BS ISO 6421:2012

BSI Standards Publication

Hydrometry — Methods for assessment of reservoir sedimentation

National foreword

This British Standard is the UK implementation of ISO 6421:2012.

The UK participation in its preparation was entrusted to Technical Committee CPI/113, Hydrometry.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

ISBN 978 0 580 59639 1

ICS 17.120.20

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 August 2012.

Amendments issued since publication

Date	Text affected

BS ISO 6421:2012

INTERNATIONAL STANDARD

ISO 6421

First edition
2012-08-01

Hydrometry — Methods for assessment of reservoir sedimentation

Hydrométrie — Méthodes d'évaluation de la sédimentation dans les réservoirs

Reference number
ISO 6421:2012(E)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 6421 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 6, *Sediment transport*.

Introduction

Most natural river reaches are approximately balanced with respect to sediment inflow and outflow. Dam construction dramatically alters this balance, creating a reservoir which often results in substantially reduced velocities and relatively efficient sediment trapping. The reservoir accumulates sediment and loses storage capacity until a balance is again achieved; this normally occurs after the reservoir fills with sediment. The rate and extent of sediment deposition depends on factors which influence sediment yield and sediment transport, as well as the reservoir's trapping efficiency.

The distribution of sediment deposition in different reservoir regions is equally important. Depending upon the shape of the reservoir, mode of reservoir operation, sediment-inflow rates and grain-size distributions, the incoming sediment may settle in different areas of the reservoir. Declining storage reduces and eventually eliminates the capacity for flow regulation and concomitant benefits such as water supply, flood control, hydropower, navigation, recreation, and environmental aspects that depend on releases from storage. Water resource professionals are concerned with the prediction of sediment deposition rates and the probable time when the reservoir would be affected in serving its intended functions.

The estimation of sediment deposition is also important in the design and planning of storage reservoirs. However, it is difficult to estimate the volume and rate of sediment deposition accurately from the known criteria and available sediment transport equations. Reservoir capacity surveys indicate patterns and rates of sedimentation, which help in improving estimation of capacity-loss rates.

This International Standard describes the following reservoir-sedimentation assessment methods:

- conventional topographic surveys (Clause 6)
  - contour method (Clause 7)
  - cross-sectional (range line) method (Clause 8)
  - sub-bottom measurements (Clause 9)
- remote-sensing techniques (Clause 10)
  - light detection and ranging (Clause 11)
    - aerial applications
    - ground-based applications
  - aerial imagery (Clause 12)
    - photogrammetry methods
    - satellite imagery methods

Hydrometry — Methods for assessment of reservoir sedimentation

1 Scope

This International Standard describes methods for the measurement of temporal and spatial changes in reservoir capacities due to sediment deposition.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any revisions) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

3 Terms and definitions

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

4 General

4.1 Origin of the sediment deposited in the reservoir

Reservoirs are subjected to several types of sedimentation as a function of the geomorphology (geology, slope, topography and land use, drainage density, climate, etc.) of the watershed and the biological cycles in the reservoir or the drainage basin, in the following order of importance.

a) **Erosion** of the drainage basin produces dissolved substances and mineral particles with an assortment of sizes, shapes and types that are related to the rock type and slope of the drainage basin. In addition, landslides produce debris flows. Sediment is delivered to the reservoir both as suspended sediment load and as bed load.

b) **Sedimentation** occurs due to plant debris from the drainage basin and from vascular plants and phytoplankton in the reservoir. The debris decomposes very slowly and often forms alternating layers with mineral deposits. The mud resulting from this type of sedimentation is very fine and extremely fluid, often with a gelatinous texture. Accumulation of mud at a rate of several centimetres per year often causes problems when a reservoir is drawn down or drained. It has a very high organic content resulting in heavy consumption of dissolved oxygen.

The proportion of sedimentation caused by each type may be assessed by on-site visual observations and by analyses of the sediment deposit.

4.2 Overview of reservoir-sedimentation assessment methods

Two basic methods for assessment of reservoir sedimentation are described.

1) Sediment transport balance:

The sediment load (bed load and suspended load) is measured over all the watercourses flowing into the reservoir and then compared with the sediment load measured at the reservoir outlet. The difference between these two quantities is assumed to represent the sediment that has been deposited in the reservoir.

The point of measurement should be sufficiently close to the reservoir periphery and particular care shall be taken to complete outflow sampling before it meets the erodible channel downstream.

For further information, see Clause 5.

2) Capacity survey of the reservoir:

Hydrographic surveys of the reservoir are carried out at regular intervals. They reveal the geographic distribution of sediment deposits in the reservoir and also help in determining lost storage capacity. A capacity survey of the reservoirs is carried out using topographic survey methods or remote-sensing techniques.

— Topographic bed surveying (i.e. bathymetry) involves measuring the depth at various locations in the reservoir, following pre-determined profiles, cross sections or using a grid for contour determination. (See Clauses 6, 7, 8 and 9.)

— The remote-sensing technique uses images taken when the water level varies between near-empty and near-full, to define the shoreline contours at various water levels. (See Clauses 10, 11 and 12.)

5 Sediment transport balance

In this method, the total sediment load (bed load and suspended load) is measured at suitable locations near the mouths of all the water courses flowing into the reservoir and at all the reservoir outlets. The difference in the incoming and outgoing total sediment load is assumed to have been deposited in the reservoir. Data on water discharge and sediment discharge at each inflow and outflow location are required to be collected in order to arrive at the total sediment load.

Generally, water discharge is calculated from stream gauge records (for which gauging stations should be set up as specified in ISO 1100-1), then calibrated in compliance with the standards describing the various stream gauging methods, e.g. ISO 748 for the velocity area method, ISO 9555 for dilution methods, etc.

A number of traditional methods are available for computing sediment transport, including an interpolation method for estimating suspended-sediment loads when measured loads are not available. When data are insufficient for the utilization of the interpolation method, sediment-transport curves may also be used to compute suspended-sediment loads. However, estimates of suspended-sediment transport from transport curves – which are also used to compute bed load, and/or total loads – may be subject to significant errors. The equations are predicated on the presence of specific relations among hydraulic variables, sedimentological parameters, and the rate at which bed load or bed-material load is transported. The theory supporting the derivation of the equations tends to be incomplete, oversimplified, or non-existent.

Additionally, even the most theoretically complete equations rely on experimental data to quantify coefficients of the equations. The availability of reliable environmental data to verify estimates from equations is often lacking, and the equations tend to ignore or underestimate the washload component, which can comprise a substantial fraction of the sediment depositing in a reservoir. Rainfall-runoff models based on watershed, meteorological, and hydrological characteristics may be useful, but tend to be time-intensive and, likewise, require reliable environmental data.

Equipment and methods for sediment load measurements are detailed in various ISO standards, such as ISO/TS 3716, ISO 4363, ISO 4364, ISO 4365 and ISO/TR 9212.

Presently, this method is not commonly used for assessment of reservoir sedimentation, because of the availability of improved techniques and because of a number of practical difficulties and limitations. These include:

1) substantial costs and human resources involved for continuous, long-term measurements at several locations;

2) inadequacy of spatial and temporal representativeness of limited observations due to typically large variations of sediment load with time and discharge, and also in the cross section;

3) change in masses, and in proportions of fine and coarse fractions of the transported sediment with time;

4) limited accuracy of sediment measurements due to issues associated with

   i) sampler efficiencies and sampling techniques, and

   ii) potential disturbances induced due to measuring equipment and procedures;

5) large variations in estimates of the bed-load transport rates (in the absence of actual measurements), made using different sediment transport relations or calculated as a fraction of a measured suspended load.

NOTE New surrogate technologies for monitoring sediment transport are being developed that may provide cost-effective and quantifiably accurate sediment-discharge data at gauging stations. ISO 11657 (under development) describes a number of sediment-surrogate monitoring technologies, including the use of continuous turbidity and stream flow measurements to estimate suspended-sediment transport. Bulk-optic, laser-optic, digital-optic, pressure-difference, and acoustic techniques for metering suspended-sediment transport are being investigated. All of these techniques require in-stream calibrations to accepted standard monitoring instruments and techniques.

6 Topographic survey methods

6.1 General

In topographic surveying, in order to assess the volume of sediment deposit along with its location in the reservoirs, direct measurements of the depths or elevations of the reservoir bed and the coordinates of the measurement points are periodically carried out. The main survey methods are the cross-sectional (or range line) method and the contour method. The selection of a method depends on the quantity and distribution of sediment indicated by field inspections, shape of the reservoir, purpose of the survey, and desired accuracy. While the contour survey method is generally applicable for all types of reservoir shapes, the use of the range method should be limited to relatively straight reaches. A suitable combination can also be used.

For smaller reservoirs, a reconnaissance sedimentation survey may be carried out. This survey has been designed to determine the approximate rate of loss of storage capacity; the thickness of the deposited sediment is measured in 15 to 20 or more well distributed locations in a reservoir by means of a simple measuring device known as a spud (see 6.4.5).

6.2 Reservoir sedimentation surveys

6.2.1 Advantages

a) A reservoir survey can be less costly than taking continuous sediment measurements at several locations in the catchment.

b) The accuracy of these surveys is usually high, particularly if advanced equipment is used.

c) The survey can be carried out at any convenient time to get the total sedimentation after the last survey.

d) The time required for a survey can be considerably shortened with the use of advanced equipment.

6.2.2 Limitations

a) Topographic surveys do not provide any information about the variation of sediment yield with time, and give only the total sediments accumulated since the last survey. The above information can only be obtained by gauging.

b) The unit weight of sediment deposits is required for estimating sediment yield. The temporal and spatial variation in the unit weight may introduce errors in the results.

c) This method does not provide sub-catchment-wise sediment yield; this can only be obtained by sediment sampling of different streams.

d) This approach is not very effective where sedimentation is small, as the error of measurement may mask the true sedimentation rates.

e) Sediment outflow data are also required to estimate the total sediment inflow.

6.3 Frequency

The frequency at which reservoir surveys are taken depends on individual site characteristics. Generally, reservoirs are surveyed every 3 to 10 years. The survey frequency depends on the sediment accumulation rate; reservoirs that have high accumulation rates are surveyed more often than those with lower rates. For reservoirs which are losing capacity very slowly, a survey interval in the order of 20 years of even longer may be adequate. For reservoirs which are losing capacity rapidly, or where the impact of sediment management is being evaluated, a survey interval as short as 2 to 3 years may be used.

The cost of running a survey also plays a critical part in deciding the survey frequency. Special circumstances may necessitate a change in the established schedule. For example, a reservoir might be surveyed after a major flood that has carried a heavy sediment load into the reservoir.

A survey may also be run following the closure of a major dam upstream in the same catchment, since the reduction in the free drainage area leads to a reduction in the sediment accumulation rate of the downstream reservoir. The volume of the sediment that has accumulated in a reservoir is computed by subtracting the revised capacity from the original capacity at a reference reservoir elevation (usually the full reservoir level). Since this is the difference of two large numbers, an error, even by a few percentages in either of the two numbers will significantly influence the results.

The minimum survey interval depends on the precision of the survey technique and the rate and pattern of storage loss. For instance, if a survey technique incorporates an error in the order of 2 % of the total reservoir volume, and if the reservoir is losing capacity at 0,25 % per year, a 4-year survey interval may be too short to produce reliable information unless most sediment inflow is focused into a small portion of the impoundment.

6.4 Survey equipment

6.4.1 General

The basic survey items are

a) horizontal or distance measurement, and

b) vertical or depth measurement.

The principal equipment and instruments required for the hydrographic and topographic coverage in relation to the measurements are detailed in the subsequent subclauses.

6.4.2 Positioning equipment

6.4.2.1 General

The global positioning system (GPS) is a space-based global navigation satellite system that provides reliable location and time information, in all weather conditions and at all times, anywhere on or near the Earth when and where there is an unobstructed line of sight to four or more GPS satellites. It is maintained by the United States government and is freely accessible by anyone with a GPS receiver.

There are two general operating methods by which GPS-derived positions can be obtained:

1) absolute point positioning;

2) relative (differential) positioning (DGPS).

6.4.2.2 Absolute point positioning

A GPS satellite continuously transmits microwave radio signals composed of two carriers, two codes and a navigation message. The GPS receiver picks up the GPS signal through receiver antenna and processes it using built-in software. GPS receivers on the ground calculate their positions by making distance measurements to four or more satellites. The satellites function as known reference points that broadcast (free) satellite identity, position and time information via codes on two carrier frequencies. Measurements of the distance to each individual satellite are made by analysing the time it takes for a signal to travel from a satellite to a GPS receiver. Trilateration is then used to establish a GPS receiver's position. The absolute point positioning is highly dependent on the accuracy of the known coordinates of each satellite, accuracy of modelled atmospheric delay and the accuracy of the resolution of the actual time measurement process performed in a GPS receiver (clock synchronization, signal processing, signal noise, etc.). For many applications, absolute point positioning does not provide sufficient accuracy.

6.4.2.3 Differential GPS (DGPS)

6.4.2.3.1 General

Differential positioning is the technique or method used to position one point relative to another. DGPS requires two or more GPS receivers to be recording measurements simultaneously. Differential positioning is more concerned with the relative difference in position between two users, who are simultaneously observing the same satellite, than with the absolute position of the individual user. Since errors in the satellite position and atmospheric delay estimates are effectively the same at both receiving stations, they cancel each other to a large extent. Differential positioning can be performed by using code- or carrier-phase measurements and can provide results in real-time or be post-processed. A DGPS utilizing code-phase measurements can provide a relative accuracy of a few metres. A DGPS utilizing carrier-phase measurements can provide a relative accuracy of a few centimetres.

6.4.2.3.2 DGPS (code-phase)

A code-phase DGPS consist of two GPS receivers, one set up over a known point and one moving from point to point or placed on a moving platform, measuring pseudo ranges to at least four common satellites. Since the satellite positions are known and one of the receivers is over a known point, a "known range" can be computed for each satellite observed. This "known range" can then be subtracted from the "measured range" to obtain a range correction or pseudo-range correction (PRC). This PRC is computed for each satellite being tracked at the known point. The PRC can then be applied to the moving or remote receiver to correct its measured range. Code-phase DGPS has primary applications to real-time positioning systems where the accuracies at the meter level are tolerable.

A real-time dynamic DGPS includes reference station, communications link and user equipment. If the results are not required in real time, the communication link could be eliminated and positional information post-processed.

a) *Reference station:* The reference station measures timing and ranging information broadcast by the satellites and computes and formats range corrections for "broadcast to user" equipment. The reference receiver consists of a GPS receiver, antenna and processor. Using the technology of differential pseudo-ranging, the position of the survey vessel can be found relative to that of the reference station. The pseudo-ranges are collected by a GPS receiver and transferred to a processor where pseudo-range corrections are computed and formatted for data transmission. The reference station is placed on a known survey measurement in the area having an unobstructed view of the sky. The antenna should not be located near objects that will cause multipath or interference.

b) *Communication links:* The communication link is used as a transfer media for the differential corrections.

c) *User equipment:* The remote receiver should be a multichannel single frequency GPS receiver. The receiver shall be able to accept the differential corrections from the communications link and then apply those corrections to measured pseudo range.

d) *Separation distances:* The maximum station separation between the reference and the remote station in order to meet hydrographic surveying standard of 2 m, can be maintained up to a distance of 300 km.

6.4.2.3.3 DGPS (carrier-phase)

Carrier-phase tracking provides for a more accurate range resolution due to the short wavelength and ability of a receiver to resolve the carrier phase down to about 2 mm. This method may be employed with either static or kinematic receivers. Methods for resolving the carrier-phase ambiguity in the dynamic, real-time mode have been developed and implemented by several GPS receiver manufacturers for real-time positioning. These methods are referred to as “Real Time Kinematic” or RTK and provide 3D positions accurate to a few centimetres.

The carrier-phase positioning system is very similar to the code-phase tracking technology. A GPS reference station shall be located over a known survey monument. The reference station shall be capable of collecting both pseudorange and carrier-phase data from the satellites. The reference station consists of a carrier-phase dual-frequency full-wavelength GPS receiver, a processor and a communication link. The processor used in the reference station will compute the pseudorange and carrier-phase corrections and format the data for the communications link. The user equipment on the survey vessel consists of a carrier-phase dual-frequency full-wavelength GPS receiver with a built-in processor. The built-in processor must be capable of resolving the integer ambiguity while the platform survey vessel is moving. This system is not designed to be used in surveys over 20 km away from the reference station.

6.4.3 Distance measuring equipment

Survey equipment (e.g. a chain, tape, plane table, transit sextant, range finder, electronic distance meter) and special hydrographic instruments (e.g. an echo sounder, distance wheels, and other electronic equipment) are generally used.

6.4.4 Depth measuring equipment

Conventional equipment (e.g. a dumpy level and sounding poles) and special hydrographic equipment (e.g. an echo-sounder; refer to ISO 4366 for details) are used to measure depth.

The selection of an echo sounder should take into account the factors affecting survey accuracy and the scope and size of the reservoir under study. The accuracy of bathymetric surveys using echo sounders depends upon several factors including water depth and turbulence, water temperature and salinity (which affect the speed of sound), and reflectivity of bottom materials. Depending upon these factors, users may select echo sounders that employ different transmitting and recording components and arrangements, acoustic frequencies, digitization techniques, and display schemes.

The beam width and depth of water determine the footprint or aerial resolution of the acoustic wave when it strikes the lakebed. For the same depth of water, a narrow-beam transducer produces a smaller acoustic footprint, provides finer resolution, and is generally more accurate than a wide-beam transducer. A narrow-beam transducer is required to measure small deformations of structures, but requires an increased number of survey ranges, or cross-sectional passes, at generally slower boat speeds than required for a wide-beam transducer. Thus, using a narrow-beam transducer could require more time and greater expense. Some echo sounders employ special digitization techniques to reduce the effective footprint.

The digitization techniques employed by the echo sounder can profoundly affect data accuracy. Many graphical or numerical-display echo sounders determine the depth when the reflected acoustic energy exceeds a predetermined threshold. The digitization technique is called “threshold detection”. When measuring depressions or holes, the reflected acoustic energy that exceeds the threshold is likely to come from the edges of the acoustic footprint. If the footprint is large and the width of the hole is small, or if the bed has a significant slope, the depth measured by the echo sounder may not be accurate.

An alternative digitization scheme is to use peak detection rather than threshold detection. The peak-detection technique analyses the return echo and computes the distance associated with the peak amplitude of the return signal rather than a predetermined threshold value; therefore, the peak detection method measures the depth at the approximate centre of the footprint and the beam width is effectively reduced. The peak-detection method is less sensitive to acoustic reflectors in the water column (sediment, debris, etc.) than the threshold-detection method. Although adequate data can be achieved with an echo sounder using threshold detection, peak detection may be more accurate and reliable in turbid and turbulent waters.

Recent developments of multi-beam and sector-scanning sonar systems permit accurate bathymetric data to be collected rapidly over a large area.

Sector-scanning sonar has been used to locate wellheads for drilling operations and as an aid to obstacle avoidance. The technology is similar to a fixed-transducer echo sounder, except that the transducer is mounted on a mechanism that rotates and tilts the transducer. The measurement location and depth of the streambed are determined from the slope distance measured by the acoustic system and the tilt and rotation of the transducer. Complete data coverage of a circular area can be obtained from a single location. If the system is mounted on a moving survey vessel, the system can effectively collect a swathe of data as the vessel is manoeuvred in the stream.

A multi-beam system is similar in capability to the sector-scanning sonar. Multi-beam systems do not actually use multiple beams, but emit a fan of sound and receive segments of the reflected sound by electronically phasing an array of transducers. The transducers are arranged in an arc – typically in configurations of 60 transducers in a 90-degree arc. Thus, a swathe of streambed is measured almost instantaneously.

The accuracy of the sector-scanning and multi-beam systems is highly dependent upon accurate measurements of the position of the transducer, or transducer array, at the time data are collected. When the transducer is at acute angles with the stream bed, small errors in the measured angle of the transducer can cause substantial errors in the depth measurement. Therefore, very stable deployment platforms, or external instruments to accurately measure and compensate for vessel attitude, are required to collect accurate data with these systems. The effective range depends upon the frequency of the acoustics and the characteristics of the water. Sector-scanning sonar has been used to measure depths at ranges of 10 m.

6.4.5 Spud

A spud is sometimes used in reconnaissance type work for a quick estimation of sediment depth. This device is also used in roughly tracing out the original profiles of the reservoir bottom in case this information is not already available.

A spud is a case-hardened steel rod about 2 m to 3 m long and about 20 mm to 40 mm in diameter into which outward-tapering grooves have been machined at regular intervals. Each groove tapers from a maximum depth of 6 mm to zero at the rim of the next one above. The spud is cast or allowed to fall vertically through water with force sufficient to penetrate the deposited sediment and the underlying original soil material. If the water is shallow, it may be driven in by hand. After the spud depth (spud plus line length) is noted, the spud is lifted slowly (so as not to wash out the sediment captured in the grooves), and is examined to determine the depth to the pre-impoundment bottom based on a change in texture, colour, presence of roots, etc. The depth to the top of the sediment deposits is simultaneously determined by using a sounding weight, and the deposit thickness is determined by subtraction.

6.5 Density measurements and sediment samplers

6.5.1 Density measurements

Sediment bulk density can be measured by different methods: namely, by removing a sample of known volume, or by using a gamma density pole, or by multiple-frequency echo sounding. Density measurements and sediment samples are taken along range lines. The number of sample and measurement locations depends on the accuracy desired and the variability of the sediment. The entire depth of each sediment deposit needs to be sampled and sample volume and weight measured accurately to determine sediment accumulation.

6.5.2 Sediment sampling

Sampling devices are described in the ISO 4364 and ISO 9195. Most are various sorts of core-drilling devices (SCS, cylindrical type, etc.), or surficial-scooping devices, suitable for different types of bed material. Piston-type samplers (such as Vibracore) and radioactive probes (such as gamma probes) can also be used.

6.5.3 Multiple-frequency echo sounding

The idea here is to use various echo-sounding frequency ranges: the lower the frequency, the better the impulses penetrate the surface. Consequently, the impulse from a 210 kHz sounder is reflected by sediment density of 1,2 kg/l, whereas the impulse from a 33 kHz sounder is reflected by a density of 1,4 kg/l. It is thus possible, by varying the frequency, to obtain a return spectrum, which can in turn be used to characterize the various layers of sediment. Multiple-frequency echo sounding is still at an essentially experimental stage and would benefit from significant improvements in the field of signal processing. It should also be noted that the aperture angle of the emitted beam varies with the frequency, which means that the signal reflected by each beam does not necessarily come from the same geographical location (x, y). Result interpretation must consequently be restricted to gently sloping areas in order to limit problems involving the different aperture angles of the beam.

The dual-frequency technique (210/33 kHz) is more reliable and is well suited to largely organic sediment; the density of 1,2 kg/l may be located well below the surface of the sediment. On the other hand, in reservoirs where the sedimentation is mainly mineral in origin, the surface sediment naturally exceeds a density of 1,4 kg/l.

Acoustic seafloor classification systems (ASCS) process the acoustic return signals from standard single-beam echo sounders, and can be used to make qualitative estimates of the composition of reservoir deposits. They gather information about bottom type, bottom sediments, and aquatic plants. Different reservoir bottom types can be discriminated by extracting data on bottom roughness (i.e. irregularities in topography) and hardness (i.e. type of substrate – rock, sand, mud, and so forth).

Acoustic reservoir-deposit characterization requires field verification. This can be done either by physical sampling of the bottom using sediment cores or grabs, or through visual observations by divers or underwater cameras. All types of substrate encountered shall be verified to interpret the data accurately and link the acoustic signatures to the reservoir deposit classification scheme. Extensive fine-scale sampling may be required, especially where the deposits are complex. Additionally, these systems require initial calibration in each unique study location in order to interpret the signal returns and classify benthic cover types.

All these techniques, whether based on multiple or dual frequencies, nevertheless require prior calibration using sediment samples such as those described in 6.5.2.

7 Topographic survey using the contour method

7.1 General

The basic objective of this method is to prepare a contour map of the reservoir bed using complete topographic or bathymetric information. For this purpose, spot levels or soundings are taken at predefined points over the entire reservoir bed. A contour map of the reservoir is then prepared with suitable scale and contour interval, from which the capacity of the reservoir at the time of the survey is computed. The difference in capacity between two surveys indicates the loss of capacity due to sediment deposition during the intervening period.

There are quite a few field techniques available for contouring, the application of which depends mostly on the physical features of the reservoir, its operation schedule, working conditions and availability of instruments and other facilities. The commonly used techniques include:

— grid contouring;

— radial contouring;

— circular contouring;

— water-surface mapping.

The basic measurements, carried out in any of the above survey techniques, are for acquiring the x, y and z coordinates at the predefined (grid) points. The methods for acquiring the x and y coordinates are given in ISO/TR 11330.

The z coordinate of points below water level is obtained by depth measurements (soundings). For small reservoirs, soundings are taken either by a sounding pole or by lead line at closer intervals, so that bottom contours are developed with sufficient accuracy. For large reservoirs, depth measurements using echo-sounding equipment are carried out at all grid points of the survey network. Commonly used techniques are explained in ISO 4366. The z coordinate of points above water level may be obtained by a land survey.

A detailed description of procedures and instruments for conducting hydrographic survey is given in IHO's Publication C-13, *Manual on Hydrography*[35].

Recent advances in automated survey techniques have made hydrographic contour surveying economical in smaller and midsize reservoirs.

7.2 Hydrographic survey

Integrated bathymetric systems incorporating a DGPS are also used for hydrographic surveys to digitally map the entire reservoir bottom. The survey system is basically comprised of three components:

a) a positioning system (a GPS in the differential mode for proper positioning of moving survey boat);

b) depth measuring units (digital echo sounder/ bathometer/ transducer for depth measurement);

c) a computer interface, including software for data logging and post-processing of positioning data; a plotter, printer, monitor, etc.

The survey is carried out in a rapid and efficient manner by using GPS in the differential mode for hydrographic surveys, using state-of-the art technology and using a "total station" (see 7.3.2) for topographic surveys on ground. A boat is equipped with the bathymetric equipment, the GPS is mounted on board and a computer is used for the bathymetric survey; its reference station is positioned on a known geographical benchmark. The survey software enables fixing of grid lines, interfacing of the bathymeter and DGPS and taking of the x, y and z values at required intervals/grids. Boat navigation can be controlled by the software so that the boat tracks the grid line accurately. The survey can also be carried out in a random mode. The data collected is then processed and analysed using specially developed software to obtain the results in various forms, e.g. point plots, contour and three-dimensional maps of the reservoir bed, area capacity elevation tables and cross sections of the reservoir.

The line spacing for the bathymetry survey depends on various factors such as the intended use of the data, complexity of the bottom, and the time and effort available. A hydrographic survey is carried out within the water-spread area at suitable line spacing. Data are available all along the lines and hence the entire survey area is covered as desired. A few tie lines in the other direction are also carried out. Similarly, the area above the ground not covered under hydrographic surveys, and up to the maximum water level (MWL), is surveyed by generally taking levels at suitable interval along the range lines laid; this interval is flexible depending on the situation.

7.3 Topographic surveys

7.3.1 General

A topographic survey should be conducted in the area between the existing water level at the time of the survey and the maximum water level (MWL)/full reservoir level (FRL). The survey is carried out around the periphery of the reservoir using suitable grid spacing.

7.3.2 Instruments

a) *Total station* – This system incorporates an electronic theodolite, an electronic distance measurement device and a computer as one unit. The capability of the system to retain data in memory, carry out calculations using its own processor, and finally its ability to create x, y, z files which can be directly transferred to the computer, makes the survey process fast and accurate.

b) *Auto level* – Auto level is used to accurately transfer the z coordinate from a benchmark to the control points in order to control the vertical accuracy of the total station during a topographic survey.

7.3.3 Total-station survey

A total-station survey starts at the reference point used for the DGPS reference station, using the same coordinates as those employed for the hydrographic surveys. Two points should be established using a nearby DGPS; these points should be used for calculating the angle (northing) for the topographic surveys.

The survey should then be conducted to cover the land area of the reservoir up to the maximum water level (MWL).The final output of the survey is an x, y, z file.

A topographic survey should also be used to pick the location and coordinates of other features (such as dam axes, dykes, etc.) within the MWL. All the data – from the total station and from the DGPS, available in digital format – are merged with the bathymetric data, with necessary formatting, in order to generate a final contour map of the reservoir.

7.4 Computation of reservoir capacity

After a contour map of the reservoir has been prepared, the areas enclosed by the respective contours are measured. Starting from the lowest contour, the area covered at different contours is obtained and the capacity between the successive contours is worked out by the formulae given below. The cumulative value of the capacity, starting from the lowest contour, will give the elevation-capacity relationship. The difference between the old capacity curve and the new curve at any given elevation will correspond to the accumulation of sediment deposited between the surveys.

a) Modified prismoidal formula:

$$V_x = \frac{2H}{6}\left(A_1 + 4A_\mathrm{m} + A_2\right) - V_y \tag{1}$$

where

V_x is the volume between the middle and top contours (i.e. the volume between A_m and A_2);

H is the contour interval (elevation difference between A_m and A_2 contours);

A_1 is the area of the bottom contour;

A_m is the area of the middle contour;

A_2 is the area of the top contour;

V_y is the volume between contour A_1 and A_m as previously determined.

The volume below the lowest contour interval may be computed by the average end area method. After finding the volume below the lowest contour, this formula can be used progressively for each succeeding higher contour.

b) Prismoidal formula:

$$V_x = \frac{H}{3}\left(A_1 + A_2 + \sqrt{A_1 A_2}\right) \tag{2}$$

8 Topographic survey using a cross-sectional (range line) method

8.1 General

The cross-sectional survey method consists of carrying out sounding, or levelling, along a fixed set of cross sections to obtain distance data from the starting point of the cross section (x and y coordinates) and corresponding elevation (z coordinate) to predetermined points along the cross-sectional line. Hydrographic surveys should be conducted as described in 7.2 to obtain x, y, z coordinates of points which are below the water surface at the time of the survey. For points in the area between the existing water level and the maximum water level (MWL)/full reservoir level (FRL), x, y, z coordinates should be obtained by topographic survey methods as described in 7.3. The objectives are to develop the end areas at different cross sections and to carry out volumetric computations.

The layout and spacing of the cross sections should be carefully planned and the reference monuments at their ends should be connected with a triangulation network. The cross sections should be set perpendicular to the longitudinal trend (planar trend) of the reservoir, and the distance along the width and the depth of cross section should change linearly as far as possible. The important points to be considered while fixing the cross-sectional lines are discussed in Annex A.

The space enclosed by the two cross sections, the riverbed boundary and the two cross-sectional lines is defined as the cross-sectional space. Cross-sectional space can be simplified into a geometric model, and suitable formula can be selected to calculate the capacity and sedimentation volume at a specified elevation. The “areas of” and the “distance between” the two cross sections are the basic elements for calculating the capacity and sedimentation volume.

8.2 Reference frames/graphs

8.2.1 General

In the cross-sectional method, the data measured and parameters computed are represented graphically by means of the following.

8.2.2 Geographical map

A geographical map is prepared to indicate geographic information including cross-sectional lines along the reservoir, monuments or end points and benchmarks along each bank, and measurement points along each cross section and dam. A geographical coordinate system such as UTM or latitude, longitude is used to prepare such a map, as shown in Figure 1.

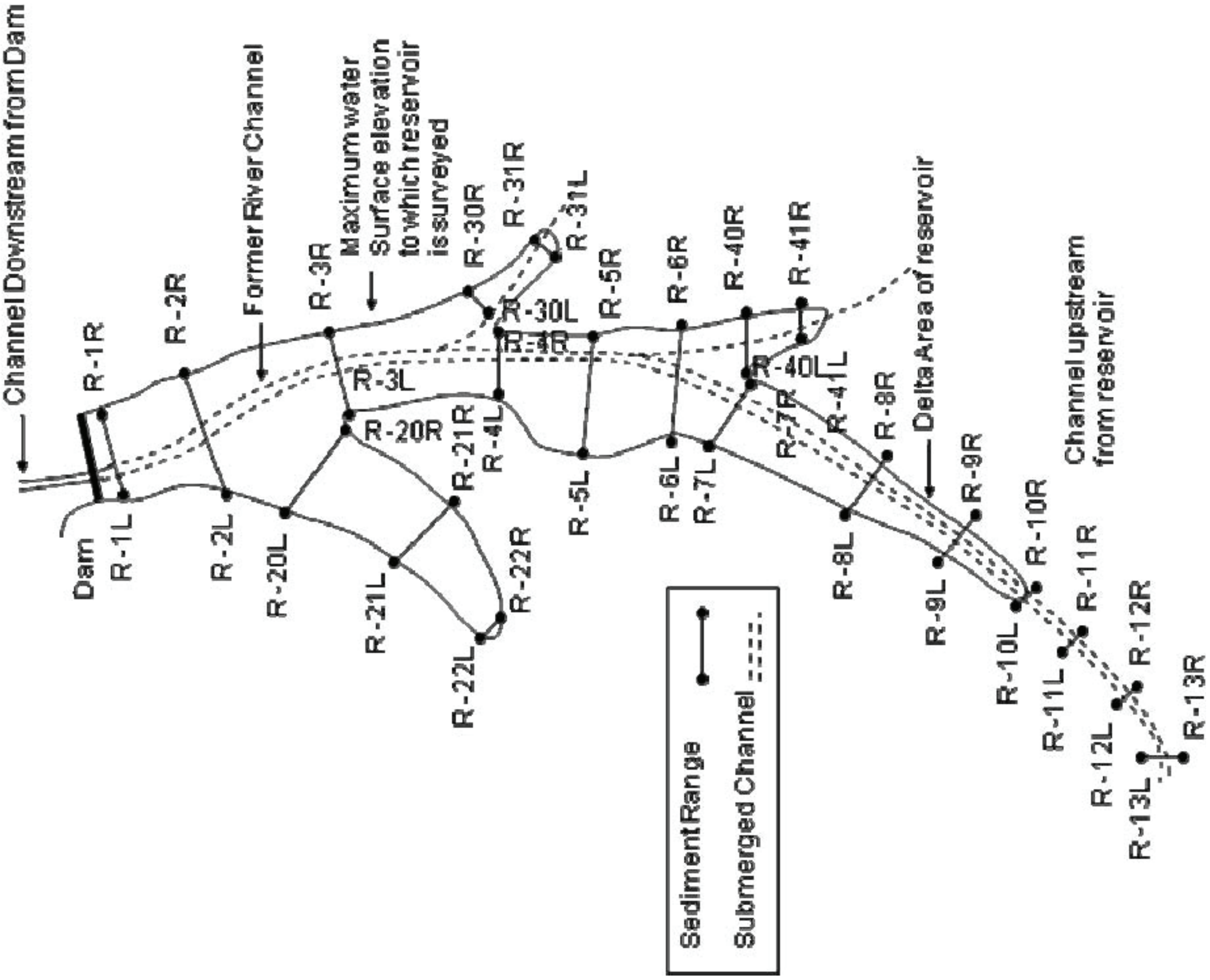


Figure 1 — Typical geographical map presenting various geographical information

8.2.3 Cross section

The aim of a plot of the cross section is to present and observe morphological changes. Data sets from different surveys of the same cross section are plotted; an example is shown in Figure 2.

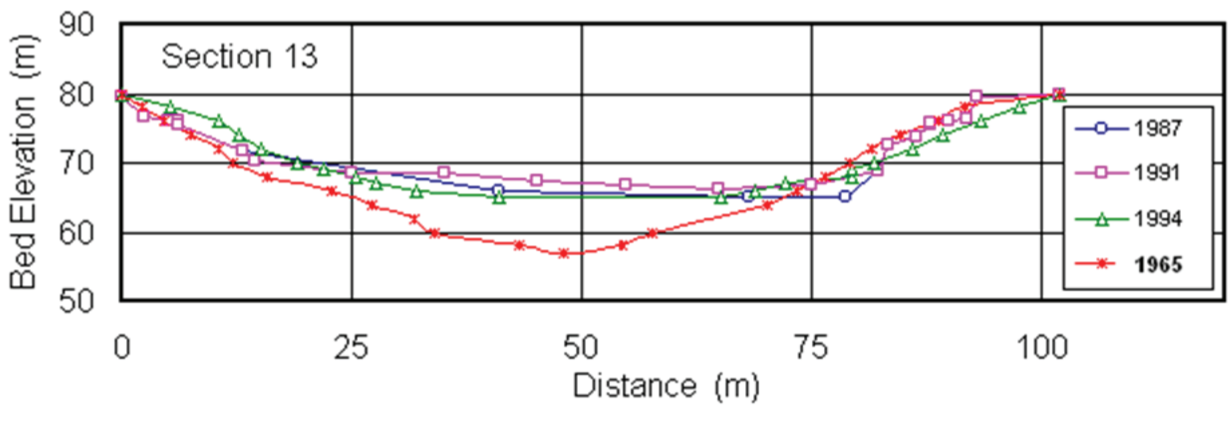


Figure 2 — Typical plot of a cross section with different surveys

8.2.4 Longitudinal profile

Morphological changes along the reservoir bed are graphically presented by plotting data sets of different surveys, with x-axis as distance from the dam, and y-axis as average bed level (can be change in bed level or change in volume) in a reach due to sedimentation/scouring. A typical plot of a longitudinal profile indicating bed levels observed in different years is shown in Figure 3.

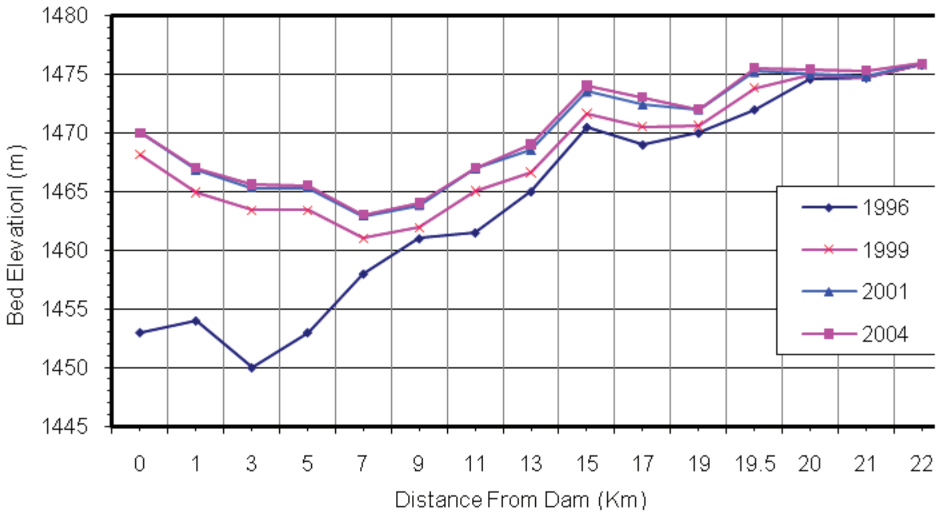


Figure 3 — Typical longitudinal profile

8.2.5 Cross-sectional space

The change in volume in a reach between the two cross sections is represented by a three-dimensional plot, with the x-axis as the distance along the cross section, y-axis the distance along the flow direction, and z-axis the depth/elevation. A typical plot is shown in Figure 4.

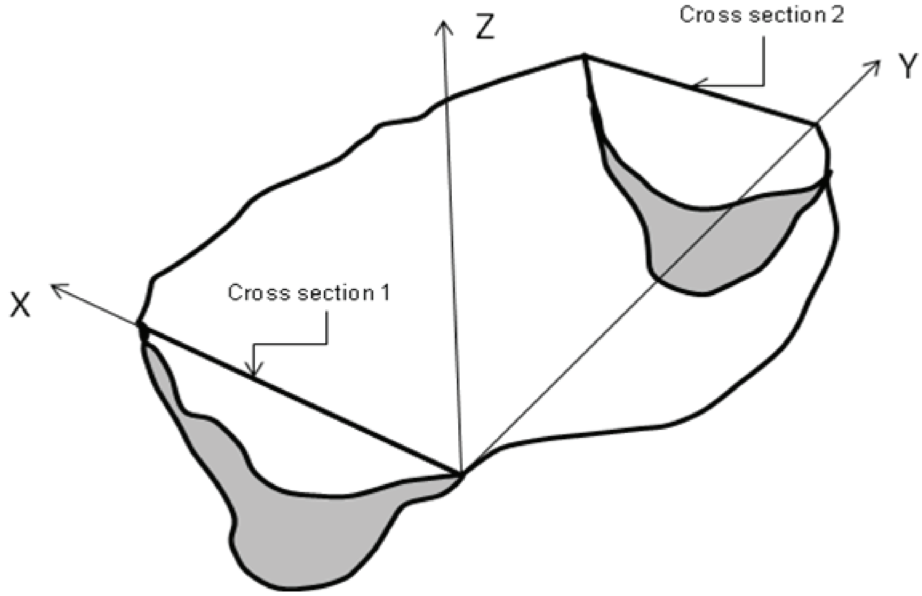


Figure 4 — Typical cross-sectional space

8.2.6 Area–elevation–reservoir capacity graph

Changes in total capacity or area of the reservoir are represented by a graph with the x-axis as the capacity or area and the y-axis as the elevation. A typical graph is shown in Figure 5.

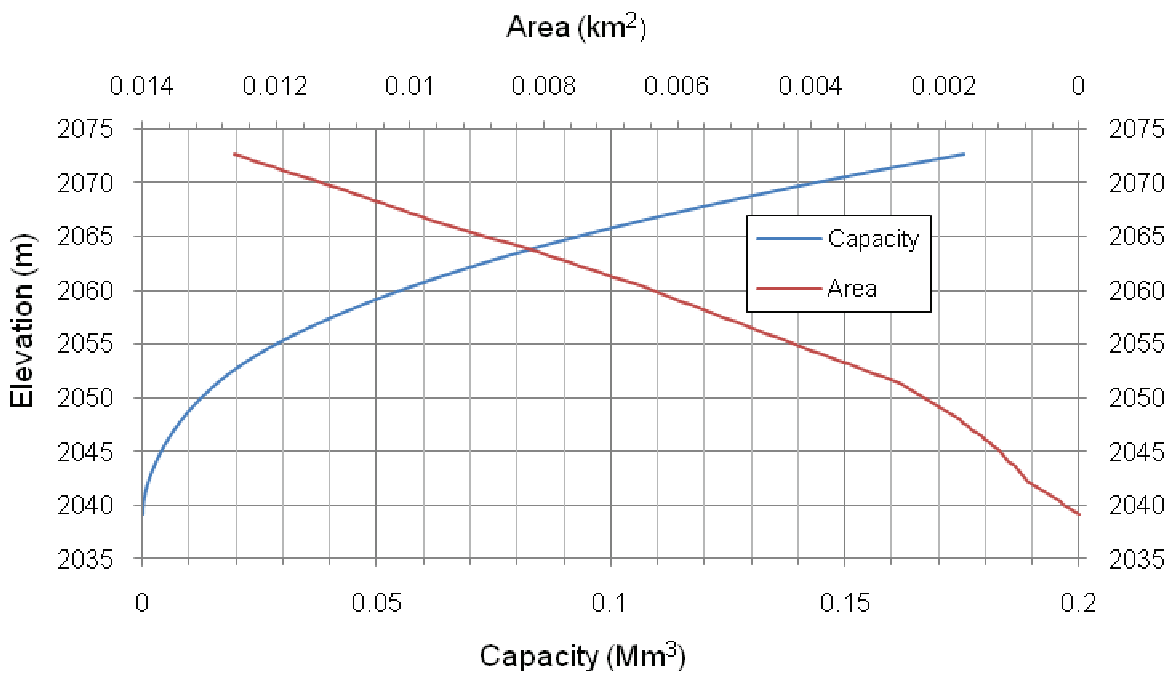


Figure 5 — Typical "area–elevation capacity" curve

8.2.7 Temporal reference graph

Temporal changes are indicated in a graph (see Figure 6) with the x-axis as time in years and the y-axis the total storage capacity (cross-sectional area, area of the reservoir, or average bed level) at a cross section.

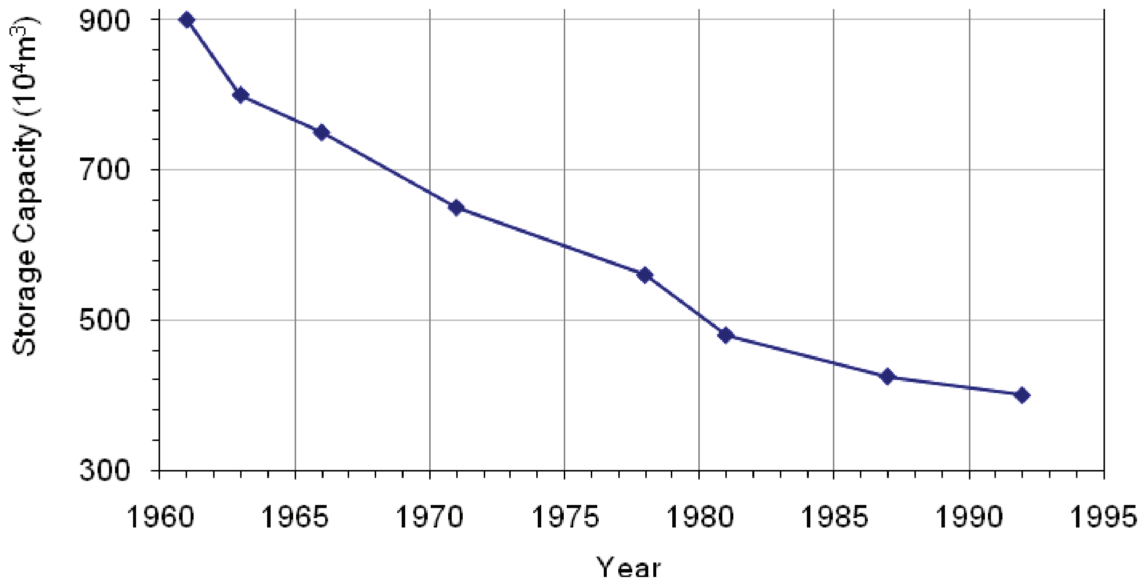


Figure 6 — Temporal reference graph indicating changes in storage capacity

8.3 Calculation of reservoir capacity

8.3.1 Calculation of area of cross section

The area of a cross section at any specified elevation is calculated from data of distance from starting point along the cross section line and elevation of reservoir bed at the measurement points. Each cross section is divided into several segments by the verticals. The area of each segment is calculated using a trapezoidal formula and sum of the individual areas; the total area of the cross section is calculated as given below:

$$A_n = \frac{1}{2}\sum (x_{i+1} - x_i)[(z_0 - z_i) + (z_0 - z_{i+1})] \quad (3)$$

where

A_n is the area of cross section with n selected points or verticals;

x_i is the distance from starting point to selected point/vertical;

x_{i+1} is the distance from starting point to point succeeding x_i ;

z_i is the elevation of reservoir bed at selected point/vertical;

z_{i+1} is the elevation of reservoir bed at point succeeding z_i ;

z_0 is the specified elevation for calculation of area of cross section.

8.3.2 Calculation of distance between two neighbouring cross sections

8.3.2.1 General

Figure 7 indicates two neighbouring cross sections, J and J+1. To calculate the distance between these cross sections when they are parallel, the distance is calculated as the length of the perpendicular line between the two cross sections. When the two cross sections are not parallel, the distance between them can be calculated using any of the following methods:

a) the method of midpoints of cross-sectional lines;

b) the method of equivalent capacity.

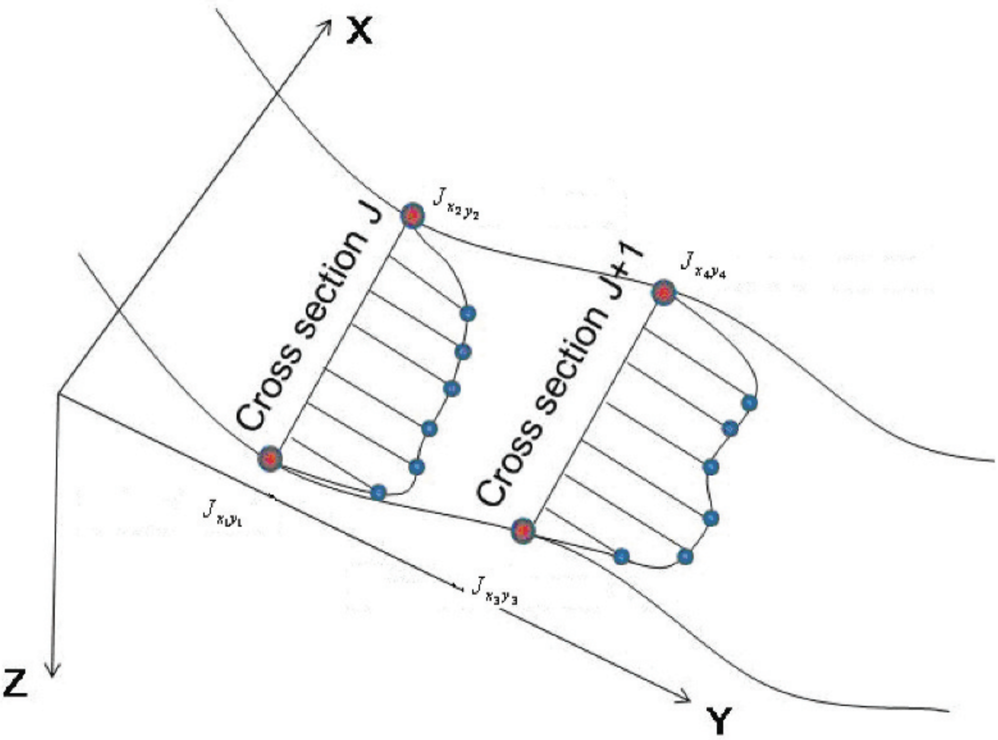


Figure 7 — Definition sketch of cross-sectional space

8.3.2.2 Method of midpoints of cross-sectional lines

In this method, the distance between two neighbouring cross sections is calculated as the length of the line joining the midpoints of cross-sectional lines.

Let the coordinates of the starting and ending points be $J_{x_1y_1}$ and $J_{x_2y_2}$ for cross section J; and those for cross section J+1 be $J_{x_3y_3}$ and $J_{x_4y_4}$. The distance y from J to J+1 is then calculated as:

$$y = \sqrt{\left(\frac{x_1 + x_2}{2} - \frac{x_3 + x_4}{2}\right)^2 + \left(\frac{y_1 + y_2}{2} - \frac{y_3 + y_4}{2}\right)^2} \tag{4}$$

8.3.2.3 Method of equivalent capacity

In this method, the distance is calculated using the concept of equivalent capacity, i.e. the distance when multiplied by the area of cross section is equal to the volume calculated by summing up the volumes of all the column units/ segments between the two neighbouring cross sections.

When cross sections J and J+*1* are not parallel, the volume between the cross sections is defined as the volume of the column with cross section J as the bottom and cross section J+1 as the top inclined plane. Since cross section J is divided into various area units, the volume of each column unit is computed by multiplying the area by the height. The average distance (height) between cross sections J and J+1 can be derived from the condition that the capacity calculated by multiplying the area of cross section J with the average distance is equal to the volume calculated by summing up the volumes of all the column units between the two cross sections. The distance ($d_{J\leftrightarrow J+1}$) between the two cross sections in equivalent capacity is defined as:

$$d_{J\leftrightarrow J+1} = \frac{d_{J,J+1} + d_{J+1,J}}{2} \tag{5}$$

where

$$d_{J,J+1} = \frac{1}{2}\frac{\sum(d_{(J,J+1)_i} + d_{(J,J+1)_{i+1}})[(z_{J_0} - z_{J_i}) + (z_{J_0} - z_{J_{i+1}})](l_{J_{i+1}} - l_{J_i})}{\sum[(z_{J_0} - z_{J_i}) + (z_{J_0} - z_{J_{i+1}})](l_{J_{i+1}} - l_{J_i})} \tag{6}$$

$$d_{J+1,J} = \frac{1}{2}\frac{\sum(d_{(J+1,J)_i} + d_{(J+1,J)_{i+1}})[(z_{J+1_0} - z_{J+1_i}) + (z_{J+1_0} - z_{J+1_{i+1}})](l_{J+1_{i+1}} - l_{J+1_i})}{\sum[(z_{J+1_0} - z_{J+1_i}) + (z_{J+1_0} - z_{J+1_{i+1}})](l_{J+1_{i+1}} - l_{J+1_i})} \tag{7}$$

$$d_{(J+1,J)_i} = \sqrt{(x_{J_j d_i} - x_{J+1_i})^2 + (y_{J_j d_i} - y_{J+1_i})^2} \tag{8}$$

where

l_{J_i}	is the distance from the initial point of cross section J for area unit i;
z_{J_i} and z_{J_0}	are respectively the elevation and the maximum elevation of cross section J for area unit i;
l_{J+1_i}	is the distance from the initial point of cross section J+1 for area unit i;
z_{J+1_i} and z_{J+1_0}	are respectively the elevation and the maximum elevation of cross section J+1 for area unit i;
$d_{(J,J+1)_i}$ and $d_{(J+1,J)_i}$	are symmetric;
(x_{J+1i}, y_{J+1i})	are the coordinates of points on the line l_{J+1};
$(x_{J_j d_i}, y_{J_j d_i})$	are the coordinates of points which are perpendicular to both line l_{J+1} and line l_J .

8.3.3 Capacity calculation of cross-sectional space

a) **Frustum/prismoidal formula**

The frustum formula for capacity calculation is:

$$V_{jz} = \frac{1}{3} y \left(A_1 + \sqrt{A_1 A_2} + A_2 \right) \tag{9}$$

where

V_{jz}	is the volume between the two cross sections;
y	is the distance between cross sections J and J+1;
A_1	is the area of cross section J;
A_2	is the area of cross section J+1.

The frustum formula is based on the assumption that the two cross sections are identical in shape and parallel to each other.

b) **Trapezoidal formula**

The trapezoidal formula for capacity calculation can be expressed as:

$$V_{jz} = \frac{1}{2} y (A_1 + A_2) \tag{10}$$

The formula can be applied in situations where the change of area between cross sections shows a linear trend.

c) **Capacity calculation for cross section that has linear change trends on width and average depth**

Let B_J and B_{J+1} be the width, H_J and H_{J+1} be the depth of cross sections J and J+1, respectively. For linear change trends, these two parameters can be expressed as follows:

$$B_y = B_J + \frac{B_{J+1} - B_J}{y_{J,J+1}} y \tag{11}$$

$$H_y = H_J + \frac{H_{J+1} - H_J}{y_{J,J+1}} y \tag{12}$$

The corresponding area is:

$$A_y = B_y H_y \tag{13}$$

The capacity between the two cross sections, V_{BH}, can be calculated using:

$$V_{BH} = \frac{1}{6} y_{J,J+1} (2A_J + 2A_{J+1} + B_J H_{J+1} + B_{J+1} H_J) \tag{14}$$

where

$A_J = B_J H_J$	is the area of cross section J;
$A_{J+1} = B_{J+1} H_{J+1}$	is the area of cross section J+1.

In a reservoir, it is important to set cross sections which have linear change trends on the width. Normally, such cross sections are located in an expanding or shrinking area/reach. For the depth, it is common to have linear change trends on depth for cross sections of steep slope reservoirs. In these situations, Formula (14) is applied.

d) **Calculation of sedimentation or scouring amount for cross-sectional space**

Adopting the volume-difference method, the amount of sedimentation or scouring can be regarded as the difference in the volumes observed twice at a specified elevation. Letting V_q indicate the first observed volume, and V_h indicate the second measurement, the sedimentation or scouring amount, V_{cy}, can be calculated as:

$$V_{cy} = V_h - V_q \tag{15}$$

A positive value of V_{cy} indicates scouring; a negative value of V_{cy} indicates sedimentation.

8.3.4 Procedure for preparing elevation-capacity curve

The volume between cross sections at a specified elevation shall be calculated using appropriate methods. The sum of volume between all cross sections will give the capacity of the reservoir associated with the specified elevation. The elevation capacity curve can be then drawn with the data obtained.

9 Sub-bottom mapping

Sub-bottom profiling systems provide opportunities to measure both the original and current reservoir capacities with one set of measurements. These systems identify and measure sediment layers that exist below the sediment/water interface. Their acoustic systems use a technique similar to that in simple echo sounders. A sound source emits a signal vertically downwards into the water and a receiver monitors the return signal that has been reflected off the reservoir deposits. Some of the acoustic signal will penetrate the deposits and be reflected when it encounters a boundary between two layers with different acoustical properties (acoustic impedance). The system uses this reflected energy to provide information on sediment layers beneath the sediment-water interface.

Acoustic impedance is related to the density of the material and the rate at which sound travels through the material. When there is a change in acoustic impedance, e.g. at the water-sediment interface, part of the transmitted sound is reflected. However, some of the sound energy penetrates through the boundary and into the sediments. This energy is reflected when it encounters boundaries between deeper sediment layers having different acoustic impedance. The system uses the energy reflected by these layers to create a profile of the sub-bottom sediments.

Sub-bottom profiling systems provide information about the subsurface sediment structure. No other acoustic techniques provide this type of information, and only physical sampling (via cores) or *in situ* photography (via sediment profile imaging) allows for the characterization of subsurface structures. Sub-bottom profiling systems may penetrate as deep as 30 m into the reservoir deposits, i.e. much deeper than most cores can penetrate. However, the penetration depth depends on the hardness of the overlying layers and the presence of gas deposits, such as authigenic methane.

Several sonar parameters (output power, signal frequency and pulse length) affect the instrument performance.

— An increase in output power provides better, and usually deeper, penetration into the sub-bottom layers. Sometimes however, if the bottom is very hard or not very deep, the increase in ouput power will cause more signal to be reflected back off the deposits. The signal might then be reflected off the reservoir surface, leading to multiple reflections and “noise” in the data.

— Signal frequency also has an effect on system performance. Higher frequency systems (2 kHz to 20 kHz) will produce high definition data of the upper sediment layers. These higher frequency signals have shorter wavelengths, and they are able to discriminate between layers that are close together. Lower frequency systems will give greater penetration, but lower resolution.

— A longer sound-pulse length transmits more energy and yields deeper penetration. However, a long pulse length may decrease the ability to discriminate between adjacent reflectors, thus decreasing the system resolution.

10 Remote-sensing methods

10.1 General

The conventional techniques of sedimentation quantification in a reservoir (such as hydrographic surveys and inflow-outflow methods) are cumbersome, costly and time consuming. Further, prediction of sediment deposition profiles using empirical and numerical methods requires a large amount of data and the results are still not accurate.

In the remote-sensing approach, imagery covering the range of reservoir water levels is obtained. This imagery is analysed to determine the area of the reservoir's water surface. Photogrammetric and digital data can provide water-spread information suitable for determining changes in reservoir capacity. Methods for determining the wetted area of the reservoir vary based on the type of data obtained and what is available to the user. Methods vary from estimation of the area of an aerial photograph, using a standard grid, to calculation of the area based on the number of picture elements (pixels) in a digital image. Multiplying the number of water pixels with the area of a pixel gives the water-spread area of the reservoir at the time of data collection.

Most reservoirs have annual drawdown and refill cycles. The actual water surface elevation in the reservoir at the time of data acquisition can be obtained from the dam authorities. An analysis of a series of imagery gives the water spread of the reservoir at various elevations over the operation range. The reservoir capacity between two levels can be computed by using either the trapezoidal or prismoidal formula and the elevation-capacity table can be prepared. A comparison of this table with a previous table yields the capacity lost during the intervening period.

10.2 Advantages

a) Remote-sensing data through its spatial, spectral and temporal attributes can provide synoptic, repetitive and timely information regarding the revised water-spread area in a reservoir.

b) By using the digital analysis techniques and GIS in conjunction, the sediment deposition pattern in a reservoir can be determined.

c) Compared to conventional methods, the remote-sensing approach is highly cost effective, easy to use and requires little time in analysis.

d) Analysis of the data of projects that are located in inaccessible areas can be done with equal ease.

10.3 Limitations

a) The amount of sediments deposited below the lowest observed water level cannot be determined through remote sensing. Thus, it is not possible to estimate the actual sedimentation rate in the whole reservoir.

b) The presence of clouds in an image above the reservoir water spread poses a problem in correctly demarcating the reservoir area.

c) This technique is not suitable for reservoirs that have been constructed in narrow valleys with steep slopes.

d) In digital image processing, errors may arise in labelling the pixels at the periphery of the reservoir as water or land pixel.

11 Light detection and ranging

11.1 General

LiDAR (Light Detection And Ranging) is an active light-based sensor, similar to radar, that transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver. The ability of LiDAR to accurately measure the ground surface is dependent upon the wavelength of the laser pulse and the amount of power produced in the laser pulse. Topographic surveys using LiDAR typically operate in the infrared spectrum; these are the most prolific type of surveys performed using LiDAR. However, infrared LiDAR cannot penetrate below the water surface; therefore, it cannot be used for bathymetry. Bathymetric surveys using LiDAR can be conducted, and typically operate, in the green spectrum; this spectrum can penetrate through the water column up to three times the Secchi depth. This technology is currently being used for high-resolution topographic mapping by mounting a LiDAR sensor, integrated with GPS and Inertial Measurement Unit (IMU) technology, onto the bottom of aircraft and measuring the pulse return rate to determine surface elevations.

The prime benefit offered by LiDAR is its capability to capture small variations in relative surface relief with a vertical accuracy of 0,1 m to 0,2 m. For bathymetric surveying, varying the wavelength, pulse-repetition frequency, and field-of view has allowed systems to be developed that can penetrate water and map submarine topography. Based upon test flights over typical Caribbean coral reef environments, the Experimental Advanced Airborne Research LiDAR (EAARL), a LiDAR-based system designed for mapping submarine topography, has demonstrated penetration to greater than 25 m, and can routinely map reefs ranging in depth from 0,5 m to 20 m below the water surface. Both surficial topographic mapping of exposed reservoir surfaces and subsurface mapping can be accomplished using these technologies.

11.2 Aerial applications of LiDAR

Area capacity tables for reservoir volumes rely on accurate topographic/elevation information of the reservoir up to the spillway elevation. This elevation data includes both the wetted and non-wetted surfaces of the reservoir. In instances where sediment has filled the upper areas of the reservoir and is exposed due to declining water levels, on-water surveying methods are not adequate to map the entire area of sediment deposition. Airborne LiDAR applications represent efficient and rapid methods for mapping the topography of a reservoir, including submarine bathymetry.

In a typical application, a LiDAR sensor system is flown over a reservoir or lake, collecting a cloud of elevation data over the entire reservoir. By measuring the time for the reflected light to return to the laser, the range, or distance, can be determined very accurately. Inertial measurement systems and GPS allow for the precise determination of the position of the sensor in the aircraft as it flies over the land surface. A contour map or gridded digital elevation model of the reservoir is then prepared with a suitable scale and contour interval, from which the capacity of the reservoir at the time of survey is computed. By utilizing two or more surveys over the reservoir, the difference in capacity due to sediment deposition during the intervening period can be calculated.

Bathymetric LiDAR surveying uses the difference between the light reflecting from the water surface and the light that passes through the water column and reflects from the lake reservoir bottom. Post-flight processing evaluates each set of returns to extract the depth below water surface. In addition to the LiDAR depth and elevation measurements, a geo-referenced, down-look camera is typically deployed to provide a visual record of the survey.

11.3 Ground-based applications of LiDAR

A modification of the aircraft-mounted LiDAR sensor system is the ground-based LiDAR system. This system is similar to the total-station system used for traditional surveys; however, the ground-based LiDAR units rely on line-of-sight to survey or scan surfaces. Ground-based LiDAR can be deployed from a traditional tripod or from an extendable platform, or a location looking down on the survey area. The system can even be mounted on the top of a boat in the middle of a small reservoir. Surveying with a tripod LiDAR instrument must usually be completed from a number of different setups to eliminate shadows and to get a complete three-dimensional survey.

A contour map or gridded digital elevation model of the reservoir is then prepared with a suitable scale and contour interval, from which the capacity of the reservoir at the time of survey is computed. By utilizing two or more surveys over the reservoir, the difference in capacity due to sediment deposition during the intervening period can be calculated.

12 Aerial imagery methods

12.1 General

The basic reason to use aerial imagery methods is to obtain the water-spread area of a reservoir at different water levels ranging from the minimum drawdown level (MDDL) to the maximum water level (MWL). The water-spread area can be captured with the use of panchromatic (black-and-white) or natural-colour near-vertical aerial photography or from digital satellite imagery. Other types of imagery (e.g. colour infrared aerial photography, thermal scanner imagery, and microwave imagery, multispectral and hyper-spectral satellite imagery) are generally used to detect unique feature data other than location and shape details. These types of images may be incorporated into a GIS and registered in other geo-referenced data sets.

The imageries can be processed manually or using digital-processing techniques to obtain the area of reservoir at different water levels.

If an analysis is to be carried out for a specified period, then the corresponding data have to be used. Otherwise, it is best to use the data for such a period when there is large variation in the reservoir water level. If historical records of the maximum and minimum water levels in each year are available, it is better to select the water year in which the maximum variation occurred for undertaking sedimentation analysis. A wet year followed by a dry year is considered to be the best period for such a study since, for such a sequence, the reservoir water level is likely to fluctuate from a maximum level to a minimum level. The remote-sensing data series for the same water year or for continuous water years shall be selected in sequence, to the extent possible.

The availability of the satellite data and its cost are additional factors, which govern the selection of period of analysis. In general, sedimentation assessment should be made for major reservoirs after a gap of 5 to 10 years.

12.2 Photogrammetry methods

Near-vertical aerial photography to be used for planimetric and topographic mapping is generally collected as stereo pairs. The photography is collected with forward overlap between each photograph as they are captured down a flight line. Mapping areas may require multiple flight lines in order to include all the necessary mapping area within the imagery. In these cases, the imagery flight lines are flown so that they overlap (side lap). Generally, near-vertical aerial photography is flown with a forward lap of 60 % and a side lap of 30 %. These parameters allow the pilot and photographer some latitude in the imagery collection and should provide enough overlap for the compiler to see stereo and to map the required features. Generally, planimetric (buildings, roads, above ground utilities, etc.) and topographic features (mass points, break lines, and contours) are collected from either black-and-white or natural-colour near-vertical aerial photography. Planimetric and topographic mapping are generally the base mapping data set in a GIS or engineering data set. The accuracy of computations and queries made from these base mapping data sets is based on their thoroughness and accuracy. Black-and-white and natural-colour aerial photography generally provide the clarity and spatial resolution required to achieve most large- and small-scale mapping accuracies.

Ground control for photogrammetry is necessary to rectify the images to the earth prior to feature collection. Ground-control accuracies must generally be greater than the accuracy required of the photogrammetric mapping. Ground control shall be planned based upon the method of image rectification to be used for the project. The process of adjusting the aerial photography to the earth is critical to the accuracy of final mapping products.

Today, most projects are adjusted using aerotriangulation methods. These methods require fewer ground-control points than conventional adjustment methods and are accomplished with computer software. The software is very efficient and allows for quality control checks throughout the process. Aerotriangulation requires that the imagery be collected in blocks; therefore, it is most efficient for large project areas. Usually, aerotriangulation of small areas or areas that have very irregular shapes is not efficient and can be costly. However, the speed and quality control may still make this process acceptable for many small or irregularly shaped projects. Aerotriangulation accuracies should generally be greater than those required for the final mapping data sets.

12.3 Satellite imagery methods

12.3.1 General

Satellite platforms operated by various countries, and by private industry provide sensors that can capture digital images of the earth. These sensors can provide panchromatic, colour, and IR digital data at various spatial and spectral resolutions. These data types may provide cost-effective imagery over large portions of the earth. The spatial data are generally at a resolution far larger than that provided by aircraft platforms and may not be suitable for many large-scale mapping and GIS projects. However, high-resolution satellite imagery may be an economical solution for some medium- to small-scale projects.

12.3.2 Selection of suitable satellite and sensor

Multi-spectral information is required for the identification of water pixels and for differentiating the water pixels from the peripheral wetland pixels. It is necessary to ascertain that good quality cloud-free satellite data are available. It is also desirable to use high-resolution data for better results. About 8 to 12 imageries are desirable for different water levels between MWL and MDDL. The accuracy of the analysis improves with an increase in the number of imageries at closer intervals of reservoir water levels.

12.3.3 Identification of water pixels

The basic output from the analysis of remote-sensing data is the water-spread area of the reservoir. The two techniques of remote-sensing interpretation (visual and digital) can be used for water-spread delineation. Visual techniques are based purely on the interpretive capability of the analyst and it is not possible to use the multispectral data available. Visual interpretation is not commonly used these days. Using digital techniques, multispectral data can be utilized to identify the boundary of water-spread area. The number of continuous water pixels in the satellite imagery gives the water-spread area. Remote-sensing and GIS software can be used in the analysis of satellite imagery to obtain the water-spread area.

12.3.4 Calculation of revised capacity

The reservoir elevation at the time of acquiring the image is to be collected from the dam authorities. The reservoir capacity or volume (V) between two consecutive reservoir elevations is computed using the prismoidal formula (7.4). The revised volume can be compared with the original volume; the difference between the two represents the capacity loss due to sedimentation.

13 Uncertainty analysis

13.1 General

This clause summarizes the uncertainty analysis for measurement of reservoir sedimentation following the methods described in ISO 25377. For a general introduction to measurement uncertainty, refer to Annex B.

13.2 Principles

Uncertainty analysis of reservoir volume calculation shall be based on the following principles.

— The observation error is expressed as relative error.

— Uncertainty is expressed as evaluation of statistic errors.

— Uncertainty sources that are from the same condition can be used to form an error sample, the sample size of which shall not be less than 30.

— Systematic error and random error are considered separately. The total error is a composite of these two types of error.

— The average of the measured values provides an estimate of the true value of the quantity; this is generally more reliable than an individual measured value. Dispersion and the number of measured values provide information relating to the average value as an estimate of the true value.

— Though it is not possible to compensate for random error of a measurement result, it can usually be reduced by increasing the number of observations, with its expected value being zero.

— Assume that the uncertainty sources, and the objective functions, follow a Gaussian normal distribution.

— Each measured state variable is independent. Uncertainties of the objective function outputs can be obtained using the uncertainty propagation method.

The combined uncertainty is characterized by the numerical value obtained by applying the usual method for the combination of variances. The combined uncertainty and its components should be expressed in the form of standard deviations. If, for particular applications, it is necessary to multiply the combined uncertainty by a factor to obtain an overall uncertainty, the multiplying factor used shall always be stated.

In accordance with practice in hydrometry, the statement of the result of uncertainty estimation shall be at the 95 % confidence limit. Combining uncertainties from Type A and Type B estimation methods enables the uncertainty to be derived at a 68 % confidence limit; however, the instrument performance is normally stated at the 95 % confidence limit.

13.3 Estimation of uncertainty

13.3.1 This clause provides information for the user of this International Standard to estimate the uncertainty of measurement for reservoir sedimentation by the sediment-transport-balance method. In this method, the reservoir sedimentation quantity, V_s, is assessed by comparing the sediment inflow L_in with the sediment outflow L_out.

$$V_\mathrm{s} = L_\mathrm{in} - L_\mathrm{out} \qquad (16)$$

The sediment inflow over the time period from t_1 to t_2 can be obtained by using the following formula:

$$L_\mathrm{in} = \int_{t_1}^{t_2} Q(t)C(t)\mathrm{d}t = \int_{t_1}^{t_2} L(t)\mathrm{d}t \qquad (17)$$

where

$$L(t) = Q(t)C(t)$$

and

$Q(t)$ is the stream flow into the reservoir at time t;

$C(t)$ is the average cross-sectional sediment concentration at time t.

The effect on the value $L(t)$ due to small dispersions of $\Delta Q(t)$ and $\Delta C(t)$ is given by

$$\left(\frac{u_c\left(L(t)\right)}{L(t)}\right)^2 = \left(\frac{u\left(Q(t)\right)}{Q(t)}\right)^2 + \left(\frac{u\left(C(t)\right)}{C(t)}\right)^2 \tag{18}$$

Since the uncertainties of $L(t)$ over a time period are likely to be independent of each other, probability requires that these uncertainties be integrated in quadrature over the time period from t_1 to t_2.

$$\left(\frac{u_\text{c}\left(L_\text{in}\right)}{L_\text{in}}\right)^2 = \left|\frac{1}{L_\text{in}}\right|^2 \int_{t_1}^{t_2}\left[\left(\frac{u\left(Q(t)\right)}{Q(t)}\right)^2 + \left(\frac{u\left(C(t)\right)}{C(t)}\right)^2\right]\text{d}t \tag{19}$$

The values $\frac{u_\text{c}\left(L_\text{in}\right)}{L_\text{in}}$, $\frac{u\left(Q(t)\right)}{Q(t)}$, and $\frac{u\left(C(t)\right)}{C(t)}$, are referred to as dimensionless standard uncertainties and are given notations $u_\text{c}^*\left(L_\text{in}\right), u^*\left(Q(t)\right)$ and $u^*\left(C(t)\right)$. Thus,

$$u_\text{c}^*\left(L_\text{in}\right) \cong \left|\frac{1}{L_\text{in}}\right| \sqrt{\int_{t_1}^{t_2}\left[\left(u^*\left(Q(t)\right)\right)^2 + \left(u^*\left(C(t)\right)\right)^2\right]\text{d}t} \tag{20}$$

The dimensionless uncertainty $u_c^*\left(L_\text{out}\right)$ can be estimated in a similar way by using the outgoing flow and its average sediment concentration as a function of time. As the quantity of sediment in the reservoir is $V_\text{s} = L_\text{in} - L_\text{out}$; the uncertainty components involved in L_in and L_out are to be combined. Thus,

$$u_\text{c}^*\left(V_\text{s}\right) \cong \left|\frac{1}{V_\text{s}}\right| \sqrt{u_\text{c}^*\left(L_\text{in}\right)^2 + u_\text{c}^*\left(L_\text{out}\right)^2} \tag{21}$$

11.3.2 This clause provides information for the user of this International Standard to estimate and state the uncertainty of measurement for reservoir sedimentation by topographic surveys, remote-sensing methods and sub-bottom mapping methods recommended in this International Standard. In these methods, the reservoir sedimentation, V_s, is assessed by comparing the present reservoir capacity V_p with the original capacity V_o.

$$V_\text{s} = V_\text{p} - V_\text{o} \tag{22}$$

The reservoir capacity, V_p, is calculated based on either the cross-sectional area (vertical) or contour area (horizontal) and the distance between those areas using either the prismoidal formula [Formula (9)] or trapezoidal formula [Formula (10)]. As such, the overall uncertainty of measurement depends on:

— uncertainty of the areas,

— uncertainty of the measurement of distance between areas.

Either the prismoidal formula (9) or the trapezoidal formula (10) can be used to calculate the reservoir capacity. The proportion in which each parameter in these equations contributes to the measurement uncertainty, $U(V_\text{p})$, in reservoir volume, V_p, is derived by analytical solution using partial differentials of the equation.

a) The prismoidal formula (9) can be used for the computation of volume between two areas A_i and A_{i+1} separated by a distance, y_i, which can be used to get the total volume by summation over the n numbers of cross sections, as:

$$V_\text{p} = \sum_{i=1}^{i=n-1}\left(\frac{1}{3} y_i\left(A_i + A_{i+1} + \sqrt{A_i A_{i+1}}\right)\right) = C_1 + C_2 + C_3 \tag{23}$$

The equation has been represented by three terms C_1, C_2 and C_3, which are functions of A_i, A_{i+1} and y_i. The A_i is the i^th cross-sectional area, A_{i+1} is the $(i+1)^\text{th}$ cross-sectional area and y_i is the distance between the i^th and $(i+1)^\text{th}$ cross sections. The effect on the value V_p due to small dispersions of Δy_i, ΔA_i and ΔA_{i+1} has three components arising out of these three terms.

$$\left(\frac{u(C_1)}{C_1}\right)^2 = \sum_{i=1}^{i=n-1}\left\{\left[\frac{u(A_i)}{A_i}\right]^2 + \left[\frac{u(y_i)}{y_i}\right]^2\right\} \tag{24}$$

$$\left(\frac{u(C_2)}{C_2}\right)^2 = \sum_{i=1}^{i=n-1}\left\{\left[\frac{u(A_{i+1})}{A_{i+1}}\right]^2 + \left[\frac{u(y_i)}{y_i}\right]^2\right\} \tag{25}$$

$$\left(\frac{u(C_3)}{C_3}\right)^2 = \sum_{i=1}^{i=n-1}\left\{\left[\frac{u(A_i)}{A_i}\right]^2 + \left[\frac{u(A_{i+1})}{A_{i+1}}\right]^2 + \left[\frac{u(y_i)}{y_i}\right]^2\right\} \tag{26}$$

Since the uncertainties of y_i, A_i and A_{i+1} are likely to be independent of each other, probability requires that the three components of Formula (23) be summated in quadrature (see B.7).

$$\left(\frac{u_{\text{c}}(V_{\text{p}})}{V_{\text{p}}}\right)^2 = \left|\frac{1}{V_{\text{p}}}\right|^2 \sum_{i=1}^{i=n-1}\left\{\frac{5}{4}\left[\frac{u(A_i)}{A_i}\right]^2 + \frac{5}{4}\left[\frac{u(A_{i+1})}{A_{i+1}}\right]^2 + 3\left[\frac{u(y_i)}{y_i}\right]^2\right\} \tag{27}$$

The values $\frac{u_{\text{c}}(V_{\text{p}})}{V_{\text{p}}}, \frac{u(A_i)}{A_i}, \frac{u(A_{i+1})}{A_{i+1}}$ and $\frac{u(y_i)}{y_i}$ are referred to as dimensionless standard uncertainties and are given notations $u_{\text{c}}^*(V_{\text{p}})$, $u_{\text{c}}^*(V_{\text{p}}), u^*(A_i), u^*(A_{i+1})$ and $u^*(y_i)$.

Thus,

$$u_{\text{c}}^*(V_{\text{p}}) \cong \left|\frac{1}{V_{\text{p}}}\right| \sqrt{\sum_{i=1}^{i=n-1}\left\{\frac{5}{4}u^*(A_i)^2 + \frac{5}{4}u^*(A_{i+1})^2 + 3u^*(y_i)^2\right\}} \tag{28}$$

As the quantity of sediment in the reservoir is $V_{\text{s}} = V_{\text{p}} - V_{\text{o}}$, the uncertainty components involved in V_{p} and V_{o} are to be combined. If $u_{\text{c}}^*(V_{\text{o}})$ is the dimensionless standard uncertainty in the original volume, then

$$u_{\text{c}}^*(V_{\text{s}}) \cong \left|\frac{1}{V_{\text{s}}}\right| \sqrt{u_{\text{c}}^*(V_p)^2 + u_{\text{c}}^*(V_{\text{o}})^2} \tag{29}$$

b) The trapezoidal formula (10) can be used for the computation of volume between two areas A_i and A_{i+1} separated by a distance, y_i, which can be used to get the total volume by summation over the n numbers of cross sections, as:

$$V_{\text{p}} = \sum_{i=1}^{i=n-1}\left(\frac{1}{2}y_i(A_i + A_{i+1})\right) = C_1 + C_2 \tag{30}$$

where

C_1 and C_2	are functions of A_i, A_{i+1} and y_i;
A_i	is the i^{th} cross-sectional area;
A_{i+1}	is the $(i+1)^{\text{th}}$ cross-sectional area;
y_i	is the distance between the i^{th} and $(i+1)^{\text{th}}$ cross sections.

Due to small dispersions of Δy_i, ΔA_i and ΔA_{i+1}, the value V_{p} has two components.

$$\left(\frac{u(C_1)}{C_1}\right)^2 = \sum_{i=1}^{i=n-1}\left\{\left[\frac{u(A_i)}{A_i}\right]^2 + \left[\frac{u(y_i)}{y_i}\right]^2\right\} \tag{31}$$

$$\left(\frac{u(C_2)}{C_2}\right)^2 = \sum_{i=1}^{i=n-1}\left\{\left[\frac{u(A_{i+1})}{A_{i+1}}\right]^2 + \left[\frac{u(y_i)}{y_i}\right]^2\right\} \tag{32}$$

Since the uncertainties of y_i, A_i and A_{i+1} are likely to be independent of each other, probability requires that the two components of Formula (30) be summated in quadrature (see B.7).

$$\left(\frac{u_{\text{c}}\left(V_{\text{p}}\right)}{V_{\text{p}}}\right)^2 = \left|\frac{1}{V_{\text{p}}}\right|^2 \sum_{i=1}^{i=n-1} \left\{\left[\frac{u\left(A_i\right)}{A_i}\right]^2 + \left[\frac{u\left(A_{i+1}\right)}{A_{i+1}}\right]^2 + 2\left[\frac{u\left(y_i\right)}{y_i}\right]^2\right\} \tag{33}$$

The values $\frac{u_{\text{c}}\left(V_{\text{p}}\right)}{V_{\text{p}}}, \frac{u\left(A_i\right)}{A_i}, \frac{u\left(A_{i+1}\right)}{A_{i+1}}$, and $\frac{u\left(y_i\right)}{y_i}$ are referred to as dimensionless standard uncertainties and are given the notation $u_{\text{c}}^*\left(V_{\text{p}}\right)$, $u^*\left(A_i\right)$, $u^*\left(A_{i+1}\right)$ and $u^*\left(y_i\right)$ Thus,

$$u_{\text{c}}^*\left(V_{\text{p}}\right) \cong \left|\frac{1}{V_{\text{p}}}\right| \sqrt{\sum_{i=1}^{i=n-1} \left\{u^*\left(A_i\right)^2 + u^*\left(A_{i+1}\right)^2 + 2u^*\left(y_i\right)^2\right\}} \tag{34}$$

As the quantity of sediment in the reservoir is $V_{\text{s}} = V_{\text{p}} - V_{\text{o}}$; the uncertainty components involved in V_{p} and V_{o} are to be combined. If $u_{\text{c}}^*\left(V_{\text{o}}\right)$ is the dimensionless standard uncertainty in the original volume, then

$$u_{\text{c}}^*\left(V_{\text{s}}\right) \cong \left|\frac{1}{V_{\text{s}}}\right| \sqrt{u_{\text{c}}^*\left(V_{\text{p}}\right)^2 + u_{\text{c}}^*\left(V_{\text{o}}\right)^2} \tag{35}$$

Annex A
(informative)

Optimization of the arrangement of ranges

A.1 Layout of cross sections

Prior to the impoundment of a reservoir, it is necessary to have an accurate map on a relatively large scale for reservoir sites and upstream areas where sediment deposition may occur.

Before a reservoir is filled, the proper location is made for a sufficient number of cross sections such that subsequent soundings on the same sections will furnish the necessary data for computation of sediment volume. The sections should first be marked on a paper, in order to get a comprehensive idea as to how the sections should lie with reference to each other and the reservoir as a whole. The alignment of sections may need some modification at site depending on topography, etc.

For existing reservoirs, the location of cross sections is also to be marked on a map of the reservoir area. To finalize the alignment of the cross sections, it is necessary to identify the original river channel. The original river channel and topography of the reservoir area can be obtained by referring to topographic maps of the area prior to the impoundment of the reservoir.

A.2 Cross-sectional/range-line monuments

The ends of the proposed cross-sectional lines should be marked in the field with a permanent type of monument. The monument may be made of concrete or masonry. To properly reference the range monuments, a network of triangles should be established with reference to an accurate base line preferably taking the base line on the dam itself. Establishment of benchmarks along the periphery of the reservoir at suitable intervals will also be necessary for establishing vertical controls, whenever and wherever necessary. All triangulation stations, benchmark pillars and range monuments should be properly indicated so that they may be identified easily. Some of the permanent objects on the shore should also be properly located so that they can be useful for horizontal control during the actual sounding work. All the range monuments may be properly numbered preferably starting from the dam. The correct location of cross-sectional lines on a contour map is necessary for obtaining the original capacity between the cross sections.

While fixing the cross-sectional lines, the following aspects need careful consideration.

a) The ends of the cross sections should be “monumented” in the field, so that these range monuments are traceable during subsequent surveys.

b) Range monuments are to be fixed above the maximum water level.

c) Range monuments should not be located on the point of a short hill or abrupt change in reservoir section, since the elevation of the ground may show a variation within a relatively short distance away from the central line of the range.

d) Close spacing of cross sections is preferable in the upper and shallower reaches than in the lower and deeper reaches.

e) If the reservoir is subject to heavy drawdown, the reaches between the drawdown level to the maximum water level should be more closely spaced.

f) The location of the tributaries with its sediment characteristics is to be ascertained; therefore, this area may necessitate close ranging.

g) A ground survey above the water level along these cross sections is essential.

h) It is preferable that the cross sections be parallel, but this need not be very rigid.

i) If it is found not practicable to lay out the ranges parallel to one another, a divergence of 10° between the ranges may be permitted for the convenience of location, but no more than 30° may be permitted.

j) Sometimes, the presence of bends or curves in the river makes it impracticable to rigidly adhere to the divergence limit set. In such cases, the stretch should be divided into short reaches where the limits of divergence are maintained in each reach. In the segments between the reaches, the reaches may have any divergence not greater than 90°. In these segments, the end ranges may be set very close to one another, or starting from a common point with a view to concentrate the irregularity into the smallest area, so that it will have the least effect.

k) If the reservoir has an embayment on the tributary joining the main river, this portion should be separately ranged and the ranges may have different orientation from the main ranges.

l) The range should cover the mouth of the tributaries joining the main river.

m) Where a tributary enters, or an arm of the lake is cut off, a new series of ranges may be started without any regard to the direction of the main ranges. The first range should be across the mouth of the tributary and nearly perpendicular to its general direction.

A.3 Base survey of cross sections

After the range monuments have been located in the field, a base profile (i.e. the cross section and longitudinal section) is necessary for future comparison, at appropriate intervals, of re-surveys. This may be done either by a topographic survey before filling the reservoir, or by means of echo sounding immediately after filling. It is recommended that in reservoirs where the sides of the valley are steep and water depth is deep, an accurate profile be taken by surveying along the reach before filling the reservoir. In reservoirs located in terrain where the topography is not steep, the water depth is shallow and the width is large, the profile along the range could also be determined by sounding immediately after the reservoir is filled. However, to supplement the soundings along the range, a land survey above the water level will be necessary.

A.4 Arrangement of ranges at reasonable intervals

A.4.1 General

A sedimentation survey for a reservoir should extend at least to several ranges upstream of the end of the backwater deposits. If the distance between the end of the backwater deposits and the hydrometric station used as an inflow sediment-measuring station is large, a number of ranges should be set up. The river bed in such a reach undergoes changes through self-adjustment of the alluvial channel. From measurements performed on these ranges, data may be obtained to verify the water surface profile or to aid in the evaluation of sediment balance. For a river reach, ranges should be arranged to reasonably cover all the bends and transition regions, pools and riffles, wide and narrow parts, etc.

The number of ranges considered “reasonable” implies a minimum number of ranges established in a river reach or reservoir which could reflect the essential pattern and distribution of sedimentation, both longitudinally and transversely, and yet with no sacrifice of desired accuracy in the computation of the total volume of sedimentation. As a general rule, it is recommended to keep the difference in the volume of sedimentation computed by the range method and by the topographic method within a limit of ±5 %. Two procedures are used (see A.4.2 and A.4.3).

A.4.2 First method

On the preliminary topographic map with a scale of 1:10 000, ranges spaced at an equal distance (for example 200 m) are drawn approximately perpendicular to the contours below the elevation of normal high water. The capacity or volume at the normal high-water level is calculated by the cross sectional (range-line) method and compared with the volume calculated from the topographic map by perimetering or other methods. Computations are then made using fewer ranges, so as to select one out of two ranges, one out of three ranges, etc. The simplification or reduction of ranges should proceed until the relative error for computation of the capacity or volume is still within the tolerance limit of ±5 %, using the volume computed by the topographic method as a reference. For instance, if the volume at a certain elevation enclosed by cross sections 1 and 3, and computed by the topographic method, is V_d , then the volume computed by the trapezoidal formula is:

$$V_d = \frac{1}{2}\Delta h\left(A_1 + 2A_2 + A_3\right) \tag{A.1}$$

where

V_d	is the trapezoidal volume, in m^3;
Δh	is the difference in elevation between contours, in m;
A_1, A_2, A_3	are areas enclosed by three different contours, in m^2.

The volume as computed by the range method should be:

$$V_{du} = \frac{1}{2}\left[L_1 w_1 + \left(L_1 + L_2\right) w_2 + L_2 w_3\right] \tag{A.2}$$

where

V_{du}	is the range method volume, in m^3;
L_1, L_2	are distances between ranges, in m;
w_1, w_2, w_3	are cross-sectional areas at a certain elevation, in m^2.

Assuming L_1, L_2 are equal, the above formula may be written as:

$$V_{du} = \frac{1}{2} \cdot L_\mathrm{r} \cdot (w_1 + 2w_2 + w_3) \tag{A.3}$$

where L_r is the optimum distance between ranges in metres.

For a reach or a reservoir, similar computations may be made with a number of ranges. The procedure is repeated several times by using a simplified number of ranges until the error of the computed volume exceeds the tolerance limits of ± 5 %, or

$$100\frac{V_d - V_{du}}{V_d} < \pm 5\ \% \tag{A.4}$$

L_r is claimed to be the optimum distance for laying out ranges (Li Zhaonan, 1980).

A.4.3 Second method

Hakanson (1978) has studied the optimum arrangement of ranges in a lake survey. The optimum number of ranges may be computed from the following formula, established by using data obtained from four large reservoirs in China (Sanmenxia Reservoir Experiment Station, 1980):

$$L_\mathrm{r} = \frac{A}{L_i F^{1/3}} \tag{A.5}$$

where

A	represents the area enclosed by the highest contour line, in km^2;

L_i is the accumulative distance between ranges, in km;

$F = L_¿ / 2(\pi A)^{1/2}$ where $L_¿$ is the length of the highest contour line, measured in km.

Based on reservoir data studies, it was found that range spacing according to the above formula will result in surveys with a fair degree of accuracy. If the range intervals are properly arranged, the accuracy in computing deposition by the range method is within 5 % of that determined by the topographic method.

The range method is based on the summation of volume segments or prisms, bounded by successive cross sections, and on the assumption of straight-line proportions along the shoreline between the cross sections. Geographical Information Systems (GIS) employ a Triangulated Irregular Network (TIN) to compute volumes. The TIN is a series of adjacent, non-overlapping triangles that define an accurate model of the bottom topography of a lake or other surface terrain.

Because the TIN method can depict a natural surface and the undulating land patterns common to most terrains, volume estimates computed using the TIN method are likely to be more accurate.

Annex B
(informative)

Introduction to measurement uncertainty

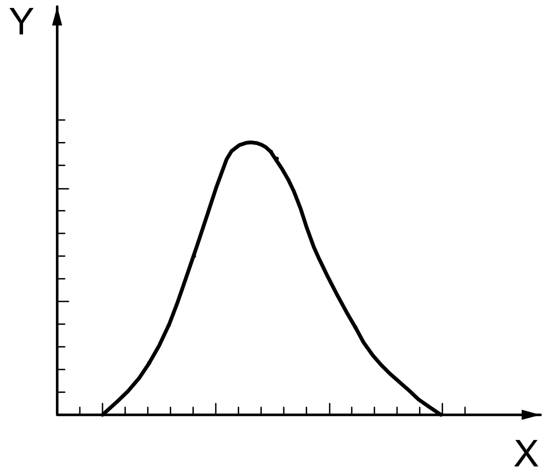
B.1 General

Results of measurements or analysis cannot be exact. The discrepancy between the true value – which is unknowable – and the measured value is the measurement error. The concept of uncertainty is a way of expressing this lack of knowledge. For example, if water is controlled to flow at a constant rate, then a flow meter will exhibit a spread of measurements about a mean value. If attention is not given to the uncertain nature of data, incorrect decisions can be made which may have financial or judicial consequences. A realistic statement of uncertainty enhances the information, making it more useful.

The uncertainty of a measurement represents a dispersion of values that could be attributed to it. Statistical methods provide objective values based on the application of theory. Standard uncertainty is defined as:

> "Standard uncertainty equates to a dispersion of measurements expressed as a standard deviation."

From this definition, uncertainty can be readily calculated for a set of measurements.

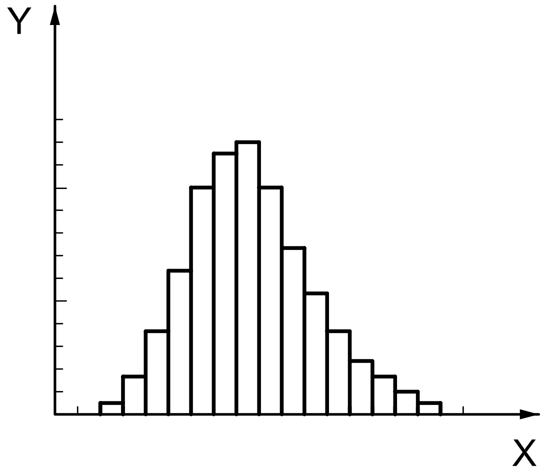


a)

Key

X flow value

Y probability

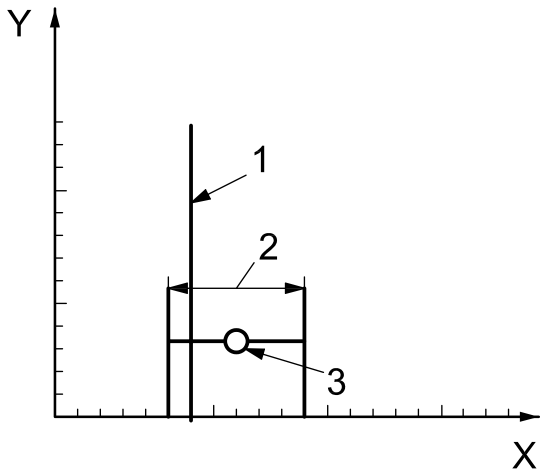


b)

Key

X flow value

Y number of samples



c)

Key

1 limit

2 standard deviation

3 mean value

X flow value

Y number of samples

Figure B.1 — Pictorial representation of some uncertainty parameters

Figure B.1(a) shows the probability that a measurement of flow under steady conditions takes a particular value due to the uncertainties of various components of the measurement process, in the form of a probability density function.

Figure B.1(b) shows sampled flow measurements, in the form of a histogram.

Figure B.1(c) shows standard deviation of the sampled measurements compared with a limiting value. The mean value is shown to exceed the limiting value, but is within the band of uncertainty (expressed as the standard deviation about the mean value).

B.2 Confidence limits and coverage factors

For a normal probability distribution, analysis shows that 68 % of a large set of measurements lie within one standard deviation of the mean value. Thus, standard uncertainty is said to have a 68 % level of confidence.

However, for some measurement results, it is customary to express the uncertainty at a level of confidence which will cover a larger portion of the measurements, for example, at a 95 % level of confidence (see Figure B.4). This is done by applying a factor, known as the coverage factor, k, to the computed value of standard uncertainty.

For a normal probability distribution, 95,45 % (effectively 95 %) of the measurements are covered for a value of $k = 2$. Thus, uncertainty at the 95 % level of confidence is twice the standard uncertainty value.

In practice, measurement variances rarely follow closely the normal probability distribution. They may be better represented by triangular, rectangular or bimodal probability distributions and only sometimes approximate to the normal distribution. So, a probability distribution must be selected to model the observed variances. To express the uncertainty of such models at the 95 % confidence limit requires a coverage factor that represents 95 % of the observations. However, the same coverage factor, $k = 2$, is used for all models. This simplifies the procedure while ensuring consistency of application within tolerable limits.

B.3 Random and systematic error

The terms random and systematic have been applied in hydrometric standards to distinguish between

— random errors, that represent an inherent dispersion of values under steady conditions, and

— systematic errors, that are associated with inherent limitations of the means of determining the measured quantity.

A difficulty with the concept of systematic error is that it cannot be determined without pre-knowledge of true values. If its existence is known or suspected, then steps shall be taken to minimize such error, either by recalibration of equipment or by reversing its effect in the calculation procedure – at which point, systematic error contributes to uncertainty in the same way as random components of uncertainty.

For this reason, ISO/TS 25377 does not distinguish between the treatment of random and systematic uncertainties. Generally, when determining a single discharge, random errors dominate and there is no need to separate random and systematic errors. However, where (say) totalized volume is established over a long time base, the systematic errors, even when reduced, can remain dominant in the estimation of uncertainty.

B.4 Measurement standards

ISO/TS 25377 and ISO 5168 provide rules for the application of the principles of measurement uncertainty, in particular on the identification of components of error, the quantification of their corresponding uncertainties and how these are combined using methods derived from statistical theory into an overall result for the measurement process.

The components of uncertainty are characterized by estimates of standard deviations. There are two methods of estimation.

Type-A estimation:

— This is done by statistical analysis of repeated measurements from which an equivalent standard deviation is derived. This process may be automated in real time for depth or for velocity measurement.

Type-B estimation:

— This is done by ascribing a probability distribution to the measurement process. This is applicable to:

  i) human judgment of a manual measurement (distance or weight);

  ii) manual readings taken from instrumentation (manufacturer's statement); or

iii) calibration data (from manufacturer).

B.5 Evaluation of Type-A uncertainty

As defined in B.1, the term ‘standard uncertainty’ equates to a dispersion of measurements expressed as a standard deviation. Thus, any single measurement of a set of n measurements has by definition an uncertainty:

$$u(x) = t_c \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{B.1}$$

where $\bar{x}$ the “best estimate”, is the mean value:

$$\bar{x} = \frac{1}{n}\left(x_1 + x_2 + ...x_n\right) \tag{B.2}$$

and t_c is a factor derived from statistical theory to account for the increased uncertainty when small numbers of measurements are available (Table B.1).

If, instead of a single measurement from the set, the uncertainty is to apply to the mean of all n values, then

$$u(\bar{x}) = \frac{t_c}{\sqrt{n}}\sqrt{\left(\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right)} \tag{B.3}$$

For continuous measurement, Type-A evaluations may be derived as a continuous variable from the primary measurement, i.e. from water level or water velocity.

By taking average values over large numbers, n, of measurements, the uncertainty of the mean value $u(\bar{x})$ is reduced by a factor of $\frac{1}{\sqrt{n}}$ compared to the uncertainty $u(x)$ of an individual measurement. For this reason, monitoring equipment should specify measurement performance in terms including both $u(\bar{x})$ and $u(x)$ to show the extent to which averaging is applied.

Table B.1 — Values of t_c

Degree of freedom	Confidence level %		
	90	95	99
1	6,31	12,71	63, 66
2	2,92	4,30	9,92
3	2,35	3,18	5,84
4	2,13	2,78	4,60
5	2,02	2,57	4,03
10	1,81	2,23	3,17
15	1,75	2,13	2,95
20	1,72	2,09	2,85
25	1,71	2,06	2,79
30	1,70	2,04	2,75
40	1,68	2,02	2,70
60	1,67	2,00	2,66
100	1,66	1,98	2,63
Infinite	1,64	1,96	2,58

B.6 Evaluation of Type-B uncertainty

B.6.1 General

When there is no access to a continuous stream of measured data or a large set of measurements is not available, then the type-B method of estimation is used:

i) assign a probability distribution to the measurement process to represent the probability of the true value being represented by any single measured value;

ii) define upper and lower bounds of the measurement; and then

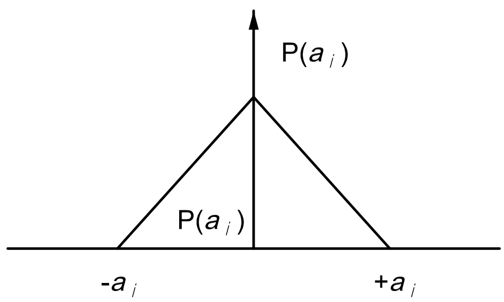
iii) determine a standard uncertainty from a standard deviation implied by the assigned probability distribution.

The Type-B methods allow estimates of upper and lower bounding values to be used to derive the equivalent standard deviation.

Four probability distributions are described in ISO/TS 25377 and these are described in B.6.2 to B.6.5.

B.6.2 The triangular distribution

The triangular distribution is represented in Figure B.2. This usually applies to manual measurements where the mean value is most likely to be closer to the true value than others between the discernible upper and lower limits of the measurement.

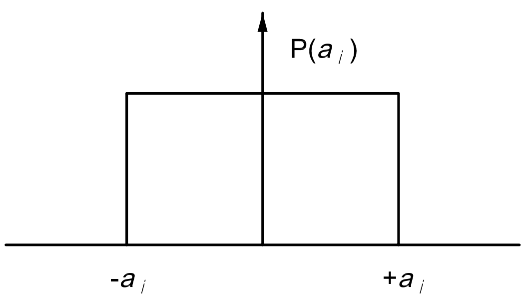


$$u\left(x_{\text{mean}}\right) = \frac{1}{\sqrt{6}}\left(\frac{x_{\text{max}} - x_{\text{min}}}{2}\right)$$

Figure B.2 — Triangular distribution

B.6.3 The rectangular distribution

The rectangular distribution is represented in Figure B.3. This probability distribution is usually applied to the resolution limit of the measurement instrumentation (i.e. the displayed resolution or the resolution of internal analogue/digital converters). However, this is not the only source of uncertainty of measurement equipment. There may be uncertainty arising from the measurement algorithm used and/or from the calibration process. If the equipment measures relative values, then there will also be uncertainty in the determination of its datum.

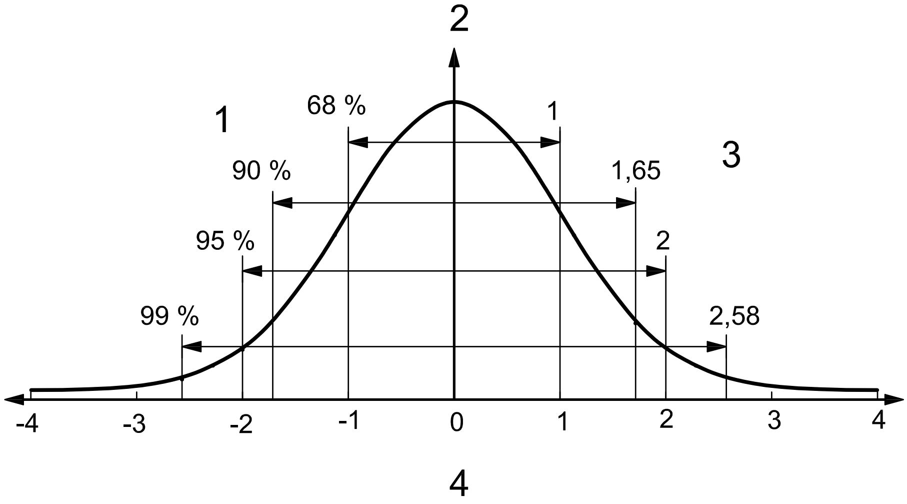


$$u\left(x_{\text{mean}}\right)=\frac{1}{\sqrt{3}}\left(\frac{x_{\max}-x_{\min}}{2}\right)$$

Figure B.3 — Rectangular distribution

B.6.4 The normal (Gaussian) probability distribution

The normal (or Gaussian) probability distribution is represented in Figure B.4.



Key

1 percent of readings in bandwidth

2 probability

3 coverage factor

4 standard deviations

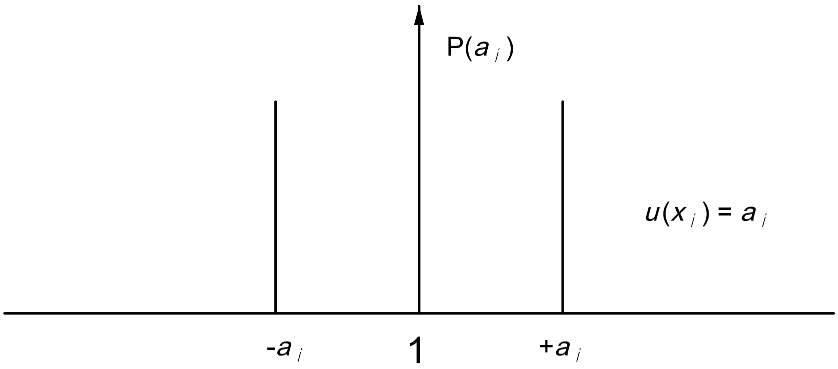
$u\left(x_{\text{mean}}\right)=\frac{u\left(\text{specified}\right)}{k}$ where k is the coverage factor applying to the specified uncertainty value.

Figure B.4 —Normal probability distribution

These are uncertainty statements based on “off-line” statistical analysis, usually as part of a calibration process where they have been derived using a Type-A process. When expressed as standard uncertainty, the uncertainty value is to be used directly with an equivalent coverage factor of $k = 1$.

B.6.5 The bimodal probability distribution

The bimodal probability distribution is represented in Figure B.5. Measurement equipment with hysteresis can only exhibit values at the upper and lowers bounds of the measurement. An example of this is the float mechanism, where friction and surface tension combine to cause the float to move in finite steps.



Key
1 $P(a_i)$

$$u(x_{\text{mean}}) = \frac{x_{\text{max}} - x_{\text{min}}}{2}$$

Figure B.5 — Bimodal probability distribution

B.7 Combined uncertainty value, u_c

For most measurement systems, a measurement result is derived from several variables. For example, capacity measurement, V_p, of a reservoir can be expressed as a function of independent variables given by prismoidal formula and has three terms:

$$V_p = \sum_{i=1}^{i=n-1} \left(\frac{1}{3} y_i \left(A_i + A_{i+1} + \sqrt{A_i A_{i+1}} \right) \right) = C_1 + C_2 + C_3 \tag{B.4}$$

where y_i is the distance between the two areas A_i and A_{i+1}.

$$C_1 = \sum_{i=1}^{i=n-1} \left(\frac{1}{3} A_i y_i \right) \tag{B.5}$$

$$C_2 = \sum_{i=1}^{i=n-1} \left(\frac{1}{3} A_{i+1} y_i \right) \tag{B.6}$$

$$C_3 = \sum_{i=1}^{i=n-1} \left(\frac{1}{3} y_i \sqrt{A_i A_{i+1}} \right) \tag{B.7}$$

Following ISO/TS 25377:2007, the uncertainty values of C_1, C_2 and C_3 can be derived as

$$\left(u_c(C_1) \right)^2 = \sum_{i=1}^{i=n-1} \left(\frac{\partial C_1}{\partial A_i} u(A_i) \right)^2 + \left(\frac{\partial C_1}{\partial y_i} u(y_i) \right)^2$$

So

$$\left(\frac{u_c(C_1)}{C_1} \right)^2 = \left| \frac{1}{\sum_{i=1}^{i=n-1} \left(\frac{1}{3} A_i y_i \right)} \right| \sum_{i=1}^{i=n-1} \left(\left(\frac{\partial C_1}{\partial A_i} u(A_i) \right)^2 + \left(\frac{\partial C_1}{\partial y_i} u(y_i) \right)^2 \right) \text{ or}$$

$$\frac{u_{\mathrm{c}}\left(C_1\right)}{C_1} = \sum_{i=1}^{i=n-1} \sqrt{\left(\frac{u\left(A_i\right)}{A_i}\right)^2 + \left(\frac{u\left(y_i\right)}{y_i}\right)^2} \tag{B.8}$$

Similarly,

$$\frac{u_{\mathrm{c}}\left(C_2\right)}{C_2} = \sum_{i=1}^{i=n-1} \sqrt{\left(\frac{u\left(A_{i+1}\right)}{\mathrm{A}_{\mathrm{i+1}}}\right)^2 + \left(\frac{u\left(y_i\right)}{y_i}\right)^2} \tag{B.9}$$

$$\frac{u_{\mathrm{c}}\left(C_3\right)}{C_3} = \sum_{i=1}^{i=n-1} \sqrt{\left(\frac{u\left(A_i\right)}{2A_i}\right)^2 + \left(\frac{u\left(A_{i+1}\right)}{A_{i+1}}\right)^2 + \left(\frac{u\left(y_i\right)}{y_i}\right)^2} \tag{B.10}$$

Combining the three uncertainty values derived above [Formulae (B.8), (B.9) and (B.10)], the combined uncertainty value for reservoir capacity can be derived as presented in Formula (B.11).

$$\frac{u_{\mathrm{c}}\left(V_{\mathrm{p}}\right)}{V_{\mathrm{p}}} = \left|\frac{1}{V_{\mathrm{p}}}\right| \sum_{i=1}^{i=n-1} \left\{ \sqrt{\frac{5}{4}\left[\frac{u\left(A_1\right)}{A_1}\right]^2 + \frac{5}{4}\left[\frac{u\left(A_2\right)}{A_2}\right]^2 + 3\left[\frac{u\left(y\right)}{y}\right]^2} \right\} \tag{B.11}$$

Similarly the combined uncertainty formula (B.12) could be derived for trapezoidal equation with two terms.

$$\frac{u_{\mathrm{c}}\left(V_{\mathrm{p}}\right)}{V_{\mathrm{p}}} = \left|\frac{1}{V_{\mathrm{p}}}\right| \sum_{i=1}^{i=n-1} \left\{ \sqrt{\left[\frac{u\left(A_1\right)}{A_1}\right]^2 + \left[\frac{u\left(A_2\right)}{A_2}\right]^2 + 2\left[\frac{u\left(y\right)}{y}\right]^2} \right\} \tag{B.12}$$

Bibliography

[1] ISO 748, *Hydrometry — Measurement of liquid flow in open channels — using current-meters or floats*

[2] ISO 1100-1, *Hydrometry — Measurement of liquid flow in open channels — Part 1: Guidelines for selection, establishment and operation of a gauging station*

[3] ISO/TS 3716, *Hydrometry — Functional requirements and characteristics of suspended sediment samplers*

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

[5] ISO 4364, *Measurement of liquid flow in open channels — Bed material sampling*

[6] ISO 4365, *Liquid flow in open channels — Sediment in streams and canals — Determination of concentration, particle size distribution and relative density*

[7] ISO 4366, *Hydrometry — Echo sounders for water depth measurements*

[8] ISO 5168, *Measurement of fluid flow — Procedures for the evaluation of uncertainties*

[9] ISO 9195, *Liquid flow measurement in open channels — Sampling and analysis of gravel-bed material*

[10] ISO/TR 9212, *Hydrometry — Measurement of liquid flow in open channels — Methods of measurement of bedload discharge*

[11] ISO 9555 (all parts), *Measurement of liquid flow in open channels — Tracer dilution methods for the measurement of steady flow*

[12] ISO/TR 11330, *Determination of volume of water and water level in lakes and reservoirs*

[13] ISO 11657[1)], *Liquid flow in open channels — Sediment in streams and canals — Determination of concentration by surrogate techniques*

[14] ISO/TS 25377:2007, *Hydrometric uncertainty guidance (HUG)*

[15] DAVIS B.E. A guide to the proper selection and use of federally approved sediment and water-quality samplers: U.S. Geological Open-File Report 2005-1087, 20 p. (http://pubs.usgs.gov/of/2005/1087/)

[16] DIPLAS P., KUHNLE R., GRAY J.R., GLYSSON G.D., and EDWARDS T.K., 2008, Sediment transport measurements, *in* Marcelo Garcia, ed., Sedimentation Engineering – Processes, Measurements, Modeling, and Practice, American Society of Civil Engineers Manual 110, Chapter 5, pp. 307-353

[17] EDWARDS T.K., GLYSSON G.D. 1999, Field methods for measurement of fluvial sediment. U.S. Geological Survey Techniques of Water-Resources Investigations Book 3, Chapter. C2, 89 p.; (http://water.usgs.gov/osw/techniques/sedimentpubs.html)

[18] GRAY J.R., SIMÕES F.J.M. Estimating sediment discharge. In: *Sedimentation Engineering – Processes, Measurements, Modeling, and Practice, American Society of Civil Engineers Manual 110, Appendix D*, (GARCIA M., ed.). 2008, pp. 1067–88

[19] GRAY J.R., GARTNER J.W. 2009, Technological advances in suspended-sediment surrogate monitoring: Invited Paper, Water Resources Research, Vo. 45, W00D29, doi:10.1029/2008WR007063, 20 p., http://water.usgs.gov/osw/techniques/2008WR007063.pdf.GRAY J. R., GARTNER J. W. 2010a, Surrogate technologies for monitoring suspended-sediment transport in rivers, in, Poleto, Cristiano, and Charlesworth, Susanne, eds., Sedimentology of Aqueous Solutions, London: Wiley-Blackwell, Chapter 1, pp. 3-45, http://water.usgs.gov/osw/techniques/sed_aq_sys_chap_1_pdf_from_wb_3_16_2010.pdf.

1) Under development.

[20] GRAY J. R., GARTNER J.W. 2010b, Surrogate technologies for monitoring bed-load transport in rivers, in, Poleto, Cristiano, and Charlesworth, Susanne, eds., Sedimentology of Aqueous Solutions, London: Wiley-Blackwell, Chapter 2, pp. 45-79, http://water.usgs.gov/osw/techniques/sed_aq_sys_chap_1_pdf_from_wb_3_16_2010.pdf

[21] NOLAN K.M., GRAY J.R., GLYSSON G. D. (2005). Introduction to suspended-sediment sampling: U.S. Geological Survey Scientific Investigations Report 2005-5077, available on CD-ROM and at: http://pubs.er.usgs.gov/pubs/sir/sir20055077

[22] PORTERFIELD G. 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, 3, C3, 66 p., http://pubs.usgs.gov/twri/twri3-c3/

[23] RASMUSSEN P. P., GRAY J. R., GLYSSON G. D., ZIEGLER A. C. 2009, Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data: U.S. Geological Survey Techniques and Methods book 3, chap. C4, 53 p. http://pubs.usgs.gov/tm/tm3c4/

[24] Sur l'exactitude de la représentation des profils du fond de la mer avec les sondeurs ultrasonores à haute fréquence. P. KELLER, F SCHULER DEUTSCHE HYDROGRAPHISCHE ZEISCHIFT, 1951, vol 4 cahier 3

[25] WMO. *Measurement of river sediments*. WMO no. 561, Operational Hydrology report no. 16, 1981

[26] KELLER, P, BOUCHARD, J.P. Étude bibliographique de l'alluvionnement des retenues par les sédiments fins: mécanismes physiques et moyens de lutte. EDF DER Rapport E4383-26-Juillet 1983

[27] Sédimentation dans les retenues hydroélectriques et vidanges. JP LEPETITEDF-DER-Rapport HE/30 85-04 1985

[28] Méthode de calcul de la sédimentation dans les réservoirs. Contribution au programme hydraulique International PH- II Project. Rapporteur: S. Bruk A2.6.1. Panel UNESCO Janvier 1986

[29] Sediments budgets IAHS Publication no. 174 Bordas, M and Walling, D (Eds.) (1988)

[30] WMO. Manual on operational methods for the measurement of sediment transport. Long Yuqian WMO Optional Hydrology Report no. 29, 1989

[31] Maîtrise de l'alluvionnement des retenues. Recommandations. Stigter *et al* Bulletin no. 67 du CIGB JCOLD 1989

[32] Hydrographie et Bathymetrie. M le Gouic. 1er congrès International de l'Association Française de topographie, 1990

[33] Un demi-siècle d'études théoriques & expérimentales sur les transports de sédiments. M. Bouvard, P. Lefort SHF Actes du colloque "Transports solides en eaux continentale et littorale". Paris Nov 93

[34] HÅKANSON L. Optimization of lake hydrographic surveys. *Water Resour. Res.*, **14**, 1978, pp. 545–560

[35] International Hydrographic Organization (IHO), May 2005, Publication C-13, *Manual on Hydrography*, (corrections to April 2010), Published by International Hydrographic Bureau, Monaco

[36] JIHN-SUNG lai, 1998, *Sediment Deposition and Desilting Operation in Tapu Reservoir, Case Studies: Rivers*. Parallel Session (*parallel34*), 01.09.1998, 16:00 - 18:15 file:///D|/user/Lehfeldt/ICHE/1998-Cottbus/Document/Cas.Rivers.166.paper.html (3 von 3) [19.11.02 14:13:41]

[37] MORRIS G.L., FAN J. *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for sustainable use.* McGraw-Hill Book Company, New York, 1997, 758 p.

[38] MURTHY B.N. *Capacity Survey of Storage Reservoirs, Publication No.89*. Central Board of Irrigation and Power, New Delhi, India, Revised Edition 1995

[39] Sanmenxia Reservoir Experiment Station, 1980: *Optimistic Density of Ranges for Sedimentation Survey*

[40] Survey Manual – 2002 Rev. 2006, Section VI, Photogrammetric Surveys, page VI-1 to VI-24 [online database], [viewed 2012-05-19], Available from http://www.dot.state.wy.us/files/content/sites/wydot/files/shared/Highway_Development/Surveys/Survey%20Manual/Section%20VI%20-%20Photogrammetric%20Surveys.pdf

[41] SLOFF C.J. Modelling reservoir sedimentation processes for sediment management studies. *Proc. conf. Hydropower into the next century.* Portoroz, Slovenia, 15-17 Sept., 1997, pp. 513–524 [Aqua Media Int., UK.]

[42] U.S. ARMY CORPS OF ENGINEERS. (USACE), 2004. *Engineering and Design – Hydrographic Surveying,* EM 1110-2- 1003,Department of Army, Washington DC, www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2- 1003/toc.htm

[43] U.S. ARMY CORPS OF ENGINEERS. (USACE), 1995. *Engineering and Design – Sedimentation Investigations of Rivers and reservoirs,* EM 1110-2- 4000, Department of Army, Washington DC.

[44] U.S. ARMY CORPS OF ENGINEERS. (USACE), 2002. *Engineering and Design – Photogrammetric Mapping,* EM 1110-2- 1000, Department of Army, Washington DC

[45] U.S. ARMY CORPS OF ENGINEERS. (USACE), 2003. *Engineering and Design – Remote sensing,* EM 1110-2- 2907, Department of Army, Washington DC

[46] U.S. Department of the Interior Bureau of Reclamation, November 2006. *Erosion and Sedimentation Manual*

[47] Yanjing Zhang, Chunhong Hu, and Yangui Wang, “1-D Mathematical Model for Heavily sediment laden rivers and its applications”, US-China Workshop on Advanced Computational Modelling in Hydroscience & Engineering, September 19-21, Oxford, Mississippi, USA

[48] XIAOQING Y. Manual on Sediment Management and Measurement, World Meteorological Organization, Operational Hydrology Report No. 47, WMO-No. 948, Secretariat of the World Meteorological Organization – Geneva – Switzerland, 2003

[49] ZHANG QISHUN and LONG YUQIAN. Sediment problems of Sanmenxia Reservoir. In: *Proceedings of the International Symposium on River Sedimentation, Beijing, China,* 1980, pp. 707-716

ICS 17.120.20

Price based on 42 pages

This page deliberately left blank

British Standards Institution (BSI)

BSI is the independent national body responsible for preparing British Standards and other standards-related publications, information and services. It presents the UK view on standards in Europe and at the international level.

BSI is incorporated by Royal Charter. British Standards and other standardisation products are published by BSI Standards Limited.

Revisions

British Standards and PASs are periodically updated by amendment or revision. Users of British Standards and PASs should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using British Standards would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover. Similary for PASs, please notify BSI Customer Services.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001

BSI offers BSI Subscribing Members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of British Standards and PASs.

Tel: +44 (0)20 8996 7669 Fax: +44 (0)20 8996 7001
Email: plus@bsigroup.com

Buying standards

You may buy PDF and hard copy versions of standards directly using a credit card from the BSI Shop on the website **www.bsigroup.com/shop.** In addition all orders for BSI, international and foreign standards publications can be addressed to BSI Customer Services.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001
Email: orders@bsigroup.com

In response to orders for international standards, BSI will supply the British Standard implementation of the relevant international standard, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Knowledge Centre.

Tel: +44 (0)20 8996 7004 Fax: +44 (0)20 8996 7005
Email: knowledgecentre@bsigroup.com

BSI Subscribing Members are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration.

Tel: +44 (0)20 8996 7002 Fax: +44 (0)20 8996 7001
Email: membership@bsigroup.com

Information regarding online access to British Standards and PASs via British Standards Online can be found at **www.bsigroup.com/BSOL**

Further information about British Standards is available on the BSI website at **www.bsi-group.com/standards**

Copyright

Tel: +44 (0)20 8996 7070
Email: copyright@bsigroup.com

BSI

389 Chiswick High Road London W4 4AL UK

Tel +44 (0)20 8996 9001
Fax +44 (0)20 8996 7001
www.bsigroup.com/standards

raising standards worldwide™