Score
Reference instrument *(T-5.2)*			Reference instrument is laboratory- or portable-type	Reference instrument is *in-situ* type	
Equivalence of *in situ* and reference instruments; linking (calibration) relationship *(T-5.3, T-5.4)*	Field and reference instruments are not equivalent, and there is no calibration relationship	Field and reference instruments are not equivalent; calibration relationship has been used from another site or deployment time, or at-site calibration relationship relative error on calibration relationship slope > 15%, or < 12 calibration points, or limited range of calibration points, or calibration only available from nearby site	Field and reference instruments are not equivalent; relative error on at-site calibration slope < 15%, 12+ calibration points covering adequate range	Field and reference instruments are equivalent (i.e., the same make and model of instrument or at-site relationship not different from 1:1 line at 95% confidence level)	
Ongoing calibration maintenance and documentation *(T-5.3.3, T-5.3.6)*		Calibration function not regularly checked, maintained, or documented (where field and reference instruments are not equivalent)		Calibration function regularly checked, maintained, and documented (where field and reference instruments are not equivalent)	
Total					

Application

All data produced and archived under NEMS Standards shall be filed with all required metadata, including a quality code assigned in accordance with NEMS *National Quality Code Schema*. The schema permits valid comparisons within and across multiple data series.

The quality coding flowchart as shown shall be used as the framework to assign quality codes to water level data.

Quality coding matrices shall be used to decide an initial quality code of QC 400, QC 500 or QC 600 for measured data within this framework. This initial quality code is the maximum achievable for the data; the final quality code may be lower.

Turbidity data can be assigned a final quality code of QC 600 (good) if the outcome of the quality coding matrices is QC 600 and the data have not been modified (ie, edited, adjusted or transformed during data processing).

Data that have undergone minor modification are eligible for a final quality code of QC 500 provided their initial quality code from the matrices is at least QC 500. An initial quality code of QC 500 from the matrices can be retained as the final quality code unless the data are subsequently significantly modified.

Regardless of the initial quality code obtained from the quality coding matrices, the final quality code cannot be higher than QC 400 if the data have undergone significant modification.

Quality coding matrices may identify data as not meeting QC 400 and needing remedial action. Data processing will then determine the final quality code to be applied. In the interim, affected data may be assigned QC 200 (not assigned a final quality code) or retain QC 0 (as recorded). Guidance on selecting and applying suitable quality codes during data processing is included in NEMS *Data Processing*.

Quality codes are determined from the Standard(s) applied at the time data are acquired. As Standards are updated there is no requirement to review and possibly revise the quality codes of data already archived. The Standard(s) and version(s) applied must therefore also be tracked in the metadata by way of a Stationarity Comment when a new Standard and/or version is adopted.

1 Site Selection and Deployment

This section contains information on:

- access considerations
- where to locate turbidity instruments in a river or stream reach
- how to orientate sensors relative to the flow direction, bed, and water surface
- how to protect the instrument, and
- other considerations; for example, accessibility.

1.1 Stationarity of record

Stationarity of record (or temporal stationarity):

- is maintained when variability in the measurements over time is only caused by changes, natural or man-made, in the environmental processes directly associated with the variable being measured, and
- ceases when variability is caused or affected by the measurement process; for example, on moving a turbidity instrument to where it becomes influenced by a local turbidity source.

Without stationarity, a time-series record cannot be analysed for changes over time (such as induced by climate or land-use change). While the accuracy of collection procedures may change, it is critical that the methods and instruments used to collect a turbidity record do not introduce bias over the lifetime of the record. For example, if an *in situ* instrument is replaced with another of different type (e.g., a nephelometer is replaced with a turbidimeter), or even of the same type but of different brand, then the signal returned from the new instrument may track lower or higher than the track of the old instrument.

In similar fashion, if the data collection objective is to compare turbidity records across multiple sites and/or catchments, it is critical that the same methods and instruments are used at each site to ensure spatial stationarity.

Because the methods of collecting continuous environmental data do change over time, an external reference should always be used against which the continuous data can be checked. In the case of turbidity data, the external reference is stock mixtures of the standard 'sediment' formazin. Moreover, with turbidity it is also necessary to retain the same sensor characteristics. As recently found (Davies-Colley et al., 2021), even formazin-calibrated instruments made to the same design standards by different manufacturers can return divergent results in natural suspensions.

Therefore, temporal stationarity at site can only be ensured by acquiring records with equivalent instruments, and spatial stationarity of turbidity records between sites can only be ensured by acquiring records of absolute turbidity that are associated with a reference instrument.

1.2 Site selection

Site selection shall consider:

- general location
- accessibility
- channel and bank characteristics, and
- proximity to other instruments and equipment.

1.2.1 General location

Where practicable, turbidity instruments should be located at, or near, flow-recording sites when monitoring turbidity in rivers and streams. This is because flow records are commonly used in the analysis of turbidity data. For example:

- turbidity records are often used to generate surrogate indicator records of suspended sediment concentration, which are then combined with flow records to compute sediment loads
- flow records may be needed to adjust for the effects of runoff events and seasonality in water quality trend analysis, and
- flow records are useful for comparing with turbidity records suspected to be corrupted by lens fouling.

1.2.2 Site access

The following accessibility factors shall be considered when selecting a site:

- general access and legal requirements
- instrument servicing
- collecting validation or supplementary verification samples:
  - by hand, or
  - with auto-samplers.

1.2.3 General access and legal requirements

If a new station is to be established, the following general access issues shall be considered:

- Is safe site access possible all year round?
- Can machinery and materials be suitably and safely positioned during construction?
- Is it possible to obtain a long-term access agreement with any landowners whose land must be crossed to access the site?
- What are the environmental effects and resource consent requirements?

1.2.3.1 Instrument servicing

The turbidity instrument shall be accessible over most of the site stage (water level) range for:

- servicing, and
- cleaning plant debris or biofilm from its lens.

1.2.3.2 Collecting validation or supplementary verification samples by hand

If validation or supplementary verification samples are collected by hand, then access shall permit these to be collected as close as practicable to the turbidity instrument.

Note: It is recognised that in many cases this will be difficult to achieve at high flows. Thus, it is preferable to collect validation or supplementary verification samples using an auto-sampler.

1.2.3.3 Auto-samplers

If auto-samplers are used to collect validation or supplementary verification samples, then the auto-sampler shall be located where:

- the auto-sampler is secure from flood damage at high stage (water level), and
- the auto-sampler's intake and the turbidity instrument are, where practicable, within 1 metre horizontally and vertically of each other.

1.2.4 Channel and bank characteristics

The following characteristics of the channel and banks shall be considered when siting turbidity instruments:

- location in channel
- turbulence characteristics, and
- bank conditions.

1.2.4.1 Location in channel

Access generally dictates that turbidity instruments are deployed from a stream bank.

1.2.4.2 Turbulence characteristics

Where practicable, turbidity instruments shall be located where turbulence is sufficient to maximise the mixing of the suspended load over the channel cross-section. For example, turbulent pools immediately downstream from rapids are ideal.

1.2.4.3 Bank conditions

It is recommended that bank conditions should be stable over time. For example, if the bankside vegetation were to change over time from grass to progressively larger trees, the bankside velocity field would change.

1.2.5 Sites to avoid

Sites that exhibit the following features should be avoided:

- banks that are eroding or are prone to slips

- banks with trees and shrubs that create low-velocity backwaters, or
- sections that have unstable beds.

Low-velocity backwaters (e.g., low-velocity pools and beaches) can trap sediment, which can build up and bury the instrument.

1.3 Practical controls

1.3.1 Site access

Site access shall be secure and safe for the complete period of deployment. A long-term access agreement with any landowners whose land must be crossed to gain access to the site is recommended.

1.3.2 Safety

Hazards (for observers, the public, livestock and wildlife) related to the location and the measurement activity shall be identified and minimised.

For further guidance on safety precautions when collecting turbidity data refer to the NEMS *Safe Collection of Environmental Data: Guidelines for safe working when undertaking environmental monitoring*.

1.3.3 Hazard review

On selection of a final site, a hazard review shall be carried out in accordance with relevant guidelines or best practise.

The potential for human activity to affect the measurement, e.g., vandalism, shall be minimised.

1.4 Deploying instruments

The *in situ* turbidity instrument shall be deployed:

- near to a flow recording site where it is practical to do so and the location of a flow recording site meets the purpose of the turbidity monitoring
- at a site that permits servicing and validation operations to be carried out on the instrument
- within 1 m horizontally and vertically of the intake point of any co-deployed automatic water sampler, and
- far enough downstream from sources of turbidity that the turbidity from these sources is well mixed across the channel by the time it passes the instrument.

Turbidity instruments are very susceptible to fouling; therefore, site visits shall be planned to enable the sensor to be cleaned at least once every two months, or more often if telemetered data indicates that fouling has occurred, or at sites where fouling is known to occur frequently.

1.5 Instrument orientation and clearances

The manufacturer's specifications shall be followed in regard to:

- how the instrument lens is orientated with respect to the ambient flow direction
- the minimum clearance between the instrument lens and the stream bed, and
- the minimum clearance between the instrument lens and the water surface.

Note: In situations where biofouling is severe and difficult to manage with mechanical or hydraulic devices and where the purpose is to monitor the suspended sediment load during floods and freshes, it may be pragmatic to position the instrument lens above water level at base flows.

1.5.1 Instrument protection

As far as practicable, instruments and their cabling shall be protected from damage by vandals, wildlife, flood scour and debris. Typical protective measures include deployment within steel casings firmly secured to the banks, and buried or ducted cables beyond the banks.

Note: Protection measures should still enable easy access to the instrument lens for cleaning it of biofilm growth and for instrument removal if necessary.

2 Turbidity Instrumentation

This section contains information on:

- the purpose of turbidity instruments
- the general and required characteristics of turbidity instruments
- the Standard
- calibration and reference suspensions
- pre-deployment calibration checks of *in situ* instruments, and
- swapping *in situ* instruments.

2.1 Purpose of turbidity instruments

Common applications of *in situ* turbidity instruments include providing a continuous record of turbidity, or surrogate continuous records of suspended sediment concentration or visual clarity, for the purpose of:

- measuring state and trends in water quality
- determining stream suspended sediment concentrations and loads, or
- monitoring compliance with resource consent conditions relating to water quality or suspended sediment load parameters.

2.2 Instrument characteristics

2.2.1 General characteristics and standards

Available turbidity instruments vary in terms of the:

- spectrum and beam width of emitted light
- angle between emitted and detected light beams
- wavelength of detected light
- reference suspension used for calibration, and
- range of turbidity able to be measured.

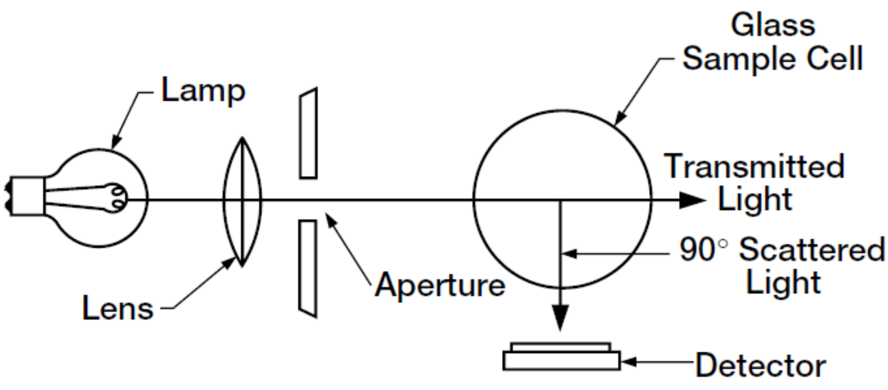


Figure 1 – Schematic of the key components of a nephelometric turbidity instrument. A nephelometric instrument detects light backscattered at an angle of 90° from the transmitted light pathway. A turbidimeter has its detector in line with the transmitted beam.

Variation in the first four characteristics can produce different results for the same suspension. Thus, a standard set of instrument characteristics is required. Data from instruments compliant with a given standard are assigned measurement units tagged to that standard.

Two common international standards used for laboratory- or field-based measurement of turbidity are:

- ISO 7027-1:2016 *Water Quality – Determination of turbidity -Part 1* (International Organization for Standardization, 2016), and
- EPA Method 180.1: *Determination of Turbidity by Nephelometry* (EPA, 1993).

Note:

The APHA2045 Standard follows the EPA Method 180.1 (for drinking water) using broad-spectrum wavelengths and focuses on a relatively low turbidity range (0–40 NTU range). Most in situ instruments follow the ISO 7027 Standard using monochromatic, near-infrared light and based around wastewater measurements with a higher turbidity range. The near-infrared instrument is also less influenced by sediment colour. Thus, the ISO 7027 Standard has broader field application, notably if the record is to be used as a surrogate for another variable (particularly suspended sediment concentration), and is the Standard preferred in this document.

The ISO 7027 Standard is protected by copyright. It is, therefore, necessary that ISO 7027-1:2016 be purchased.

Results obtained with different standards are not inter-convertible.

2.2.2 Standard for *in situ* turbidity instruments

In this NEMS, turbidity instruments deployed *in situ* for continuous field monitoring shall meet the ISO 7027-1: 2016 *Water Quality – Determination of turbidity – Part 1: Quantitative methods* Standard, except in regard to instrument range (see 2.2.2.1).

ISO 7027-1:2016 permits use of two types of turbidity instrument, both using near infrared radiation in the 830–890 nm range:

- a nephelometer, for measuring diffuse radiation in suspensions with low-range turbidity, or
- a turbidimeter, for measuring attenuated radiation in suspensions with relatively high-ranging turbidity.

The key requirements of ISO 7027-1:2016 for nephelometry are:

- light source: monochromatic radiation with wavelength 860 nm ± 30 nm
- beam convergence angle < 1.5°
- aperture angle between 20° and 30° in water
- measurement angle: 90° ± 2.5°
- calibration standard: formazin or a manufacturer-approved secondary standard such as AMCO CLEAR, and
- reporting units: formazin nephelometric units (FNU)

The key features of ISO 7027-1:2016 for turbidimetry are:

- light source: monochromatic incident radiation with wavelength 860 nm ± 30 nm
- aperture angle between 10° and 20° in water
- measurement angle: 0° ± 2.5°
- calibration standard: formazin, and
- reporting units: formazin attenuation units (FAU).

Note: Nephelometers and turbidimeters are different instruments, so: (i) they will not necessarily return consistent turbidity readings from natural suspensions even when both are formazin calibrated, and (ii) FAUs and FNUs are not equivalent units.

Note: Most New Zealand experience to date involves nephelometers, and the tolerance specifications included in this standard reflect that experience. Until further experience is accumulated with turbidimeters, it is assumed that the tolerance specifications provided herein apply to both instrument types and are simply specified in FNU units henceforth through this document.

Note: ISO 7027-1:2016−compliant instruments that utilise multiple light beams and sensors are permitted in this NEMS. Examples are instruments that use ratio-metric methods to measure turbidity and instruments that use multiple sensors to measure multiple ranges of turbidity.

2.2.2.1 Instrument range

A point of difference between this NEMS and ISO 7027-1:2016 relates to the turbidity ranges applicable to nephelometric and turbidimetric instruments. While ISO 7027-1:2016 restricts the use of nephelometers to the 0–40 FNU range, this NEMS permits use of otherwise-ISO-7027−compliant nephelometers that range up to 4000 FNU. This is because there are several well-performing high-range nephelometers currently available on the market, including multi-ranging instruments that match measurement precision to the active range.

2.2.2.2 Non-conforming instruments

Instruments that are non-compliant with ISO 7027, including instruments meeting the EPA Method 180.1 Standard, are permitted for applications requiring raw turbidity data only, but their records shall be assigned a quality code of QC 200.

2.2.2.3 Reporting in nephelometric turbidity units

Data from existing instruments meeting the EPA Method 180.1 Standard shall be reported in nephelometric turbidity units (NTU).

2.2.2.4 Reporting in formazin backscatter units

Data from existing instruments meeting neither the ISO 7027 nor EPA Method 180.1 Standards but using a backscatter-type detection system and using formazin as the calibration standard shall be reported in formazin backscatter units (FBU).

2.2.2.5 Limited accuracy

Accuracy may be limited at low turbidity, depending on instrument type, range, and output settings. Accuracy shall be assessed from field verification measurements.

2.3 Calibration

Irrespective of the turbidity record application and whether this application requires standard or absolute turbidity data, all instruments shall be initially calibrated to, and then maintained against, a reference suspension of stable and characteristic physical properties according to manufacturer specifications.

2.3.1 Need for calibration

Calibration is needed to:

- maintain temporal (and, as need be, spatial) stationarity of record
- ensure the instrument provides a linear response over its factory-calibrated range, and
- monitor/validate for instrument drift.

If this is not done, then:

- the instrument may be unwittingly used outside its optimum and linear performance range, possibly resulting in spurious results (e.g., non-linear, plateau, or inverse response at high turbidity ranges)
- stationarity may be compromised, and
- true instrument drift may be confused with environmental drift (e.g., a change in the physical properties of the suspended material passing the monitoring site) which, in turn, may confuse calibration relationships between turbidity and suspended sediment concentration or visual clarity.

Note: New instruments that have been factory calibrated do not require an initial calibration.

2.4 Reference suspensions

2.4.1 Primary reference suspensions

The primary reference suspension for instruments meeting this standard is formazin (hydrazine sulphate). Formazin has known issues relating to health hazards and stability of its physical and optical properties. Both issues can be mitigated by following appropriate protocols for handling, storage, and 'shelf-life', as detailed in ISO 7027-1: 2016.

Stabilised formazin suspensions ((e.g., Stablcal™) are supplied by some instrument manufacturers and used for factory calibration of their instruments. Their use for calibration checks and recalibration are permissible in this NEMS, providing these are done to manufacturer specifications.

2.4.2 Secondary reference suspensions

Alternative reference suspensions, such as those composed of polymer beads (e.g., AMCO CLEAR™), have been developed to mitigate the health and stability issues associated with formazin.

As per ISO 7027-1:2016, this NEMS permits these alternatives to be used as secondary reference suspensions for calibrating nephelometric instruments, providing their use is approved by the instrument manufacturer and they are validated against formazin standards at least 6-monthly.

As per ISO 7027-1: 2016, secondary reference suspensions are currently not permitted for calibrating turbidimeters.

2.4.3 Initial calibration

Most new turbidity instruments that meet the instrumentation standard described above will have been factory-calibrated to formazin or the approved alternatives and do not require an initial re-calibration before field deployment.

2.5 Pre-deployment validation

2.5.1 Purpose

Even when factory-calibrated, a pre-deployment validation check is required to ensure that the factory calibration remains accurate. This applies both to:

- brand-new instruments, and
- older instruments that have had previous field deployments but may not have been used for some time.

A check of factory calibration shall be done irrespective of whether the purpose of the monitoring is to:

- collect a record of standard or absolute turbidity, or
- to use turbidity as a surrogate for other variables, for example, for sediment concentration or visual clarity.

2.5.2 Validation procedure

Instrument validation involves:

- securing fresh stock solutions of formazin or secondary standard that cover the full FNU range of the instrument
- measuring the FNU of these stock solutions accurately with an already-calibrated laboratory instrument that meets the ISO 7027 Standard
- measuring their FNU with the field instrument being checked
- measuring a clear-water (zero turbidity) sample of distilled water with both instruments, and
- checking that the agreement between the laboratory and field instruments is within the tolerance levels.

Note: If standard turbidity data from the in situ field instrument are to be converted to instrument-specific absolute turbidity data, and if the reference instrument is a laboratory instrument, then it will be expedient to also use the reference instrument for the pre-deployment validation check (see section 5.2 for further comment on reference instruments).

Note: If the in situ instrument has multiple turbidity ranges, then the calibrations of all ranges to be used in the field deployment must be validated, including the alignment of adjacent scales at their cross-over points.

2.5.3 Validation solutions

The solutions used to validate the instrument calibration in the laboratory shall either be composed of formazin or an approved secondary reference suspension that has been validated against formazin.

WARNING! Formazin contains carcinogenic compounds. Ingesting formazin can cause serious illness or death.

All staff must be trained in the use of formazin. A health and safety plan that includes a Material Safety Data Sheet or Safety Data Sheet (MSDS/SDS) is required.

2.5.4 Tolerance levels for validation

Generally, the field instrument measurements of the stock solutions shall lie within a specified percentage of the laboratory instrument.

2.5.4.1 Mean difference between instruments

The mean absolute value of the relative difference between the two instruments shall be less than 10% when compared across a minimum of 10 stock solutions with turbidity values greater than or equal to 20 FNU.

For turbidity values less than 20 FNU, the mean absolute difference between the two instruments shall be within 3 FNU when compared across at least four stock solutions (which may include a clear water sample).

See Figure 2 for an example validation dataset.

2.5.4.2 Zero turbidity difference between instruments

The clear-water, near-zero turbidity comparison shall provide instrument values within ± 1 FNU.

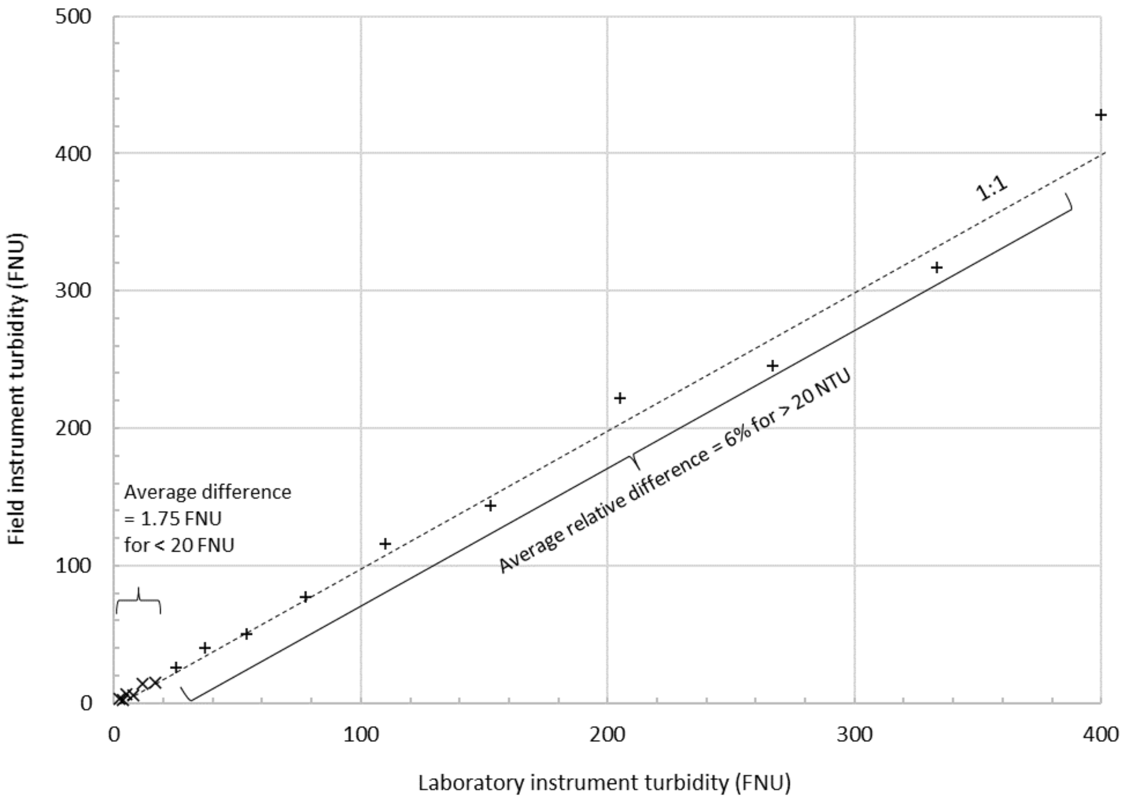


Figure 2 – Pre-deployment validation check comparing measurements of turbidity made by a field instrument and a calibrated laboratory instrument. Average difference is < 3 FNU for turbidity < 20 FNU (points labelled x). Average relative difference is < 10% for turbidity > 20 FNU (points labelled +).

2.5.5 If the validation fails

If the instrument calibration is not validated to acceptable accuracy, then the instrument shall be recalibrated or returned to the supplier. If recalibrated locally, the calibration shall be undertaken as detailed in the instrument reference manual and conforming to the ISO 7027 standard.

A calibration certificate shall be provided by the agency undertaking the calibration and it shall be inspected by field technicians prior to deployment.

2.6 Instrument swapping

The NIWA study of stationarity across ISO 7027–compliant nephelometers (Davies-Colley et al., 2021) showed reasonable agreement across field and laboratory instruments of the same brand and model but not necessarily across different brands. This has implications for:

- replacing *in situ* instruments that have failed or require removal for servicing/re-calibration, and
- changing the verification reference instrument.

2.6.1 Replacing an *in situ* instrument with an equivalent instrument

When *in situ* instruments need to be replaced with another instrument, to maintain temporal stationarity of record the replacement instrument shall be equivalent in all respects to the one being replaced. That is, it shall be of the same brand and model, cover the same range of turbidity, and be calibrated/validated as per the original instrument as specified in subsections 2.3 and 2.4.

In these circumstances, the records from the original and replacement instruments can be regarded as equivalent and record stationarity will not be compromised.

When a replaced instrument is used to collect standard turbidity data to provide a surrogate record of suspended sediment concentration (SSC) or visual clarity (VC), or to be adjusted to provide a record of absolute turbidity, then its replacement with an equivalent instrument allows:

- continued use of the turbidity–SSC or turbidity–VC calibration relationships developed using the replaced instrument, and
- continued use of the relationship between standard turbidity of the replaced instrument and the turbidity measured on the reference instrument.

Note: Such relationships are typically only established after considerable expense. The expense of creating new relationships for non-equivalent instruments may far outweigh the cost of purchasing a replacement instrument of the same type as that being replaced and is best avoided if possible.

2.6.2 Replacing an *in situ* instrument with a non-equivalent instrument

Replacing an *in situ* instrument with a non-equivalent instrument should be avoided since this potentially:

- breaks record stationarity, and
- renders invalid any future use, with the new instrument, of calibration relationships between standard turbidity and suspended sediment concentration, visual clarity, or absolute turbidity on a reference instrument.

If a non-equivalent instrument is used as a replacement, then the rating with the verification reference instrument, and any surrogate and absolute calibration relationships, will need to be re-established with new data.

2.6.3 Changing the verification instrument

Changing the verification reference instrument (see section 3.3.3) should be avoided unless it is swapped for an equivalent instrument (ie, same brand and model). If a different instrument is used, then a new rating will need to be established between the new verification instrument and the *in situ* instrument.

3 Data Acquisition

This section contains information on the acquisition of standard turbidity data and associated verification data. It covers:

- time-series data collection specifications
- monitoring and management of instrument fouling
- collecting verification data with an independent instrument, and
- procedures for checking the status of the instrument's calibration from the field verification measurements.

Note: Procedures for collecting associated samples/measurements to enable conversion of standard turbidity records to absolute turbidity and to use turbidity as a surrogate for suspended sediment concentration are addressed in Sections 5 and 6, respectively. If a Water Clarity NEMS is developed in the future, it will outline procedures for relating turbidity to visual clarity.

3.1 Data collection specifications

Turbidity instruments output a turbidity value measured over a fixed observation period.

The observation period varies between instrument types and may sometimes be adjusted during instrument set-up. The data logger shall be capable of providing one-second time resolution with an accuracy of +/- 90 s/month. The observation period shall span at least 10 seconds and shall be no longer than 20 seconds.

All turbidity data shall be collected in New Zealand Standard Time (NZST), or Chatham Islands Standard Time for data collected in the Chatham Islands.

Typically, the measurement is the average over the observation period, but the average may sometimes be substituted by an alternative "central" statistic, such as the median or mode, that is less sensitive to extreme values.

The measurement shall be filed as "instantaneous" data.

The logging interval shall be no longer than 15 minutes for catchments greater than 25 km^2 and no longer than 5 minutes for catchments less than 25 km^2.

These specifications shall be recorded in metadata.

Note: Some instruments require a warm-up period. Also, the observation period may be limited by the power budget available. These are managed either in the on-board control systems or with a programmable data logger.

3.2 Environmental factors degrading data quality

Turbidity records from *in situ* instruments are vulnerable to various environmental/site factors that can induce errors in the recorded data. These include:

- biofouling
- chemical fouling
- exposure to light, and
- burial by gravel.

Field personnel shall be alert to these effects in order to mitigate their occurrence and severity, while data processing personnel may need to make adjustments to affected data through editing.

Note: Guidance to recognise and manage affected segments of turbidity data are provided in Annex E of the NEMS Processing of Environmental Time-Series Data*.*

3.2.1 Biofouling

Biofouling includes micro-biofouling (by algae growing on the turbidity sensor lens) and macro-fouling (by plant debris interfering with light scattering or transmission in the sensing volume of the instrument). Unmonitored or unmanaged biofouling may compromise a turbidity record. Micro-biofouling is most prevalent during summer and where the water has high nutrient concentrations. A management plan shall be devised and implemented to minimise biofouling.

3.2.2 Chemical fouling

Chemical films can also accumulate on turbidity sensor lenses, altering the apparent turbidity. Examples include tannin-based compounds sourced from swamps and forested catchments. Such effects, if present, should become apparent through verification and validation checks.

3.2.3 Fouling inhibitors

Turbidity instruments deployed *in situ* for continuous monitoring shall generally include a mechanism for continuously inhibiting lens biofouling.

Mechanisms may consist of a:

- mechanical wiper
- ultra-sonic vibrator
- micro water jet
- micro bleach jet, or
- high pressure air jet.

Note: Lens fouling may also be inhibited by specialised, factory-applied polymer coatings.

Multi-beam turbidity instruments that use ratio-metric techniques to compensate for lens fouling may not need a continuous de-fouling mechanism but should be checked and cleaned (according to manufacturer instructions) during inspection/verification visits.

Note: It is recommended that all sites prone to fouling (whether micro or macro) be equipped with telemetry so that the early signs can be checked in the office on a regular, even daily, basis *and appropriate measures taken to clean or clear the instrument before the record deteriorates to the point of corrupting or losing data.*

3.2.4 Instrument exposure

Instrument sensors may become exposed inadvertently because of bed scour or deliberately to avoid biofouling at low flows. The value returned when the sensor is exposed varies according to the type and brand of sensor and may not necessarily be zero.

To mitigate the risk of false data through exposure:

- an at-site water level threshold, below which the turbidity data must be regarded as compromised, should be determined from the level of the sensor lens in relation to the water surface and the minimum required deployment depth of the sensor to avoid ambient light contamination, and
- field personnel shall be alert to situations when this threshold is met and, if need be and exposure is not intended, adjust the instrument elevation, noting any such changes in metadata.

3.2.5 Instrument burial

Sensors will give false readings when buried by gravel deposits or even if the streambed aggrades to the point where the bed intrudes into the sensor measurement volume. Such incidents will usually be observed after high-flow events.

Field personnel shall be alert to burial effects when inspecting telemetered data and during site visits. If need be, the streambed may be excavated by hand or the instrument height adjusted, noting any such changes in metadata.

3.3 Verification

3.3.1 Purpose

Verification involves using an independent instrument to make concurrent measurements of the turbidity of the water passing beside the *in situ* turbidity instrument. The independent instrument shall meet the same standards in terms of instrument characteristics and calibration as does the *in situ* instrument.

The primary purpose of verification is to check, on an ongoing basis, that the *in situ* instrument is performing as expected and remains in calibration, thus verifying the reliability of the data being collected. Verification shall be repeated at regular intervals throughout the duration of the instrument deployment.

The verification process also helps determine the quality code assigned to the archived data.

Note: Neither the suspended sediment concentration nor visual clarity of natural waters should be relied on for verification of turbidity instruments. This is because the relationships of turbidity with both suspended sediment concentration and visual clarity are influenced by *suspension physical properties. If these suspension properties change at the site they can confuse the detection of instrument drift.*

3.3.2 Basic options

There are two acceptable methods for regular verification of *in situ* instruments.

The preferred method is using a calibrated portable turbidity instrument (conforming to ISO 7027) in the field to:

- measure turbidity directly, or
- to measure the turbidity of water samples immediately after they have been taken.

The other method involves transporting water samples to the laboratory where their turbidity is measured with a laboratory instrument (also conforming to ISO 7027).

The laboratory approach:

- enables multiple analyses of samples, which ensures greater reliability (repeatability) in the verification result
- enables the same sample to be analysed for suspended sediment concentration or visual clarity, but
- risks post-sampling changes in turbidity due to algal growth and changing sediment characteristics (e.g., from flocculation) in the sample bottle before analysis.

Whichever approach is used, the verification instrument shall be recorded in the *in situ* instrument's metadata and its calibration certificate shall be sighted by the field/laboratory technicians undertaking the verification measurements.

3.3.2.1 Direct turbidity measurements

Direct measurements of turbidity made for verification purposes with the portable instrument shall be:

- made as close as practicable to, and within 1 metre of, the *in situ* turbidity instrument, and
- taken several minutes before the time of the data logger reading.

3.3.2.2 Water sampling

Water samples collected for verification shall be:

- collected as close as practicable to, and within 1 metre of, the *in situ* turbidity instrument
- collected either by hand into a bottle or a DH48 water sampler, or with an automatic sampler
- at least 100 mL in volume
- taken several minutes before or after the time of a turbidity data logger reading, and
- analysed immediately if being analysed with a portable sample analyser, or
- analysed within 48 hours of sampling if being analysed in the laboratory.

3.3.2.3 With either method

When making direct turbidity measurements or collecting water samples for turbidity measurement for verification purposes, it is necessary to:

- firstly, clean the lens on the *in situ* turbidity instrument, and note the time of this action (*Cleaning the instrument lens lessens the likelihood that any instrument drift is confused by lens fouling).*
- be alert for and avoid turbidity gradients between the measurement/sampling location and the *in situ* instrument. Such gradients can develop as a result of incomplete mixing of nearby sources of turbidity, such as a culvert outlet or tributary inflow.
- record the measurement/sampling time to the nearest minute, and ensure that the time is cross-checked against the clock on the *in situ* turbidity instrument.

Note: Collecting samples, making direct measurements with a portable instrument, and cleaning the in situ instrument lens can all stir up fine sediment, temporarily increasing the turbidity. Therefore, it is important that the matching turbidity taken from the in situ instrument is recorded several minutes after these activities.

3.3.2.4 Laboratory analysis

(NEMS Water Quality – Part 2 *of 4: Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data* provides further information on laboratory measurement of turbidity.)

If the water samples are to be measured for turbidity in the laboratory, they shall be:

- stored in a refrigerated, dark space
- transported as soon as practicable to the laboratory, and
- measured for turbidity within 48 hours of field collection.

Note: In sunlight and warm temperatures, algae can grow quickly in sample bottles, increasing the turbidity above what it was in the field.

3.3.3 The independent turbidity instrument

The independent turbidity instrument used for the *in situ* instrument verification, whether it is field-portable or laboratory-based, shall meet the required ISO 7027 Standard in terms of instrument type and calibration against the formazin standard or manufacturer-approved alternatives. For more information, see section 2 'Turbidity Instrumentation'.

Note: If the turbidity data are to be converted to absolute turbidity data associated with a laboratory-based reference turbidity instrument, then it will be expedient to also use the reference instrument as the verification instrument.

3.3.4 Laboratory analysis of verification samples

The method used in the laboratory for analysing turbidity samples taken for verification purposes shall be as specified in the NEMS *Water Quality – Part 2 of 4: Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data* .

3.3.5 Frequency of verification data collection

Verification samples/measurements shall be collected at least once every month and whenever the instrument is serviced.

Ideally, a verification sample/measurement shall be undertaken before and after any servicing of the instrument; for example, when cleaning the lens of biofouling. If this is not practical, then a sample/measurement shall be collected after the servicing.

Note: Measurements associated with instrument servicing often provide data helpful for editing the instrument record.

In addition, verification measurement/sampling over a range of turbidity shall be obtained at least once per year during a runoff event in which the turbidity range exceeds 100 FNU.

If the purpose of the turbidity monitoring is to provide a surrogate record of suspended sediment concentration, a corresponding set of water samples should be collected during this runoff event and analysed for suspended sediment concentration (See NEMS *Measurement of Fluvial Suspended Sediment Load and its composition V2.0.0*).

If the purpose of the turbidity monitoring is to provide a surrogate records of visual water clarity, practitioners should refer to the appropriate sections of the NEMS *Water Quality – Part 2 of 4: Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data*, for further guidance.

3.3.6 Multiple use of turbidity verification samples

Water samples may also be required to establish calibration relationships between turbidity and:

- suspended sediment concentration
- visual clarity, or
- absolute turbidity on a reference laboratory instrument.

The same sampling considerations and sample treatments as described in subsection 3.3.2 “Basic options” apply if these samples are also to be measured for turbidity and used to verify the *in situ* turbidity instrument.

Note: Samples collected for other purposes may have additional sampling constraints to those required for turbidity verification.

Note: While the respective Standards for laboratory analysis of turbidity (ISO 7027) and suspended sediment concentration (ASTM D-3977-97, see Annex C) strictly require collection of separate duplicate samples for each analysis, in practice the one sample may be used for both analyses providing:

- *the turbidity analysis is undertaken first*
- *the aliquot extracted for turbidity measurement is returned to the original sample prior to analysis for suspended sediment concentration, and*

- *the volume of any wash-water added in the process of returning the aliquot to the original sample is accounted for in the calculation of suspended sediment concentration.*

Note: An example situation is when samples have been collected by auto-sampler during a runoff event in which turbidity and suspended sediment concentration changed rapidly.

3.4 Assessing verification measurements

As described above, the primary purpose of field verification measurements is to provide field operations personnel with a running check that the *in situ* instrument is performing as expected and remains in calibration. Should it be discovered that this is not the case, then prompt follow-up action is required. This section outlines procedures for how this performance check should be undertaken and responded to.

The procedures for assessing verification measurements for calibration status involve:

- extracting the turbidity records from the *in situ* instrument that are concurrent with the verification measurements
- plotting both sets of results, as well as their differences, on working plots (see Figure 3), and
- checking if the *in situ* instrument meets verification criteria or requires a laboratory validation check or recalibration.

Note: Procedures for using verification results to assign data quality codes during data processing are documented in Annex E of the NEMS Processing of Environmental Time-Series Data*.*

3.5 Extracting the concurrent *in situ* turbidity value

The concurrent turbidity values that match with verification samples shall be extracted from the record after the times of the verification measurement/sample collection and instrument cleaning, allowing time for any fine sediment stirred up by these activities to have settled or drifted away.

Note: The time of the concurrent in situ measurement is best judged by inspection of the in situ turbidity record, whereon any signals due to cleaning and silt stirring can be identified and avoided. A record from after the lens cleaning shall be the one plotted against the verification measurement, but it is important not to have too long a time lag if the background turbidity is changing. Any difference related to the effect of cleaning the in situ instrument lens shall be noted and, as appropriate, used in subsequent data editing.

3.5.1 Working plots

3.5.1.1 Scatterplots

Two working scatterplots shall be created that relate the verification turbidity measurements to the concurrent turbidity records from the *in situ* instrument.

These scatterplots shall include the clear-water zero-point validation results and shall be extended as data become available:

- one showing only data points in the 0–20 FNU range, and
- the other showing all data points over the full range of the *in situ* instrument.

These scatterplots are used to derive the relations used to normalise the differences between the *in situ* and verification instruments' measurements (see section 3.5.1.2)

Note: Low- and full-range plots are required because verification data will mostly be collected during base flows at relatively low turbidity values, so those and clear-water data will not be adequately resolved on a full-range plot.

3.5.1.2 Normalised differences

A consequence of the standardisation issue between ISO 7027compliant instruments identified by the NIWA study (Davies-Colley et al., 2021) is that in stream water there could potentially be systematic differences observed between the *in situ* and verification instruments' data even if there is no drift in the *in situ* instrument calibration. These will appear as systematic deviations from the 1:1 line in the scatterplots (see section 3.5.1.1). Therefore, before assessing differences between the two instruments it is necessary to equate their values.

This shall be done by developing a 'rating' between the verification instrument and the *in situ* instrument (across as much of the full range of the *in situ* instrument as possible) early in the deployment, and then using this rating to 'normalise' the *in situ* instrument reading to the verification instrument scale.

This rating shall be developed by linear regression of the data in the full range scatterplot and shall be of the form $V = o + gF$, where V is the verification instrument value, F is the *in situ* instrument value, and o and g are the rating offset and gain. Normalised *in situ* instrument data, F^*, are then calculated as $F^* = o + gF$.

Absolute differences between normalised field values and their matching verification values equal (F^*- V) and are to be calculated for $V < 20$ FNU.

Relative (proportional) differences between normalised field values and their matching verification values equal $(F^*- V)/V$ and are to be calculated for $V \geq 20$ FNU.

Initial verification ratings shall be compiled over at least six verification measurements over a reasonable turbidity range, with at least three under 20 FNU and at least three above 20 FNU.

Note: While this might require six months to acquire, the risk of an instrument drifting significantly over that duration is low.

Note: If the measurements from the in situ and verification instruments are equivalent, their data will cluster on the 1:1 lines on the scatterplots and the rating coefficients will be o = 0 and g = 1.

The verification rating should be reviewed and, as need be, updated as new verification data are acquired and added to the working scatterplots. Situations where the verification rating should be updated include:

- *when the instrument has only been deployed for a short period, so the uncertainty on the rating relationship is large because there are only a few verification data points, or*
- *when the instrument has been recalibrated following verification and validation failure (section 3.5.2).*

Note: Verification data collected while an instrument is found to be out of calibration should not be used to derive a verification rating.

3.5.1.3 Deviation-with-time plots

Two working deviation-with-time plots (or run-charts) shall be made using the normalised differences and extended as data become available:

- one showing the absolute difference between the normalised *in situ* instrument value and the verification measurement for values less than 20 FNU (see Figure 3 for an example), and
- the other showing the relative difference between the normalised *in situ* instrument value and the verification measurement for values greater than or equal to 20 FNU.

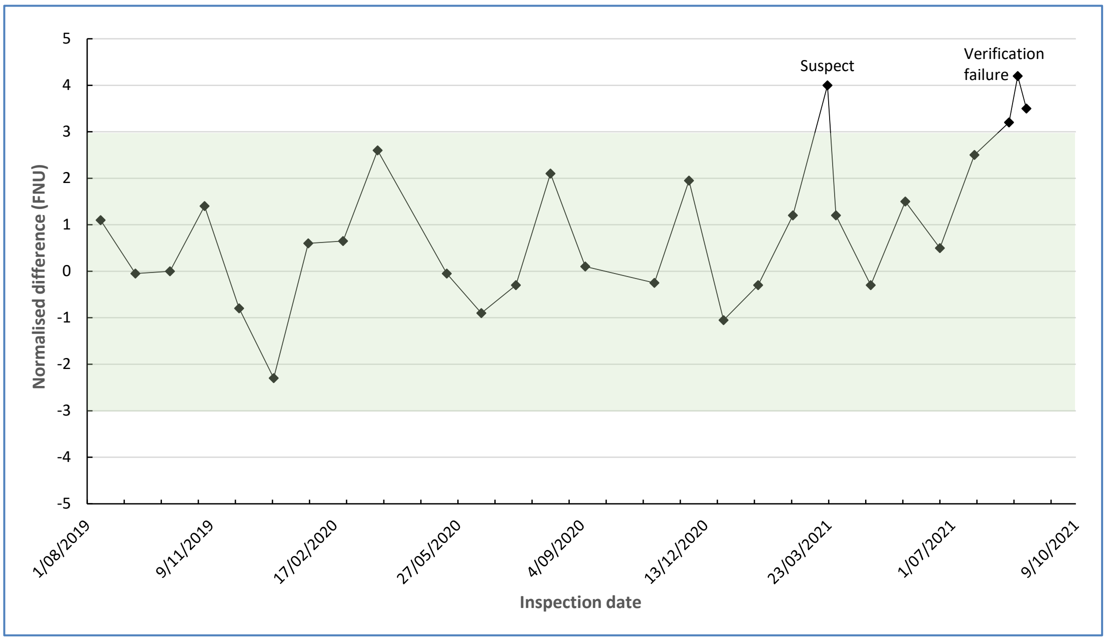


Figure 3 – Deviation-with-time plot (or run-chart) of normalised difference between *in situ* instrument turbidity and verification measurements for turbidity < 20 FNU. The acceptable range, within ± 3 FNU, is shaded in green. Verification is suspect when any point plots out of this range. Verification fails if three or more consecutive data points plot outside this range.

3.5.1.4 Evaluating the differences

Separate evaluation criteria apply for turbidity measurements less than and greater than or equal to 20 FNU.

Any single verification result is considered acceptable when:

- for turbidity values less than 20 FNU, the absolute value of the normalised difference is less than or equal to 3 FNU, and
- for turbidity values greater than or equal to 20 FNU, the absolute value of the normalised difference is less than or equal to 15% of the verification measurement.

If either of these tolerances are exceeded during a verification measurement, the *in situ* instrument shall be regarded as "suspect" and the frequency of verification checks shall be increased to at least weekly.

Note: This increase in verification frequency is to confirm a potential data quality issue more quickly.

With a "suspect" instrument, if the subsequent verification result is acceptable, the "suspect" status is removed and the verification frequency can revert to the normal frequency.

Instrument verification shall be considered "unacceptable" when at least three consecutive "suspect" results of the same sign are observed. That is:

- for turbidity values less than 20 FNU, the absolute value of the normalised difference exceeds 3 FNU for at least three consecutive measurements with the same difference sign, or
- for turbidity values greater than or equal to 20 FNU, the absolute value of the normalised difference exceeds 15% of the verification measurement for at least three consecutive measurements with the same difference sign.

See Figure 3 for an example deviation-with-time plot for turbidity values < 20 FNU showing suspect and unacceptable verification results.

Note: The verification focus is on identifying persistent tolerance failures of the same sign. Isolated verification results that exceed the tolerance values should be expected occasionally due to sampling errors in the verification and in situ instrument data and variability in composition of the suspended and dissolved material causing the turbidity. Where verification results frequently exceed the tolerance values but show no systematic pattern, then (as in section 3.5.1.4 checks should be made of the values extracted from the in situ instrument e.g., could the instrument be fouled?) and the integrity of verification data (e.g., was there algal growth in the sample bottle, or was there a turbidity gradient where the sample was collected/measurement made?).

Note: It is recommended that instrument verification performance decisions are not based on laboratory-measured samples with turbidity values exceeding 750 FNU. This is because the dilution procedure required to measure these samples with laboratory instruments reduces the accuracy of the result.

3.5.2 Verification check failure

If the instrument verification status exceeds the unacceptable threshold, then in the first instance the verification data and results shall be:

- evaluated, and

- the evaluation shall be reviewed.

The evaluation shall include checking:

- the values extracted from the *in situ* instrument in the context of adjacent data, being alert for the signature of residual lens fouling (after cleaning)
- for any error or noted issues with the verification data (e.g. algal growth in sample bottle, turbidity gradient where sample collected/measurement made)
- that the verification rating is up-to-date
- the scatterplots and deviation with time plots for visual confirmation of a performance change, and
- all calculations.

The evaluation findings shall be reviewed by an experienced colleague.

If the verification check remains unacceptable, the *in situ* instrument shall be recovered and its calibration checked in the laboratory using the Pre-deployment Validation procedure detailed in Section 2.4.

If this validation check fails, then this confirms instrument calibration drift and the instrument shall be recalibrated or returned to the manufacturer for repair/recalibration.

If the validation check shows that the instrument remains in calibration, then this signals that the verification 'failure' likely stems not from electronic drift in the *in situ* instrument but from a systematic change in the characteristics of the stream suspended material causing turbidity (e.g. a change in particle size grading or composition associated with a changed sediment supply regime), which can potentially cause drift in the relationship between the verification and *in situ* instruments. In that case:

- the data collected over the period of the verification incident should not have its quality down-graded
- the verification incident should be noted in comments
- the instrument may be returned to the field, and
- the relationship between the verification and *in situ* instruments should be begun anew.

3.6 Clear-water, zero-point validation

After the first year in the field, the *in situ* instrument shall be removed from its mounting hardware, cleaned thoroughly, and used to measure the turbidity of clear distilled water in a black plastic container with near-zero turbidity, as also measured with a calibrated portable or laboratory instrument.

The comparison shall provide instrument values within ± 1 FNU.

If this tolerance is met after the first year, then further annual zero-point validations are not required. If it is not met, then annual zero-point verifications should continue.

Note: This test is required to check for the effects of lens degradation due to abrasion (by suspended sediment) or chemical fouling (which is affected by water chemistry). Most modern in situ instruments should not demonstrate zero-offset characteristics due to lens abrasion, because most utilise sapphire lenses or other methods to prevent lens degradation. If lens degradation does not occur after the first year of deployment, then it is unlikely to occur in subsequent years.

Note: Those performing this test should be familiar with the clear-water sensing range of the in situ instrument and ensure that the clear-water container is sufficiently large and the instrument is far enough away from the container walls that no back-scattering off the walls is detected.

4 Data Preservation

4.1 Field data preservation requirements

The following field data and information shall be collated and retained indefinitely by the recording agency:

- unedited original turbidity data
- any backup or supplementary data collected
- all required site metadata (as detailed in section 4.2)
- any data used for verification, validation, calibration, adjustment of data, or infilling of gaps
- completed initial data quality assessments giving information on data provenance and status, annotated with the:
  - site identifier
  - period of data for which assessment applies
  - date of assessment, and
  - name of person who did the assessment
- any other information that may affect data quality, and
- any other information that may affect interpretation of the data.

Note: Data preservation requirements for processed turbidity records, including metadata and data quality assignments associated with the processing of turbidity data, are covered in the NEMS Processing of Environmental Time-Series Data*; see Annex E (Turbidity Data Processing) of that document in particular.*

4.2 Site metadata

4.2.1 Turbidity instrument metadata

Metadata for the *in situ* turbidity instrument shall be filed as electronic 'comments' with the data archive.

The metadata shall include:

- the instrument model, manufacturer and serial number
- the instrumentation standard and version; for example, ISO 7027-1:2016
- the turbidity range(s) of the instrument, as deployed

Note: Some instruments have multiple user-definable ranges and automatic cross-over between ranges.

- characteristics of the on-board anti-fouling mechanism
- the date, laboratory, and identification number of the instrument calibration against formazin or equivalent standards

- updated calibration information with each re-calibration
- the date and time of deployment
- the date and time of all subsequent site visits
- the data logging interval and a statement that instantaneous data (or incremental data, as appropriate to the measurement duration) are being logged
- what on-board numerical processing is undertaken to provide each original measurement; for example, "a 20-second average of turbidity sampled at 1 hertz is measured and logged every 5 minutes"
- any additional statistics of turbidity that may also be logged; for example, some instruments or coupled data loggers may calculate additional statistics such as the variance of each 20-second duration high-frequency data burst
- the method employed for collecting verification data
- the date and time of any relocating of the instrument and the reason for any relocation, and
- any supplementary data streams.

The above metadata for the *in situ* turbidity instrument shall be included in the time-stamped comments filed with the archived turbidity data.

4.2.2 During site setup

The following information shall be collected from the deployment site at set-up:

- photographs of the deployed instrument, showing detail and bankside context, and
- the level of the sensor relative to the local staff gauge datum.

4.2.3 During verification

At times of verification measurements/sampling, the following information shall be collected:

- observations of changes in the composition of the channel bed material (with estimated percentages of boulders, gravel, sand, mud and bedrock), and
- observations of the level of the bed under the sensor.

4.2.4 Annually

Photographs of the deployment site shall be taken at least once per year.

Note: The purpose of the photos is to capture any site changes, for example, changes and/or growth in bankside vegetation.

4.2.5 Archiving

Site metadata shall be archived:

- in hard copy, if the original is a paper record, and
- electronically.

The archiving procedures, policies and systems of the recording agency shall consider:

- future data-format changes
- off-site duplication of records, and
- disaster recovery.

5 Absolute Turbidity

This section presents additional field and office procedures for acquiring records of absolute turbidity, which is turbidity data that is derived directly from or is equivalent to data from a primary reference ISO 7027-1:2016–compliant nephelometer. It covers:

- the need for absolute turbidity data
- the choice of primary reference instrument
- converting standard turbidity data to absolute turbidity data
- quality code assignment, and
- data filing.

5.1 Need for absolute turbidity

Records of absolute turbidity are required to guarantee the equivalence of records collected across time and space by different brands and models of ISO 7027-1:2016–compliant nephelometers.

The need for absolute data emerged from a recent NIWA study (Davies-Colley et al., 2021) which showed that different ISO 7027–compliant nephelometers did not provide consistent results across natural suspensions. This probably arises from small differences in design features and different optical properties of natural suspensions compared to formazin stock.

See 'About this Standard', page viii, for further detail.

Note: Since a study of the equivalence of ISO 7027–compliant turbidimeters (measuring attenuation turbidity) has not been undertaken at this time, the need for instrument-specific attenuation turbidity data remains unknown.

5.2 Primary reference instrument

The primary reference instrument may be:

- a laboratory instrument,
- a portable instrument, or
- a field instrument designed for *in situ* deployment.

It should also:

- be an ISO 7027-1:2016 compliant nephelometer calibrated and validated as specified in section 2
- have known reliability, and
- if an *in situ* instrument, have a range large enough to span as much as possible of the turbidity range expected across the network of sites for which absolute turbidity is to be monitored, or
- if a laboratory or portable instrument, have a range of at least 1000 FNU.

Note: With a laboratory or portable instrument, field samples with turbidity values greater than 750 FNU may be measured after appropriate dilution with clear, distilled water. While these instruments may range up to 1000 FNU, it is conservative to not measure at their maximum range.

Note: Choosing a in situ-type primary reference instrument and deploying identical instruments across the turbidity monitoring network:

- *removes the need for any conversion from standard to absolute data (and associated calibration measurements), and*
- *allows assignment of a maximum quality code of QC 600 to the absolute data, but*
- *may limit the wider inter-compatibility of absolute turbidity records at a regional/national scale (e.g., among regional council networks using different in situ instruments).*

Note: Choosing a laboratory- or portable-type primary reference instrument:

- *may assist wider-scale networking (e.g., if all regional councils / data collection agencies adopt the same laboratory/portable reference instrument), but*
- *requires a site-specific conversion relationship to be developed with in situ instruments, with associated calibration measurements, and*
- *limits quality code assignment of the converted data to a maximum of QC 500.*

Note: A potential laboratory primary reference instrument is the Hach TL2310, since this was shown by Davies-Colley et al. (2021) to align reasonably well with two in situ instruments in common usage in New Zealand (Hach Solitax and WTW VisioTurb). However, this does not preclude the choice of any other instrument as either primary reference instrument or in situ instrument.

5.3 Converting standard data to absolute data

Converting standard, as measured, turbidity data to absolute turbidity data requires a relationship between measurements from the primary reference instrument and measurements from the *in situ* instrument. The relationship is calibrated empirically to the natural suspended material typical of the field site. Developing and maintaining this relationship requires:

- collecting a calibration data set
- developing a calibration function and determining its accuracy
- applying the calibration function, and
- checking/maintaining the calibration function.

5.3.1 Collecting calibration data

5.3.1.1 Data needs

The absolute turbidity calibration dataset shall comprise:

- processed (ie, verified and edited) measurements from the *in situ* instrument that are synchronous with either direct measurements from a portable primary reference instrument or samples collected to be analysed on a laboratory primary reference instrument
- at least 12 measurements, covering as much of the full range of the turbidity anticipated at the site or of the *in situ* instrument's range, whichever range is the lesser.

5.3.1.2 Scheduling

Calibration data:

- shall be collected during baseflows and during runoff events
- need not be collected on a regular basis (while compiling the initial calibration relationship)
- may be collected at multiple times during the same runoff event, and
- shall be sufficient to define a calibration relationship within the first year of monitoring.

5.3.1.3 Overlap with *in situ* instrument verification measurements

Absolute turbidity calibration data collection can be combined with verification data collection (see section 3) if the primary reference and verification instruments are the same.

5.3.1.4 Procedures

Procedures for collecting absolute turbidity calibration datasets shall follow those specified for field verification monitoring (see section 3.3.2).

Similarly, procedures for extracting the concurrent turbidity from the *in situ* instrument record shall be as specified for field verification (see section 3.5).

5.3.2 Calibration function

5.3.2.1 Deriving the calibration function

A function relating the absolute turbidity value from the primary reference instrument (A) to concurrent turbidity on the *in situ* instrument (F) shall be derived as detailed in Annex B. This shall involve:

- assembling the data
- plotting the data on a scatterplot
- checking for linear or non-linear behaviour
- fitting an appropriate function, and
- examining the residuals for any time-trend and outliers.

5.3.2.2 Accuracy of the calibration function

The following statistics shall be calculated to rate the accuracy of each calibration relationship:

- the regression coefficient (r^2),
- the standard error of the regression estimate, and
- the standard errors of the regression coefficients.

Note: When using untransformed data, the standard errors of the estimate and regression intercept and slope coefficients are additive errors (ie, + or –). If using log-transformed data, the standard errors of the estimate and of the intercept coefficient become factorial (ie, × or ÷) errors, which approximate to relative errors. For example, if the factorial error is × or ÷ 1.15, this approximates to a relative error of (1.15 – 1.0) x 100% = 15%.

5.3.3 Maintaining the calibration function

The accuracy of the calibration should improve as further data are added to the calibration dataset unless the site experiences a systematic change in the physical properties of its suspended material that causes the calibration to diverge (that is, the calibration function is observed to be non-stationary).

Therefore, after establishing an initial absolute turbidity calibration at a site (typically after the first year of monitoring), calibration measurements shall be continued on a quasi-regular basis to:

- update the calibration and its error statistics, and
- check for change in the calibration relationship associated with systematic change in stream-water suspended material characteristics.

5.3.3.1 Ongoing calibration function measurements

Ongoing calibration function measurements:

- shall be made on an at least quasi-monthly basis, and
- may be combined with instrument verification measurements if appropriate.

5.3.3.2 Updating the calibration function and checking stationarity

The calibration functions shall be updated with new data as detailed in Annex B, at least annually or more frequently if indicated by the data.

A temporal stationarity check shall be undertaken with every update. The calibration relation shall be considered non-stationary if:

- a time shift is visible on the residuals run-plot, and
- a trend line fitted to the new data batch lies outside the confidence interval defined by the standard error of the regression for the existing calibration function.

If the calibration function is considered non-stationary then absolute turbidity calibration sampling shall focus on establishing a new function with all new data.

5.3.4 Using a calibration function from another site or time

In the absence of a current at-site absolute turbidity calibration function, it is permissible to use a calibration function established for the same pairing of primary reference and *in situ* instruments at a different site or at the same site during a different period of deployment. The absolute turbidity data so generated, however, can only be assigned a maximum quality code of QC 400.

Note: Using an existing calibration function may be required, for example, to convert past records of standard turbidity collected without or before any calibration sampling at-site. The stationarity of the calibration into the past cannot be guaranteed, however, so the quality coding of the derived absolute turbidity record is degraded.

5.3.5 Applying the calibration function

The calibration function shall be used to convert standard *in situ* turbidity records to absolute turbidity records equivalent to the primary reference instrument.

Note: This task will usually be undertaken following data processing of the source standard turbidity data.

When multiple functions have been developed for low and high turbidity ranges, each function shall be applied to the *in situ* turbidity record in a way consistent with the way in which the calibration data were separated.

Absolute turbidity records calibrated off an existing function may be recalibrated off a statistically improved function. If this is done, then:

- the quality coding should be updated as need be, and
- the updated calibration function should be documented in metadata.

5.3.6 Documenting the calibration function

Documents shall be compiled that list:

- the absolute turbidity calibration functions
- the instruments being inter-related
- the conditions that they relate to, for example, low and high turbidity ranges
- the time periods to which they apply
- the range of turbidity data over which they were calibrated, and
- accuracy statistics (r^2, standard errors of the estimate, and regression coefficients).

5.4 Assigning quality codes

All absolute turbidity data is sourced from processed standard *in situ* turbidity data that will have been assigned a quality code.

The final quality code assigned to absolute turbidity data:

- cannot exceed the quality code assigned to the source data after verification and editing, and
- may be degraded by the quality of the absolute turbidity calibration function.

For absolute turbidity data, conditional on the quality code assigned to the standard turbidity data after verification and editing:

- A maximum QC 600 is possible if:
    - the primary reference and *in situ* instruments are the same brand and model, or
    - the calibration relationship is linear and has intercept and slope not significantly different from 0 and 1, respectively, at the 95% confidence level.

In other words, the data from the *in situ* instrument matches that from the primary reference instrument with no correction needed.

A maximum QC 500 is possible if the calibration relationship:

- is significantly different from the 1:1 line, but
- the relative standard error of its slope coefficient does not exceed 15%.

A maximum QC 400 is possible if the calibration relationship:

- is significantly different from the 1:1 line, and
- the relative standard error of its slope coefficient exceeds 15%.

Alternatively, if a calibration relationship has not been developed at-site and the data have been converted to absolute turbidity using a calibration relationship between the same primary reference instrument and same *in situ* instrument but with data from either another site or the same site at a different deployment time, the maximum quality code possible is QC 400.

Otherwise, a maximum QC 200 (not assigned a final quality code) shall be assigned, which essentially indicates that the data cannot be rated as absolute turbidity data.

A list of examples of quality code assignment to absolute turbidity data follows.

- A period of standard turbidity data verified and edited at QC 600 and converted to absolute turbidity at QC 600 is assigned QC 600.
- A period of standard turbidity data verified and edited at QC 600 but converted to absolute turbidity at QC 500 is assigned QC 500.
- A period of standard turbidity data verified and edited at QC 500 and converted to absolute turbidity at QC 600 is assigned QC 500.

- A period of standard turbidity data comprising synthetic data (QC 300) but converted to absolute turbidity using a QC 400 calibration relationship is assigned QC 300.
- A period of standard turbidity data verified and edited at QC 600 but lacking any known relationship with the primary reference instrument is assigned QC 200.
- A period missing any data is assigned QC 100.

Periodic fouling of sensors is inevitable in most monitoring situations; however, an operational target of < 30 days total missing data from one year of any two consecutive years should be achievable in most monitoring situations where good field practice is implemented.

5.5 Data archiving

Absolute turbidity data shall be stored:

- as a separate variable named Absolute Turbidity
- with FNU units
- with a quality code assigned as detailed in NEMS *Processing of Environmental Time-Series Data, Annex E*, and
- with the primary reference and *in situ* instruments identified in metadata.

5.6 Quality assurance

Absolute turbidity data shall be subject to the same auditing procedures as specified in NEMS *Processing of Environmental Time-Series Data, Annex E* for standard turbidity data.

In addition, audits shall report on:

- the accuracy and temporal stationarity of the calibration relationship between the *in situ* and primary reference instruments, and
- any catchment history or other data that could account for any temporal stationarity issues observed. For example, concurrent changes in relationship between turbidity and suspended sediment concentration, suspended sediment particle size data, or newly active catchment sediment sources in response to a major flood event or catchment disturbance.

6 Using Turbidity as a Surrogate for Suspended Sediment Concentration or Visual Clarity

Field turbidity instruments may be used to collect surrogate records of:

- suspended sediment concentration, and/or
- visual clarity.

If a Water Clarity NEMS is developed in the future, it will outline procedures for relating turbidity to visual clarity.

Procedures for using at-site turbidity as a surrogate for at-site suspended sediment concentration (SSC) are addressed in Annex C.

The surrogate record of at-site SSC generated from the turbidity record should be converted to cross-section mean SSC before determining the stream suspended sediment load. In particular, this requires developing a calibration function to relate at-site SSC to cross-section mean SSC. Procedures for this (and associated tasks) are detailed in the NEMS *Measurement of Fluvial Suspended Sediment Load and its Composition (version 2.0.0).*

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Annex A – List of Referenced Documents

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Annex B – Developing Absolute Turbidity Calibration Functions

This annex details how to develop or update functions that equate turbidity data between a primary reference instrument and an *in situ* instrument of a different brand.

After assembling the data, the key tasks are to:

- plot the data
- examine the plots for:
  - linear or non-linear behaviour
  - outliers
- check the residuals for time trends
- fit appropriate functions, and
- calculate error statistics.

Plot data

Data pairs from the primary reference and *in situ* instruments shall be plotted on a scatterplot, with the *in situ* instrument data on the horizontal axis, and with a preliminary ordinary least squares regression line fitted.

If there are existing data, the new data shall be over-plotted.

Check for linear or non-linear behaviour

The scatterplots shall be examined for evidence of linearity or otherwise. A linear relationship is appropriate where:

- the data points plotted are along a straight line
- there is no trend for the data scatter to increase or decrease as turbidity increases, and
- the residuals appear to be normally distributed.

Note: Residuals are the difference between the observed absolute turbidity from the primary reference instrument and that predicted by the regression function off the in situ instrument data.

If one or more of the above conditions fail, then it is likely that an improved calibration function will be found by transforming the turbidity data; for example, as logarithms.

Examine residuals for stationarity

If there are existing data and an existing calibration function, then checks shall be made for a time-shift in the inter-instrument relationship by inspecting both the scatterplot and a run-plot (i.e., time-series plot) of the residuals for a systematic shift in the new batch of data.

If a shift is visible, and a trend line fitted to the new data batch lies outside the confidence interval defined by the standard error of the regression for the existing calibration function, then a new calibration function shall be established and applied from the most likely point in time at which the divergence would have occurred.

Remove outliers

The scatterplot and the run-plot shall be examined for outliers. Data producing residuals greater than 30% of the estimated absolute turbidity shall be suspected as outliers. For outliers, both reference and *in situ* turbidity values shall be checked. If a clear explanation for the outlying point appears, the outlier may either be corrected (e.g.(e.g., if a data-entry error was made for the *in situ* instrument data point) or removed (e.g., the *in situ* instrument was not cleaned of biofouling).

Notes shall be kept of removed outliers by annotating plots or in the site comments file/metadata, either electronically or on hard copies.

Fit functions

Calibration functions shall be fitted to the data (whether in their original values or as logarithms) using linear regression methods.

If the data have been transformed to logarithms, the re-transformed regression function shall be corrected for logarithmic bias using the method of Duan (1983).

With either untransformed or log-transformed data, the reliability of the calibration function shall be checked at low values of turbidity. If the function does not follow the trend of the low-range data, a separate function shall be fitted to the low-turbidity range. This function shall intersect the function developed for the higher-range data.

Calculate error statistics

The following statistics shall be calculated for each calibration relationship:

- the regression coefficient (r^2)
- the standard error of the estimate, and
- the standard errors of the regression coefficients (slope and intercept).

Note: When using untransformed data, the standard errors of the estimated absolute turbidity and function coefficients are additive errors (ie, + or –). When using log-transformed data, the standard errors of the estimate and regression intercept become factorial (ie, × or ÷) errors on the predicted absolute turbidity and function gain, respectively.

Annex C – At-Site Turbidity to At-Site Suspended Sediment Concentration

Preamble

In rivers and streams, a typical purpose of turbidity monitoring is to provide a surrogate record of suspended sediment concentration (SSC). This is often combined with a discharge (river flow) record to determine the suspended sediment load, which is then integrated over a span of record to give the suspended sediment yield.

The conversion of turbidity to suspended sediment concentration is a two-step process:

- converting the at-site turbidity at the instrument location to at-site SSC, and
- converting the at-site SSC to the discharge-weighted, cross-section mean SSC.

The second step is necessary because suspended sediment is usually not perfectly mixed over the cross-section. The degree of mixing depends on the intensity of turbulence across the section (which typically varies with discharge) and the size grading of the suspended sediment load. Mixing is greatest for clay and silt sediment grades but may be poor for suspended sand.

For both steps, it is necessary to develop empirical calibration functions by collecting water samples and analysing them for SSC.

This annex outlines procedures for converting turbidity records to suspended sediment concentration records at the point location of the turbidity instrument (ie, at-site). In particular it covers:

- collecting calibration water samples
- laboratory procedures for analysing SSC

Note: This annex aligns with equivalent guidance provided in the NEMS Measurement of Fluvial Suspended Sediment Load and its Composition (version 2.0.0).

Collecting water samples

Where to sample

Water samples collected for the purpose of relating turbidity to suspended sediment concentration shall be collected as close as practicable to the lens of the turbidity instrument, ideally within 1 metre of the instrument.

How to sample

By preference, water samples shall be collected using an automatic pumping sampler (auto-sampler) that has its water inlet nozzle fixed in location beside the turbidity instrument. Auto-samples shall:

- be collected on a one-sample, one-bottle basis
- be at least 300 mL in volume
- have their time of sampling recorded on a data logger (preferably the same logger that records the turbidity record), and
- be preceded by a purge cycle.

Alternatively, a sample may be manually collected using either a handheld bottle or a specialised handheld sampling device; for example, a DH-48 suspended sediment sampler held stationary beside the instrument. For more information, refer to the NEMS *Suspended Sediment*.

Note: An auto-sampler is preferred because:

- *its location is fixed*
- *it employs an identical sampling procedure for all samples*
- *it can be scheduled to sample through all conditions, night and day, and*
- *it can sample safely during floods.*

Note: Commonly available auto-samplers are limited to a 4-metre lift between the intake and the auto-sampler. This limits their usefulness in rivers with high banks that are inundated frequently. In these latter situations, pump rigs may be designed and installed, providing mains power is available at the site.

When and how often to sample

Samples for turbidity–SSC calibration shall be collected:

- over the full range of turbidity experienced at the site
- during at least one, preferably three, freshes and floods per year, including on rising and falling stages of the same event, and
- more frequently during the first year that the turbidity instrument is installed, in order to quickly:
    - identify typical site-specific characteristics of the turbidity–SSC relationship, and
    - establish a turbidity–SSC calibration function.

Note: Samples should still be collected if the turbidity exceeds the manufacturer-certified range of the instrument. This will give information on the response of the instrument to increasing SSC beyond its certified range. Even if this response becomes non-linear, it may still be useful for extending the range of SSC estimation.

Scheduling auto-samples

When using an auto-sampler to collect calibration samples during freshes and floods:

- only one auto-sample shall be collected into each sample bottle
- samples shall ideally be collected for as long as the stage (water level) exceeds a threshold level, and
- by preference, samples shall be scheduled on a flow-proportional basis, or
- samples may be collected at fixed time intervals.

Note: Flow proportional sampling:

- *triggers a sample when a fixed volume of water has flowed past the site*
- *requires a programmable data logger that has the current stage–discharge rating registered into it*
- *collects more samples the higher the flow rate, and*
- *helps to ensure that samples are collected around flood peaks.*

Stage-level thresholds, water-volume thresholds for flow proportional sampling, and time intervals for fixed time sampling shall be set so that there are enough sample bottles for samples to be collected over both the rising and falling limbs of high-flow events.

Note: Most auto-samplers have 24 to 28 bottles available. Site-specific simulations are helpful for optimising auto-sampling thresholds.

Data collection plan

A data collection plan shall be developed annually that identifies the range of turbidity over which sampling for the coming year should focus. This shall be based on information derived from the calibration data collected to date.

Laboratory analysis of suspended sediment concentration

Water samples shall be measured in the laboratory for suspended sediment concentration using the ASTM Designation: D-3977-97 standard procedure (ASTM, 1997).

This procedure may employ one of the following methods:

- filtration method, or
- evaporation method.

Whichever method is used, the analysis shall be undertaken on the whole of the water sample.

Note: Sometimes, SSC analyses have been undertaken on sub-samples drawn from the original sampling container. Procedures that do this include the Total Suspended Solids method (see NEMS Water Quality: Part 2 of 4: Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data *and shall be avoided because they can deliver erratic, biased results. This stems from differential settling of different size fractions of the suspended load within the sample bottle during the sub-sampling process. For details, refer to Guo (2006).*

Note: Sometimes, it may be desirable to derive separate concentrations of the sand and mud fractions of the suspended load. In this case, a variant of the filtration approach is used that involves wet-sieving the sample prior to filtration. This procedure is described in ASTM D-3977 Test Method C—Wet-sieving-filtration (ASTM, 1997).

Associated laboratory measurements

Prior to analysis of water samples for SSC, the turbidity of the water sample (or a sub-sample of it) shall be measured on an ISO 7027-1:2016–compliant laboratory nephelometer.

Note: If a sub-sample is extracted for turbidity analysis, this shall be returned to the field sample bottle before SSC analysis.

Ideally, this laboratory instrument shall:

- be the same instrument used for regular verification of the *in situ* turbidity instrument (see section 3.3), and
- also be the reference turbidity instrument if the site's turbidity recording objectives include an absolute turbidity record (see section 5.2) as well as a surrogate record of SSC.

Associated observations

Any unusual features of the water samples shall be noted; for example, unusually high sand or organic content, unexpectedly small water volume, or evidence of leakage such as a loose cap.

Reporting units

SSC results shall be reported as mg/L.

Note: Sometimes, SSC analyses, such as from the evaporation method, are reported as parts per million (ppm) by weight. These are equivalent to mg/L up to concentrations of approximately 12,000 mg/L. This extends beyond the typical range of turbidity instruments. The equation for converting ppm to mg/L is given below.

Converting units

The conversion factor, C, for converting ppm to mg/L is:

$$C = (\rho_s \times \rho_w \times 1{,}000{,}000)/(\rho_s \times 1{,}000{,}000 - [(\rho_s - \rho_w) \times \text{ppm}])$$

where:

ρ_s = density of sediment, in g/cm^3 (ρ_s typically assumed to be 2.65 g/cm^3)

ρ_w = density of water, in g/cm^3 (ρ_w typically assumed to be 1.00 g/cm^3)

ppm = sediment concentration, in parts per million.

Annex D - Developing Calibration Functions between Turbidity and Suspended Sediment Concentration

Preamble

The relationship between turbidity and SSC is strongly influenced by the suspended sediment size grading. For a given suspended sediment concentration, the finer the sediment size, the higher the turbidity. For sand/silt/clay mixtures, the turbidity signal is dominated by the clay and silt concentrations, and the sand may barely affect turbidity value.

The suspended sediment size grading typically varies at a site during a fresh or flood. The sand concentration is often in-phase with the water discharge, but the silt and clay concentrations depend more on the travel time of water from the sediment source locations, and may lag or lead the peak discharge. Thus, the turbidity versus suspended sediment concentration relationship may show a hysteresis loop (or several hysteresis loops for multiple sources) throughout a high-discharge event.

Longer-term shifts or drift in the suspended sediment grading (and so the turbidity–SSC relationship) can also occur:

- because of seasonal effects on sediment supplies
- after a large catchment-disturbance event (e.g., a large rainstorm or earthquake), or
- due to catchment land-use change.

It is, therefore, important to be familiar with the characteristic responses shown by a given site in order to:

- design a suitable conversion function, and
- quantify the magnitude and the time scale of the error inherent in the calibration function.

This annex outlines procedures for developing calibration functions between turbidity and suspended sediment concentrations. In particular it covers:

- developing calibration functions between turbidity and SSC
- applying calibration functions, and
- documenting calibration functions.

Key tasks

The key tasks are to:

- assemble the turbidity and SSC data
- plot the data

- examine the plots for:
  - time trends
  - hysteresis loops during events
  - systematic differences between events
  - outliers, and
  - linear or non-linear trends
- fit appropriate functions, and
- calculate error statistics.

Assemble data

Turbidity data that are concurrent with the sampling times of suspended sediment concentration results shall be extracted from the edited turbidity records.

Discharge data that are concurrent with the sampling times of suspended sediment concentration results shall be extracted from the edited discharge records.

The quality code of the turbidity data and the discharge (river flow) data shall also be noted.

Care shall be taken that the turbidity value is not taken from any momentary pulse in turbidity associated with manual sampling or the purge cycle of an auto-sampler.

Plot data

The SSC and turbidity data pairs shall be plotted on a scatterplot, with turbidity on the horizontal axis (e.g., Figure 4). Consideration should be taken of event trends and isolation of unique events by indicating data points from individual events on the plot where applicable.

SSC and discharge (river flow) data pairs shall also be plotted on a scatterplot, with discharge on the horizontal axis (e.g., Figure 5). Consideration should be taken of event trends and isolation of unique events by indicating data points from individual events on the plot where applicable.

If there are existing calibration functions, a time-series plot shall be made of the residuals of the new data (e.g., Figure 6).

Note: Residuals are the difference between the measured SSC and the SSC predicted by the current calibration function. Typically with turbidity–SSC relations, these differences are best expressed as relative residuals, i.e., (measured SSC – predicted SSC)/measured SSC. This is because the data scatter tends to increase as SSC and turbidity increase.

If there are existing data, the new data shall be over-plotted.

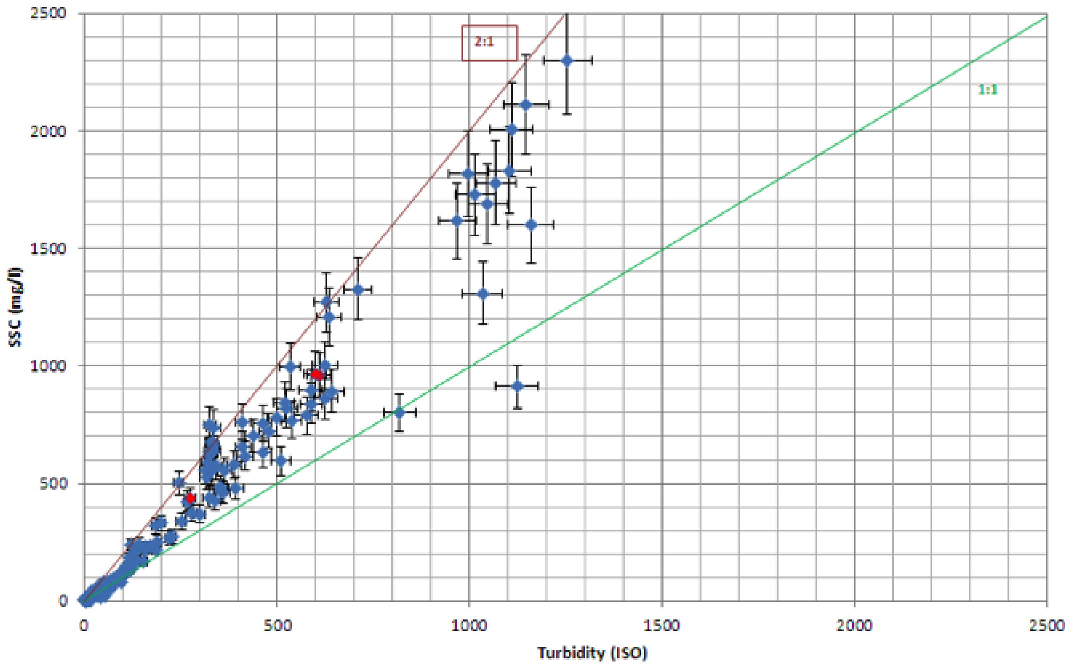

Figure 4 – Example plot of turbidity versus suspended sediment concentration (SSC). ***Crosses show uncertainties*****. Note how scatter and uncertainty increase as turbidity values and suspended sediment concentrations increase.**

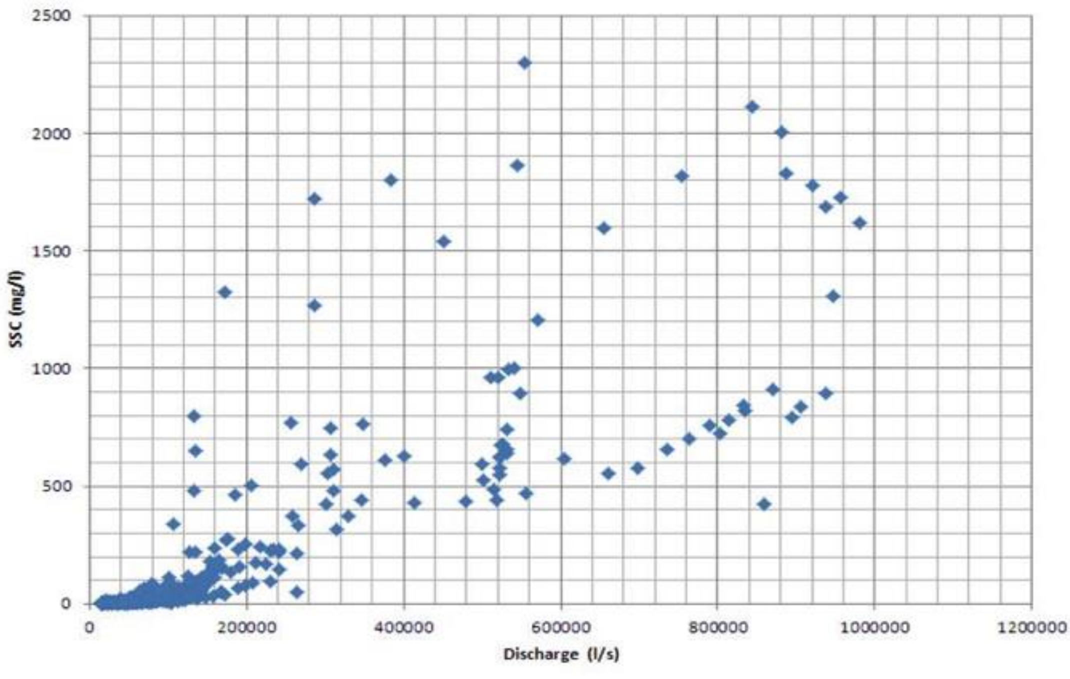

Figure 5 – Example plot of discharge versus suspended sediment concentration (SSC). Note wide scatter associated with loop ratings during discrete events.

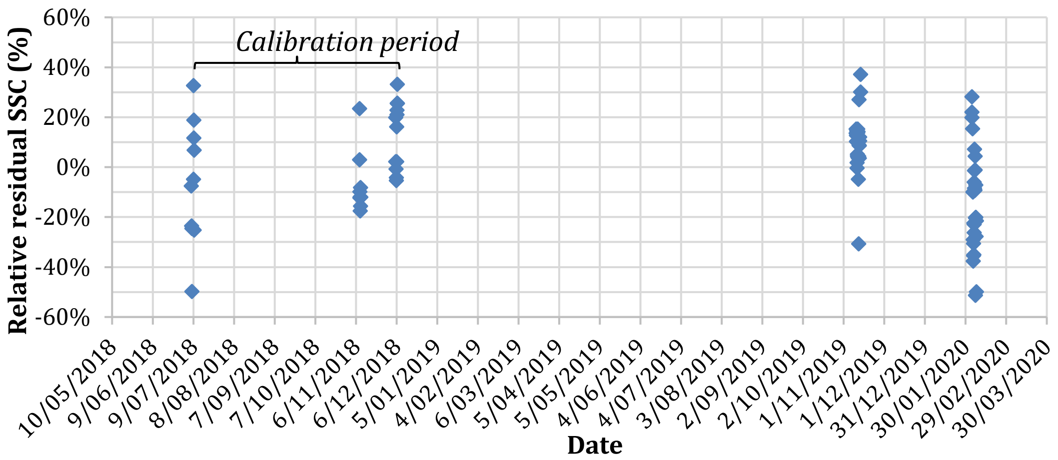

Figure 6 – Example plot of relative residuals of (measured SSC – predicted SSC)/measured SSC. ***Data from 2019-2020 plot within same bounds as 2018 data used to derive calibration relation.***

Examine residuals for a time trend in SSC on a run-plot

If there are existing data and an existing calibration function, then checks shall be made for a time-shift/trend in the turbidity–SSC relationship, by inspecting both the turbidity–SSC scatterplot and residuals plot (e.g., Figure 6) for a systematic shift in the new batch of data.

If a shift is visible, and a trend line fitted to the new data batch lies outside the confidence interval defined by the standard error of the regression for the existing calibration function, then a new calibration function shall be established.

Check for consistent hysteresis behaviour and different rising/falling stage behaviour

All event data on the turbidity–SSC scatterplot shall be examined for hysteresis loops. If a consistent difference emerges for rising- and falling-stage data, then the rising- and falling-stage data shall be split into separate data sets and separate functions shall be fitted to each data set.

Check for systematic differences between events

The data from separate events shall be examined on both the turbidity–SSC and residuals time-series plots for differences that are systematic between events but appear random over many events.

Note: The time scale of systematic differences, whether within events or over several events, determines how error in the calibration functions affects the error in the time-integrated sediment load.

Remove outliers

The data on the turbidity–SSC scatterplot, residuals plot and the run-plot shall be examined for outliers. Data producing residuals greater than 30% of the estimated SSC shall be suspected as outliers. For outliers, both the SSC and turbidity values shall be checked. If a clear explanation for the outlying point appears, the outlier may either be corrected (e.g., if a data-entry error was made for the SSC value) or removed (e.g., the water sample had an unusually high sand content or a loose bottle cap, the turbidity value was collected during an auto-sampler purge cycle, or the turbidity value was based on synthetic data of dubious quality).

Notes shall be kept of removed outliers by annotating plots, either electronically or on hard copies.

Check for linear or non-linear behaviour

The turbidity–SSC scatterplots shall be examined for evidence of linearity or otherwise. A linear relationship is appropriate where:

- the data points plotted are along a straight line
- a scatterplot of the residuals and turbidity shows no trend for the residuals to increase, decrease, or curve as turbidity increases
- a scatterplot of the residuals and turbidity shows no trend for the scatter in the residuals to increase as turbidity increases, and
- the residuals appear to be normally distributed.

If one or more of the above conditions fail, then it is likely that an improved calibration function will be found by transforming the turbidity and SSC data; for example, as logarithms.

Fit functions

Calibration functions shall be fitted to the data (whether in their original values or as logarithms) using linear regression methods.

If the data have been transformed to logarithms, the re-transformed regression function shall be corrected for logarithmic bias using the method of Duan (1983).

With either untransformed or log-transformed data, the reliability of the calibration function shall be checked at low values of turbidity. If the function does not follow the trend of the low-range data, a separate function shall be fitted to the low-turbidity range. This function shall intersect the function developed for the higher-range data.

If the data have been split into rising and falling stage subsets, then separate functions shall be fitted to each subset.

Calculate error statistics

The following statistics shall be calculated for each calibration relationship:

- the regression coefficient (r^2), and
- the standard error of the estimate.

Note: When using untransformed data, the standard error of the estimate is an additive error (ie, + or –) on the predicted SSC. When using log-transformed data, the standard error of the estimate becomes a factorial (ie, × or ÷) error on the predicted SSC.

Where data quantity and range permit, standard errors of the estimate shall also be calculated separately for each turbidity quality code.

Note: The standard error of the estimate in the turbidity–SSC calibration, when combined with an appreciation of the time span of systematic variation in the residuals, helps determine the error in the time-integrated suspended sediment load.

Applying calibration functions

The turbidity–SSC calibration functions shall be used to convert turbidity records to SSC records.

When multiple functions have been developed, e.g. for low and high turbidity ranges, rising and falling stages, or separate seasons, each function shall be applied to the turbidity record in a way consistent with the manner in which the calibration data were separated.

When changing between two functions that do not overlap, a suitable algorithm shall be applied that effects a smooth transition from one function to the next.

For example, if using separate functions for rising and falling turbidity values, an algorithm shall be used that progressively shifts the weighting from the rising to falling turbidity function. The time domain of the transition may be linked to automatically identifiable features on the turbidity hydrograph; for example, points of inflexion or fixed periods before and after the peak turbidity.

Documenting calibration functions

If the software used to apply the calibration functions does not file these functions as ratings, then documents shall be compiled that list:

- the turbidity–SSC calibration functions
- the conditions that they relate to, for example, all flows, rising and falling stages, low or high turbidity ranges
- the time periods to which they apply
- the range of turbidity data over which they were calibrated, and
- accuracy statistics (r^2, standard error of the estimate) for:
  - the overall data set, and
  - if possible, also by quality code of the turbidity data.

Archiving derived suspended sediment concentration

The at-site SSC records generated by applying the turbidity–SSC calibration functions may be archived, providing that:

- the quality codes of the underpinning turbidity records are included for each derived suspended sediment concentration record, and
- the above documentation of the calibration functions is also filed.

Note: Organisations may prefer not to archive the derived SSC but to generate this as required; for example, when suspended sediment yields are to be calculated.

Annex E – Advice Notes for Using Turbidity for Compliance Monitoring as a surrogate for visual clarity

This annex includes advice notes for:

- using relative turbidity from upstream and downstream sites to monitor resource consent compliance at earthworks, and
- using turbidity as a surrogate for monitoring visual clarity to meet National Policy Statement for Freshwater Management (NPS-FM) 2020 obligations.

Relative turbidity at earthworks sites

Background

Projects involving earthworks (e.g., roading, subdivision, in-channel mining, forest harvesting) may be required to ensure/demonstrate that their impact on the turbidity of an adjacent waterway is not significantly different from that of the project's footprint without the development.

Where the works cover only the local catchment of a stream segment or a tributary joining a mainstem river/stream, monitoring only downstream of the project footprint may be inconclusive. This is because the impact of the project footprint cannot be isolated from that of the catchment upstream. In such cases, it is expedient to monitor turbidity both upstream and downstream of the footprint. This must be undertaken using pairs of identical (or otherwise proven equivalent) instruments to avoid the stationarity issues discussed in this NEMS.

Similarly, compliance should be based on the relative difference between the upstream and downstream records (relative to the upstream record) to avoid issues with setting tolerances around specific turbidity values.

Data assessment is focused on elevated turbidity events, where the turbidity exceeds a given threshold level (e.g., 20 FNU/FAU). Such events need not be runoff events, ie, an elevated turbidity event can occur due to in-stream earthworks (e.g., diversions) during baseflows.

Specification

Application: Erosion and Sediment Control compliance at earthworks sites/projects.

Monitoring objective: Measure relative difference in stream turbidity between upstream and downstream sites over project footprint reach during elevated turbidity events.

Locations: The instruments should be located as close as practical to the project footprint, minimising inflow from non-project runoff sources. For example, avoid locate the upstream site upstream of any significant tributary that joins the mainstem river/stream upstream of the project site (and vice-versa for the downstream site).

Note: The temptation to utilise existing turbidity monitoring sites should be avoided if these have compromised locations for this purpose.

Turbidity variable: Standard turbidity (unless there is a separate need for absolute turbidity data for broader scale comparison of data, eg, one or both sites are included in a regional network of sites that measure absolute turbidity).

Instrumentation: Matching pair of ISO 7027-1:2016–compliant nephelometers or turbidimeters operated as per NEMS *Turbidity Recording* version 2.0.0.

Note: The temptation to utilise different turbidity instruments because one site has an existing instrument (possibly operated by a different agency) should be avoided. Uncertainty over the alignment of data from different instrument manufacturers in natural suspensions may render the upstream/downstream comparison pointless.

Quality control: Generally, work with verified, edited data (QC 400 – QC 600), but may use original, unverified data (QC 0) if the monitoring purpose requires an urgent response to trigger follow-up monitoring (e.g., stream ecology).

Duration: Duration of earthworks project consent.

Baseline monitoring: Ideally, it is best to monitor for at least 6 months prior to project commencement to determine characteristics of baseline turbidity contribution from project footprint to inform tolerance thresholds. In the absence of baseline data, assume a neutral baseline (ie, runoff from project footprint induces no significant change in stream turbidity).

Key data analysis:

- Overplot turbidity time-series results at event scale.
- If event has multiple turbidity peaks, identify matching turbidity peaks based on expected lag time (from analysis of prior single-peak events).

Results to extract: Event-scale results from the paired instruments, including:

- Individual turbidity peaks
    - peak count
    - matched peak turbidity values, and
    - matched peak turbidity time lag.
- Overall
    - maximum turbidity
    - event average turbidity
    - event duration (above threshold, eg, 20 FNU/FAU), and
    - event compliance score (see below).

Results to assess: Relative difference in event results, ([D-U]/U *100%, where D is upstream instrument result and U is downstream instrument result), including:

- peak count
- maximum turbidity
- average turbidity
- event duration, and/or
- event compliance score (see below).

Note: The relative turbidity statistics should compare the ratios of statistical parameters derived from each of the paired instruments, not parameters derived from ratios of the instantaneous time-series data.

Note: If using original (unverified) data, care should be taken to avoid confusing data "spikes" with true turbidity maxima. Spikes generally result from electronic transients or macro-fouling due to organic debris, typically last for only one record, and are identified and edited-out during quality-assurance checks.

Note: Additional turbidity peaks can appear in the downstream record. These may appear early in the event due to erosion of proximal earthworks or flushing of fine sediment deposits from the intervening channel, and/or they may occur later in the event following fill and spill of sediment retention ponds.

Note: Turbidity peak values may reduce downstream if the project site delivers cleaner water (e.g., due to sediment interception in retention ponds).

Non-compliance indicators:

- Single parameter threshold exceedance, eg, average and/or peak turbidity ratios exceed a threshold % (e.g., +30%) for more than a specified number of consecutive events (or a specified number of events in any time period), or
- non-compliance score exceeds a threshold value for a given number of consecutive events.

Non-compliance may:

- signal consent failure, or
- trigger further monitoring.

Compliance scoring scheme and example

A scheme for scoring compliance of individual elevated turbidity events is shown in Table 6. This is illustrated with results from the example dataset shown in Figure 6.

Compliance tolerance values shown are suggested only. These may be refined using results of baseline monitoring (if available).

Table 6 – Compliance scoring scheme for upstream/downstream turbidity monitoring of an earthworks site. Scores assigned according to parameter difference between downstream (D) and upstream (U) sites, relative to upstream site. Non-compliance signalled by total score > 1. Example scores based on turbidity records shown in Figure 6 and signal "non-compliance" based on total score of 3. Note: Tolerance values (10%, 20%, 30%) are suggested only.

Event Result Assessed	Scoring			Score
	-1	0	1	
Peak count [(D-U)]	More upstream	Same	More downstream	1
Duration [(D-U)/U*100%]	<-10%	Within ±10%	>10%	1
Maximum turbidity [(D-U)/U*100%]	<-30%	Within ±30%	>30%	0
Average turbidity [(D-U)/U*100%]	<-20%	Within ±20%	>20%	1
			Total	3

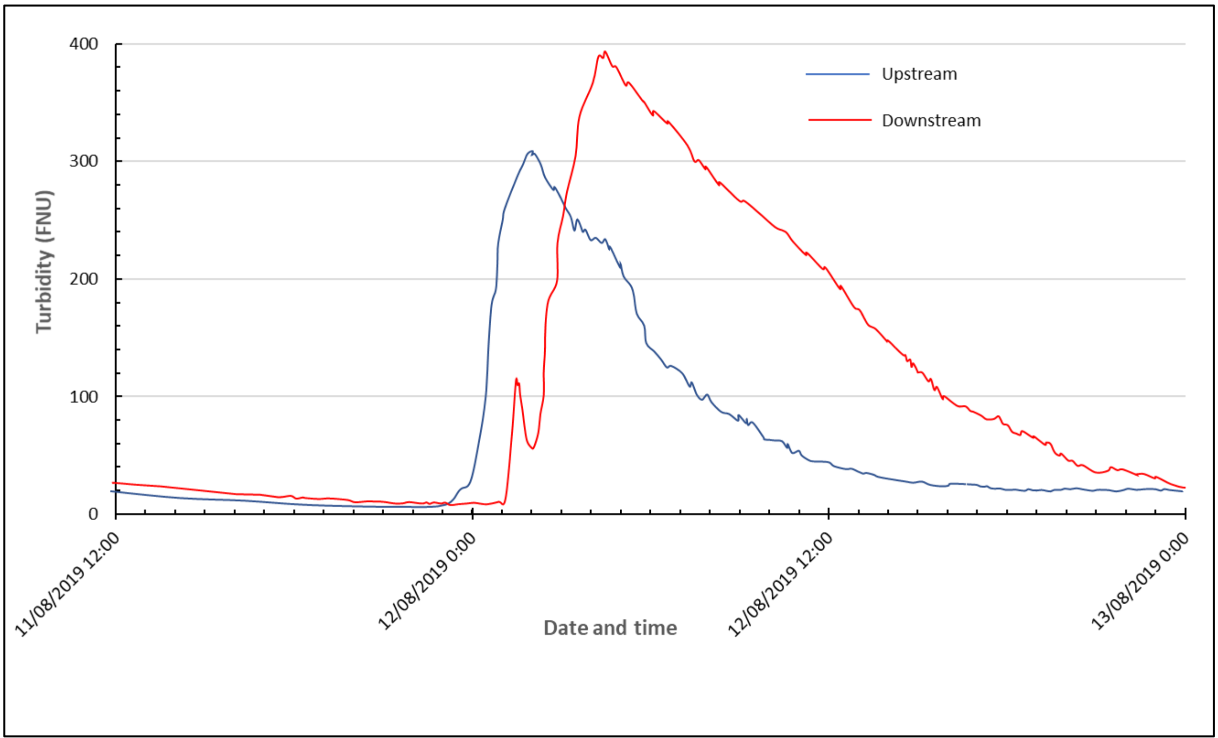

Figure 6 – Example concurrent turbidity records acquired upstream and downstream of an earthworks site.

Downstream site: lags upstream site (by 2.5 h), has an additional peak early in event from proximal erosion, has a longer event duration (by 27%) while turbidity > 20 FNU and a more steady (less exponential) recession, has higher (by 26%) maximum turbidity, and higher (by 31%) average turbidity. Compliance scoring shown in Table 6. Only the relative maximum turbidity difference is within tolerance.

Generic resource consent conditions

The conditions below relating to turbidity monitoring are suggested for earthworks resource consents involving potential sediment discharge into, or works within, stream channels. These generic conditions should be altered as required by the consenting authority and each situation.

X The Consent Holder or their agent shall, at their own expense, install, operate and maintain telemetered turbidity recorders upstream and downstream of the footprint of the proposed earthworks, located as close as practical to the project footprint to minimise inflow from non-project-influenced runoff sources.

x.1 The turbidity recorders shall be a matching pair of ISO 7027-1:2016–compliant nephelometers or turbidimeters, and shall be calibrated and validated prior to installation as specified in the current NEMS *Turbidity Recording*, and shall be field-verified on a regular basis as specified in the NEMS *Turbidity Recording*.

x.2 The turbidity recorders shall be installed and operated for at least xxx months prior to the commencement of earthworks and shall be operated until all earthworks have ceased and the ground stabilised to the satisfaction of the Consent Authority.

x.3 The turbidity instrument calibration, validation, and installation shall be verified by a suitably qualified and experienced person, approved by *[insert job title and Consent Authority]* or their agent.

x.4 The Consent Holder shall provide evidence of the verification required by condition x.3 in writing to the *[insert job title and Consent Authority]* or their nominated agent within one month of the verification being completed.

x.5 Any verification failure issue detected during the regular field verification checks shall be resolved within xxx days, either by re-calibrating/validating the instrument or replacing it with an equivalent instrument, and the issue shall be documented and reported to the Consent Authority within xxx days of its detection.

x.6 Turbidity shall be recorded at intervals of 5 minutes or less and shall be updated at least hourly to a database which is accessible to authorised users, including *[insert job title and Consent Authority]* or their agent.

x.8 Data from the paired turbidity instruments shall be inspected, edited as necessary, and quality coded as specified in the NEMS *Turbidity Recording* within xxxx days of collection.

x.9 The processed data shall be analysed by:

- a) identifying elevated turbidity events exceeding a threshold turbidity value of xxx FNU at either site.
- b) overplotting the records from the paired instruments over each event
- c) extracting the following parameters associated with each instrument for each event:
    - a. event duration over the threshold
    - b. number of turbidity peaks
    - c. maximum turbidity, and
    - d. event-averaged turbidity
- d) deriving downstream/upstream ratios of these parameters, and

e) deriving a compliance score for the event [using Table 1 above or a variation thereof].

x.10 Event results, including plots, parameters, and compliance scores shall be reported to and discussed with the Consent Authority every xxx months. Compliance scores exceeding 1.0 over xxx consecutive events shall be reported within xxxx days of detection.

Turbidity as a surrogate for visual clarity for NPS-FM related monitoring

Background

As reviewed in Haddadchi et al. (2021), the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020) requires councils to monitor visual clarity (VC) for two purposes:

- to assign a baseline state, and thereafter assess current state, of the suspended fine sediment attribute, which is based on median VC over a 5-year record
- to detect any trends in degrading (ie, decreasing) VC.

The NPS-FM 2020 allows the conversion of *in situ* turbidity measurements to high-frequency surrogate records of VC for these purposes after appropriate at-site calibration between turbidity and VC.

A VC-calibrated, high-frequency turbidity record offers several advantages over simply measuring VC as part of monthly state of the environment programmes, including:

- the turbidity record may also be calibrated to provide a surrogate record of suspended sediment concentration (SSC) which can be used for analysis of catchment sediment loads (e.g., to verify the effectiveness of efforts to reduce catchment erosion and sediment delivery), and
- trend analysis using high-frequency records appears to offer improved trend-detection power over monthly sampling (e.g., Liu et al., 2020; Yang et al., 2020).

However, some cautionary notes are:

- As detailed in the NEMS *Turbidity Recording* with regard to turbidity–SSC relationships, relationships between turbidity and VC also depend both on instrument type and the characteristics of suspended and dissolved constituents (e.g., sediment size, composition, shape; water colour). Thus, at-site instrument-specific calibration relationships between turbidity and VC are required, and the turbidity monitoring is subject to the same protocols to ensure record stationarity as are detailed in the NEMS *Turbidity Recording*.

- At-site turbidity–VC relationships can change with time if the characteristics of the suspended and/or dissolved constituents change. For example, mitigation works in the catchment upstream may substantially reduce delivery of clay-grade sediment from a key source that impacts baseflow and median clarity (e.g., riparian fencing excluding stock from channels), which may alter the turbidity–VC relationship. Hence, the stationarity of the calibration relationship should be monitored, particularly when sediment mitigation measures are being implemented upstream.
- For monitoring VC state at least, the median VC invariably occurs during baseflows, when turbidity values are relatively low, are prone to influence by multiple factors (e.g., higher influence of water colour and organic material relative to mineral sediment), and the risk and significance of lens biofouling is high. Thus, it is not uncommon to find a relatively "noisy" relationship between instrument-recorded turbidity and VC under baseflows, and care should be taken to avoid worsening this with suspect data stemming from lax attention to fouling prevention and field verification checks.

Hence, turbidity monitoring as a surrogate for VC should be subject to the same protocols to ensure record stationarity and quality as detailed in the NEMS *Turbidity Recording*.

For VC trend analysis using high-frequency data, and also for sediment load analysis if that is an additional monitoring purpose, high-range turbidity data are also required. Hence, it is desirable to select a turbidity instrument that meets these multiple purposes of low- and high-range monitoring (ie, a multiple-range / multi-sensor instrument).

Specification

Application: Monitor VC state and trend for NPS-FM (2020) purposes.

Monitoring objective: Generate a surrogate record of VC suitable for deriving the 5-year median VC and trends in VC.

Locations: Instruments shall be located at SOE monitoring sites, coinciding with flow recording sites (the flow record is needed for trend analysis and for determining sediment load if the turbidity record is also for monitoring SSC).

Turbidity variable: Standard turbidity (unless there is a separate need for absolute turbidity data for broader scale comparison of data, eg, one or both sites are included in a regional network of absolute turbidity sites).

Instrumentation: An ISO 7027-1:2016–compliant nephelometer operated as per the NEMS *Turbidity Recording*; ideally one with multiple turbidity ranges.

Additional data: Continuous flow record; VC data sampled concurrently with turbidity across as much as practical of the full range expected at the site, sufficient to establish an at-site calibration relationship between turbidity and VC.

Note: The calibration dataset may be compiled either concurrently with the turbidity instrument deployment for NPS-FM purposes or from existing/parallel at-site measurements *(e.g., collected as part of a monthly state-of-environment monitoring programme), providing the existing turbidity measurements were made using an instrument equivalent to the one currently deployed for turbidity recording (refer to the NEMS Turbidity Recording for what constitutes an equivalent instrument).*

Note: In either case, VC may be measured directly in the field or from a water sample taken to the laboratory and analysed for beam attenuation.

Note: If the calibration dataset uses turbidity data from the in situ turbidity instrument, the protocols for field sampling VC and extracting matching data from the in situ turbidity record shall be the same as those specified in Annex C of the NEMS Turbidity Recording for collecting calibration samples for SSC.

Note: The stationarity of the calibration relationship shall be checked at least every two years with appropriate sampling campaigns.

Quality control: Work with verified, edited turbidity data (QC 400 – QC 600) prior to conversion to VC with calibration relationship.

Duration: Ongoing.

Key data analysis:

- Derive turbidity–VC calibration relationship.
- Calibrate quality-graded turbidity record to VC.

Note: The relationship between turbidity and VC is hyperbolic (i.e., VC decreases as turbidity increases in an inverse power function) and the magnitude of data scatter typically increases as turbidity decreases (and clarity increases), hence the power-function relationship is best fitted via linear regression of log-transformed data.

- Determine rolling 5-year median VC from derived VC record.

Note: The same 5-year median VC result is found by inserting the 5-year median turbidity value into the turbidity–VC calibration relationship.

- Analyse derived VC record for trend (e.g., using methods of Liu et al., 2020, or Yang et al., 2020).

Key questions to consider:

- Is VC state/grade (5-year median VC) greater or less than bottom line median VC specified for site or value after initial site grading?
- Is there a significant VC time trend? If so, is VC degrading or improving?

Example

An example turbidity–VC calibration relationship is shown in Figure 7. The data were collected over two years of quasi-monthly state-of-environment monitoring, with VC measured using a back disk and turbidity measured using an instrument equivalent to the one being deployed for high-frequency *in situ* monitoring of VC. When plotted on log scales, the data show a linear inverse trend with uniform data scatter over the turbidity range, including in the vicinity of the median turbidity, hence a linear regression model was fitted to log-transformed data. This de-transforms to a power function with an exponent of -0.91.

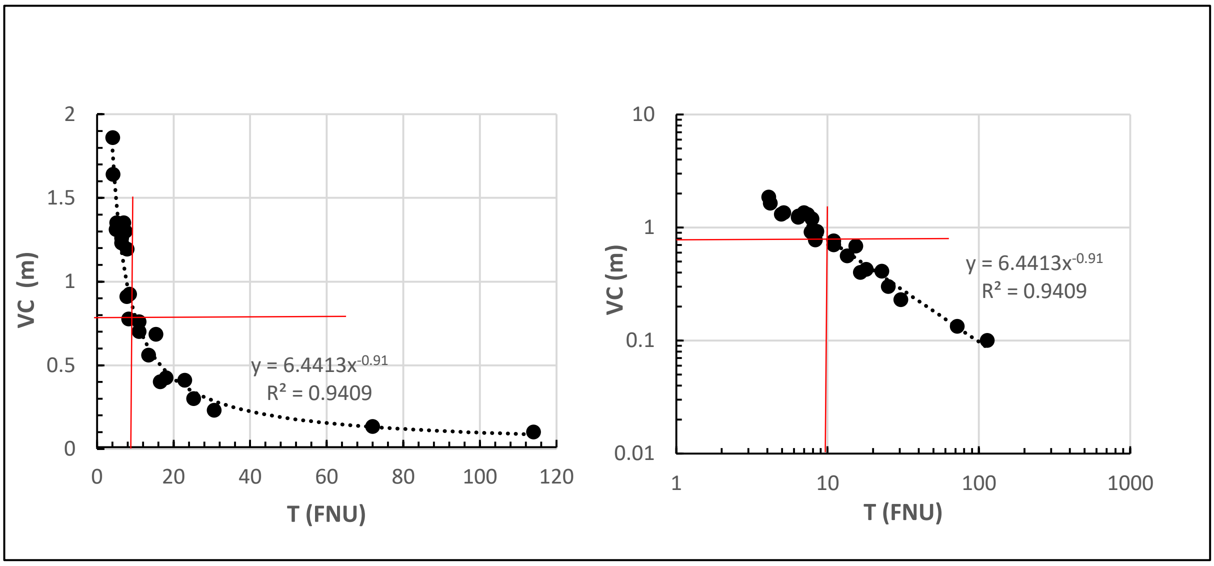

Figure 7 – Example relationship between turbidity (T) and visual clarity (VC)

Left plot shows data on linear scales; right plot shows data on log scales. Red vertical and horizontal lines show median turbidity and VC, respectively. Calibration relationship is VC = 6.411$T^{-0.91}$ with a standard factorial error of ×/÷ 1.15, derived from linear regression of the log-transformed data. If the 5-year median turbidity is 8.5 FNU, the 95% confidence interval on the predicted 5-year median VC is 0.92 ± 0.04 m. This assumes that the regression residuals are normally distributed so that the standard error on the median estimate of log(VC) can be estimated as 1.253 × the standard error on the mean estimate of log(VC).

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