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Hydrometric Field Manual: Levelling

Water Survey of Canada
Environment and Climate Change Canada
qSOP-NA005-05-2023

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Front Cover Photographs
Left: Allison Taylor at Pincher Creek at Front Range Road, AB © Julia Schneider
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Version Control

Version	Date	Source	Description/Rationale for Change
0.0	**1973**		First Edition
1.0	**1984**	2nd edition	Change from imperial to metric system
1.1	**2005**	F. Rainville	Reformatting
3.0	**June 2017**	SAM, FR, JAW, CT	Overhaul of qSOP-NA005-02 to clarify and update requirements
4.0	**May 2019**	SAM	Corrected two incorrect sentences and clarified one diagram.
5.0	**June 2023**	SAM, KOB, GL	- added required naming convention for measuring points - improved requirements for benchmark descriptions to help locating them on site - Changed statement about operating datums, clarified the benefit of only operating in assumed datums - removed requirement for all benchmarks independent of the gauge structure. - improved guidance on total station use

Foreword

The Water Survey of Canada (WSC) is the operational arm of the National Hydrological Service. It is responsible for the collection, interpretation and dissemination of standardized hydrometric data and information in Canada, as the main operator of the National Hydrometric Program for over 115 years.

The Water Survey of Canada is an International Organization for Standardization 9001 certified organization committed to the principle of continuous improvement. Adopting standard procedures for levelling is essential to water level and flow monitoring. We recognize that throughout our program there is diversity with respect to how some procedures are implemented and these differences are the result of geography and historical legacies. We also recognize that important learning can come from different approaches and that there is not a single solution to every challenge. We endeavour to develop standards that prioritize data integrity and usefulness.

This document outlines our field methods for all levelling activities, including the assessment of benchmark stability and gauge stability. This update to *qSOP-NA005-04-2019* is intended to clarify and update some requirements. These procedures replace the previous levelling procedures and will be implemented by WSC moving forward, they will not be retroactively applied.

Many of our employees offered support which enabled the development of this document and its update. We thank the following recent contributors in alphabetical order: Lindsay Armstrong, Amber Brown, Marcena Croizier, Aaron Donahue, Chris Kahler, Theodore Mlynowski, Stephanie Pow, Leigh Sinclair, Melanie Taylor, Julie Thérien and Jerry Yeung. We thank Ismael Foroughi and Mahmoud Abdel-Gelil of Natural Resources Canada for their contributions to the section on total stations, as well as Brian Donahue of Natural Resources Canada for his contributions to the section on RTK-GNSS. We are confident this work will help to unify, stabilize, and modernize the National Hydrometric Program.

R. Wayne Jenkinson
Executive Director, National Hydrological Service
June 2023

Glossary

Backsight (BS): A sight taken on a benchmark or point of known elevation in order to determine the instrument height.

Benchmark (BM): A permanent, fixed reference point of known elevation.

Benchmark History: The record of surveyed elevations of all benchmarks and reference gauges used throughout a station's history.

Closed circuit: A line of levels that ends at the point of origin.

Closure error: The difference between the elevation of the starting point of a closed level circuit and the elevation of that same point from the final instrument setup**.**

Collimation error: The deviation of a level's line of sight from horizontal, often given as a vertical deviation per horizontal distance, such as *x* millimetres per *y* metres.

Data computation system: the software system in which data corrections and validation are conducted (as of the publication of this document, WSC is using Aquatic Informatics Aquarius Time-Series).

Double run leveling: Also known as double-rodded leveling. Leveling of a circuit in which two independent foresights and two independent backsights are obtained on each point to be surveyed.

Differential levelling: The process of measuring the height difference between a point of known elevation and a point of unknown elevation in order to determine the unknown elevation.

Established elevation: The documented elevation of a benchmark or reference gauge. This elevation is the value to which subsequent surveyed elevations are compared.

Foresight (FS): A sight taken on a point for which an elevation is to be determined.

Full tie-in: Levelling of all benchmarks and reference gauges at a gauging station, beginning on the primary benchmark.

Gauge correction (GC): A correction that is applied to recorded water levels to account for vertical movement of the reference gauge.

Gauge height: The height of the water surface above the gauge datum. This term is used interchangeably with stage and water level.

Gauging station: A location where systematic records of stage (and often discharge) are obtained. Synonym of hydrometric station.

Height of Instrument: The elevation of the horizontal line of sight of a surveying instrument.

Intermediate foresight: A foresight obtained using the same instrument setup that was used for a previous objective point.

Level circuit: A line of levels that ends at the point of origin or at another previously established benchmark.

Level check: The procedure followed to determine the vertical movement of a reference gauge with respect to the operating datum.

Levelling rod: A graduated rod used in measuring the vertical distance between the point of interest (e.g. Benchmark or water level) and the height of instrument (see definition above).

Local reference network: The assemblage of benchmarks at a site.

Measuring point: A stable, accessible point (for example on a bridge, pier, or abutment) from which the distance to the water surface may be measured.

Objective point: A point for which the elevation is to be determined. This is the point on which the levelling rod is placed, and the levelling instrument's line of sight is focused.

Operating datum: The surface to which gauge height elevations are referenced. It is sometimes referred to as the gauge datum.

Primary benchmark: The benchmark considered to be the most stable within the local reference network. Also referred to as the holding benchmark.

Reference gauge: A gauge used to reference water level to the operating datum. This includes an electric contact gauge (a.k.a. electric tape gauge), a measuring point, or a benchmark from which direct water level measurements are taken.

Returning point: The objective point that is the last point surveyed on the forward run of a level circuit and the first point surveyed on the return run. It is the turning point that is used to establish a new instrument height from which second elevations of previously shot points are determined.

Rod level: A circular level mounted on an angle bracket which is held against the levelling rod and is used to align the rod in a vertical position.

Sighting: A reading of the levelling rod through the level.

Staff gauge: A graduated plate or rod that is set vertically in a streambed or attached to a solid structure.

Station Analysis: The document describing all interpretive details and decisions that were used in data production at a hydrometric station.

Surveyed elevation: The elevation of a point that is obtained via surveying.

Survey tolerance: The maximum closure error allowed for a given levelling circuit. It depends on the number of instrument setups and the circuit length.

Turning point: A fixed point on which a foresight rod reading is taken, then the instrument is moved, and a backsight rod reading is taken in order to establish a new instrument height.

Levelling SOP Table of Key Points

The following is a table of the main rules and standards found within this document. Some sentences have been shortened for brevity. Context for all items is found within the main body of the text. In this document, the terms **must** and **should** are used intentionally. **Must** statements are requirements, while **should** statements are best practices. If **should** statements are not followed, the reasoning behind the choice to do something else **must** be documented.

Reference Gauge and Operating Datum	It is best to only have one reference gauge per station as this will reduce the chance of making errors when applying gauge corrections. The reference gauge and benchmarks **must** be referred to a fixed datum, known as the operating datum. Hydrometric stations **should** be operated in assumed datums. When establishing a new site, it is recommended to assign an elevation of 100.000 m to the primary benchmark. Every reasonable effort **should** be made to express elevations at a given gauging station relative to the same assumed datum throughout the station's period of record.
Benchmarks	There **must** be a system of at least three permanent and stable markers (benchmarks) that are independent of each other. Benchmarks **should** be spread apart and away from the riverbank and areas of destructive human activity. If feasible, at least one benchmark **must** be above the floodplain. All benchmarks **must** have a unique identifier (ID). See main body for details. Benchmarks **must** be adequately described in the data computation system and in any other relevant station records. See main body for details. Temporary Benchmarks **should** only be used for relatively short periods until permanent benchmarks can be established. Measuring Points **should** follow the same convention for identification and description as benchmarks.
Monitoring Benchmark Stability	Levels **must** be run between all benchmarks and reference gauges at least once a year at stable sites, preferably after the spring thaw, and two or more times per year at unstable sites. Benchmark stability **should** be assessed after each full tie-in. A **benchmark or reference gauge is stable** if its surveyed elevation has fluctuated about a consistent value throughout the last **three years** and the deviation from the mean surveyed elevation has not exceeded the survey tolerance.

	Benchmarks and reference gauges are unstable if their surveyed elevation differs from its established elevation by more than the survey tolerance, and/or there is a trend in the deviation of the surveyed elevation (even if the deviation is within the survey tolerance). If a benchmark elevation has remained constant following a period of instability, the benchmark elevation **should** be re-established as the average value from at least three consecutive level runs covering at least 18 months. If a primary benchmark becomes unstable, the role of primary **should** be assigned to the next most stable benchmark. A new benchmark **should** be installed to replace an unstable one. The elevations of both benchmarks **should** be monitored until the new one proves to be the more stable of the two based on results from at least 3 full tie-ins obtained over a period of at least 18 months. Once a new benchmark is stable, the old (unstable) benchmark **must** be removed or destroyed. If the reference gauge is unstable, consider surveying it every visit to avoid the complications associated with gauge corrections. All decisions about benchmark replacement or changes to established elevations **must** be documented in the data computation system and in the Station Analysis. Established elevations **must** only be changed after consultation with your supervisor and/or your data control supervisor.
Instrumentation	**Surveyor's levels (optical and digital):** • are accepted for use in all aspects of height measurement. • the recommended instrumentation specification for 1 km double run levelling is 2 mm accuracy. **Total stations:** • may be suitable for use over steep slopes or longer sight lines to reduce the number of instrument setups. • The recommended technical specification is 1.5 mm +2 ppm accuracy for horizontal distance and 1" angular accuracy. For shorter sightings, less stringent specifications are required. **Global Navigation Satellite Systems (GNSS)** • can provide more accurate height differencing than spirit levelling when benchmarks are separated by kilometres. The validation tests outlined in each instrument's operation manual **must** be conducted prior to full tie-ins, at least once a year and after any rough usage. Typically, modern digital instrumentation requires annual servicing by an authorized agent for each type of instrument. Test and calibration results **should** be documented according to regional procedures.

	If a two-peg test is not done prior to differential levelling, all sighting distances from a given instrument set-up **must** be equal to mitigate collimation error. Level rods **should** not be extended beyond 3 m unless needed.
Error	Survey results **must** be checked in the field before leaving the site in order to detect and eliminate errors. Closure error **must** be within survey tolerance to be acceptable. If this is not the case, the circuit **must** be rerun. For leveling circuits with three or less setups, the survey tolerance is ±0.003 m. If Closure Error ≤ ±0.003 m, elevations of objective points **should** be recorded as surveyed on the forward run. For circuits with four or more setups, see section 6.2. Closure error is never distributed for circuits with three or less setups.
Acceptable Levelling Circuits	When assessing the stability of the local reference network, the starting point must be the primary benchmark. Therefore, if a series of smaller loops is used, the first loop must begin on the primary benchmark.
Monitoring Reference Gauge Stability	The frequency with which the elevation of the reference gauge **must** be monitored depends on its documented stability. At a minimum, it must be surveyed once a year. If the absolute value of a gauge correction is ≤ 0.003 m, no correction is applied. If it exceeds 0.003 m, a gauge correction is applied to all stage data. Gauge corrections **must** only be applied in the data computation system. They **must not** be applied in the data logger. Deciding to change the established elevation of the reference gauge **must** be based on an assessment of stability using the Benchmark History.
Documentation	Refer to section 10 for required documentation regarding benchmarks and reference gauges.

1. Introduction

Hydrometric stations are installed to measure accurate, high-frequency water levels on a river, stream or lake. A lack of permanent datum or instability of the stage sensor, benchmarks or reference gauge can contribute to inaccuracy of water level and discharge records. Although some problems can be overcome by careful and proper positioning of benchmarks and installations, periodic levelling must be carried out to assess their stability.

Levelling is the process by which elevations of points of interest are determined. Levelling for hydrometric operations serves four main purposes:

1. Monitoring stability of a system of benchmarks;
2. Monitoring vertical displacement of a reference gauge to determine gauge corrections (a.k.a. a level check);
3. Performing direct water level measurements to determine sensor reset corrections;
4. Obtaining elevations of other points such as a high-water mark or the elevation of the riverbed.

All levelling activities rely on benchmark stability monitoring since the elevation of the primary benchmark is used to determine the elevations of all other surveyed points.

2. Reference Gauge and Operating Datum

2.1 Reference Gauges

Readings from the stage sensor are routinely compared to readings from the reference gauge at each station. The reference gauge may be a staff gauge, a wire-weight gauge installed on a bridge or an electric contact gauge (ECG) inside the station shelter. The reference gauge may also be a permanent point from which direct water level measurements are taken, such as a benchmark or measuring point. It is best to only have one reference gauge per station as this will reduce the chance of making errors when applying gauge corrections.

Measuring points, also known as MPs, are consistent locations used to determine a direct water level. Examples of measuring points are a concrete bolt in a bridge abutment, a V groove filed into a steel plate on a walkway, or a rod driven in the river. If used on more than a temporary basis, naming of measuring points should follow the identification convention of benchmarks. Furthermore, adequate descriptions in the data computation system and station records should accompany to ensure that tracking of elevations is conducted and that locating them during all seasons is possible. The use of measuring points should be done with caution, and their elevations should be determined on a frequency sufficient to avoid the need to apply gauge corrections. An example of a measuring point ID is MP O2022-302, with the description “Concrete bolt located in concrete retaining wall, 0.3m down from lip, 5.1m S of gauge house door, in line with handle. Concrete edge painted for reference.” Measuring Points should follow the same convention for identification and description as benchmarks (see Section 3.1) but the identification number should start with MP.

2.2 Operating Datums

To obtain accurate and reliable stage data at a station, the reference gauge and benchmarks must be referred to a fixed datum, known as the operating datum (Figure 1). All elevations are expressed relative to this level surface. The operating datum is most often an assumed datum, whose zero is defined by assigning an arbitrary elevation to the primary benchmark. When establishing a new site, it is recommended to assign an elevation of 100.000 m to the primary benchmark. This ensures that stage values will remain positive even if significant ground movement or scour occurs. While negative stage values are not problematic, they are often less desirable.

A datum conversion is used to express stage data relative to a different datum, whether arbitrary (assumed) or absolute (geodetic). The conversion is the difference between the elevation of the reference gauge in the datum of interest and the elevation in the operating datum. This value is added or subtracted from the stage data outside of the computation system, often by the end user. For example, a datum conversion can be used to express stage data relative to the Canadian Geodetic Vertical Datum of 2013. Geodetic datums change over time as the planet's shape and size changes, therefore the operating datum should not be a geodetic datum. Operating in a geodetic datum would require regular confirmation of the reference gauge elevation relative to the geodetic reference frames and would introduce an uncontrolled source of error and unnecessary station data non-stationarity. **Hydrometric stations should be operated in assumed datums**.

To ensure the quality of records, each station's operating datum must be documented in HYDEX. If additional datum references are required, they must be entered in HYDEX as conversions along with all available information on how the conversions were obtained.

Every reasonable effort should be made to express elevations at a given station relative to the same assumed datum throughout the station's period of record. This is particularly important when a station is reactivated. Continued use of the same datum at a site leads to consistency in the stage record, enhancing the value of hydrometric data for numerous hydrologic and engineering purposes.

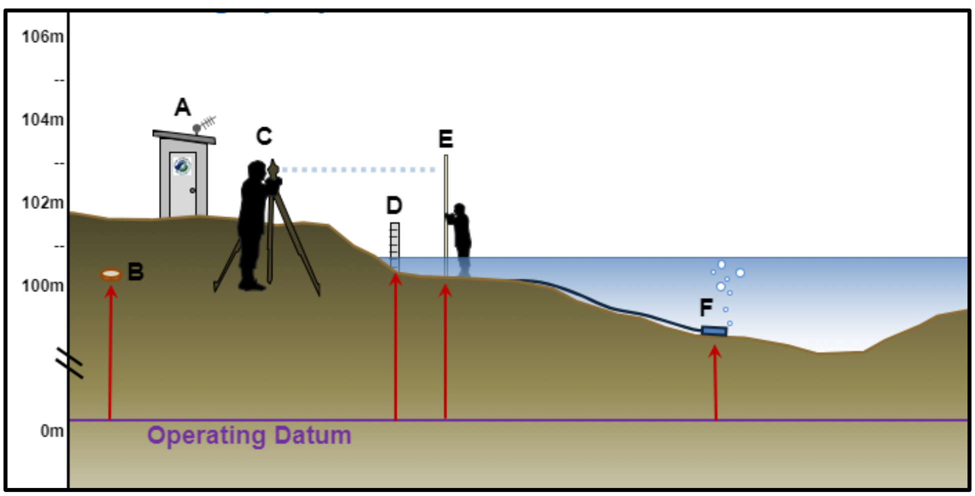

Figure 1: Sketch illustrating (A) gauge house, (B) primary benchmark, (C) survey level and surveyor, (D) reference gauge, (E) levelling rod, (F) stage sensor or orifice.

3. Benchmarks

All benchmark and reference gauge elevations must be referenced to the operating datum to ensure data accuracy and continuity. To ensure continuity of the datum there must be a system of at least *three* permanent and stable markers (benchmarks) that are independent of each other. If a site has only two benchmarks, it is not possible to determine which benchmark is responsible for any deviation in the surveyed elevation from the established elevation. On the other hand, there is no benefit of having more than four benchmarks for determining benchmark stability. Throughout the remainder of this document, the assemblage of benchmarks at a site is referred to as the local reference network.

In addition to being used as a reference system for the operating datum, benchmarks are used to monitor site stability. Benchmarks can be disturbed or destroyed by natural processes such as erosion, tremors, structural settling, or human activities such as construction work or snow plowing. Therefore, to reduce the risk of losing the reference to the operating datum and to best assess site stability, the benchmarks should be spread apart and away from the riverbank and areas of destructive human activity. At least one benchmark should be above the floodplain. If possible, all stations should have at least one benchmark that offers a large unobstructed view of the sky to enable sampling of Global Navigation Satellite System data from that marker.

3.1 Benchmark Installation and Identification

A variety of benchmark installations are used by the Water Survey of Canada. Installations should:

- Include at least one benchmark installed above the known, or anticipated, highwater marks
- Provide safe access to at least one benchmark during all seasons, and all water levels
- Have benchmarks located to reduce potential damage from ice, motorized equipment, and human activities
- Consider location of utilities, right of ways, and private property around the hydrometric station – obtain permission and underground utility locates as appropriate
- Have threaded rods driven to the point of refusal when using threaded rod benchmarks
- Prioritize bedrock locations that are sufficiently robust to ensure long term benchmark stability
- Have benchmarks in a variety of locations and material types to ensure that each benchmark is independent of the others

Brass caps are used to identify benchmarks in two ways. A brass plug can be mounted vertically or horizontally in a rock or concrete surface (see subsections on benchmark placement below), or a brass cap can be screwed onto coupled threaded rods. Coating the brass cap and any rod couplers with thread locking adhesive will ensure longevity. If it is impractical to install a WSC benchmark, the use of another agency's permanent benchmark is acceptable if it is considered stable. This may alleviate any concerns about putting a WSC benchmark in an engineered facility like a bridge or dam. All WSC benchmarks must have a unique identifier (ID) that is controlled by each region and assigned when the benchmark is installed. The identifier is placed on the crowned surface of official benchmark (see Figure 2). Benchmark IDs must be used consistently in the station description, benchmark history in the gauge house, and in the data computation system. When using benchmarks from other agencies, the pre-existing unique identifiers should be used to document benchmark use and history.

The format of the unique ID should follow: PROVINCEYEAR-SERIALNUMBER. For example, benchmark A2016-118 was installed in Alberta in 2016 and it was the 118th benchmark to be assigned an ID that year. A second example is NS2023-7, which was installed in Nova Scotia in 2023, and it was the 7th ID assigned that year. The abbreviations for the provinces and territories are listed below.

A: Alberta	NO: Northern Ontario	PE: Prince Edward Island
BC: British Columbia	NS: Nova Scotia	Q: Quebec
M: Manitoba	NT: Northwest Territories	S: Saskatchewan
N: Newfoundland	NU: Nunavut	YT: Yukon Territory
NB: New Brunswick	O: Ontario	

Figure 2: An image of a WSC benchmark complete with a benchmark identifier.

If there is an operational need to use unmarked components of an engineered facility such as a bridge bolt, every effort must be taken to permanently identify it with its WSC ID. This can be done using a stamp, plaque or sign nearby the benchmark location and displays its ID (e.g. A2016-118).

Benchmarks must be correctly named and adequately described in the data computation system and in any other relevant station records. Names should include the appropriate prefix (e.g. BM, TBM or MP), followed by a space (e.g. BM A2016-118). These descriptions must enable them to be easily located at any time of the year. The descriptions must include their location relative to permanent features, using distance and heading, and should include a physical description of the benchmark. Descriptions should include multiple references to a benchmark's location and should refrain from referencing other benchmarks. An example of a suitable description would be, "BM S2017-129: Brass cap on threaded rod driven 8 m deep, located 12.3 m NW of NW corner of shelter and 6.1 m N of old precipitation gauge mount."

Temporary benchmarks, such as those that may be installed in a flood situation, do not need brass caps. These benchmarks are used for newly constructed stations and for existing stations where permanent benchmarks have recently been destroyed. They should only be used for relatively short periods, until permanent benchmarks can be established. They follow the same naming conventions as other benchmarks; however, a "T" is included in the label to indicate it is temporary, e.g., "TBM S2017-129: Spike in 40 cm diameter spruce tree, 5 m NW of N corner of shelter".

3.2 Horizontally mounted Benchmarks

Horizontally mounted benchmarks are often set in rock, soil, or cement. It may sometimes be difficult to install a benchmark on a perfectly horizontal plane, as can be seen in Figure 3b where the benchmark cap is slightly slanted. Therefore, when obtaining the elevation of these benchmarks, the level rod must be placed on the highest point for the reading.

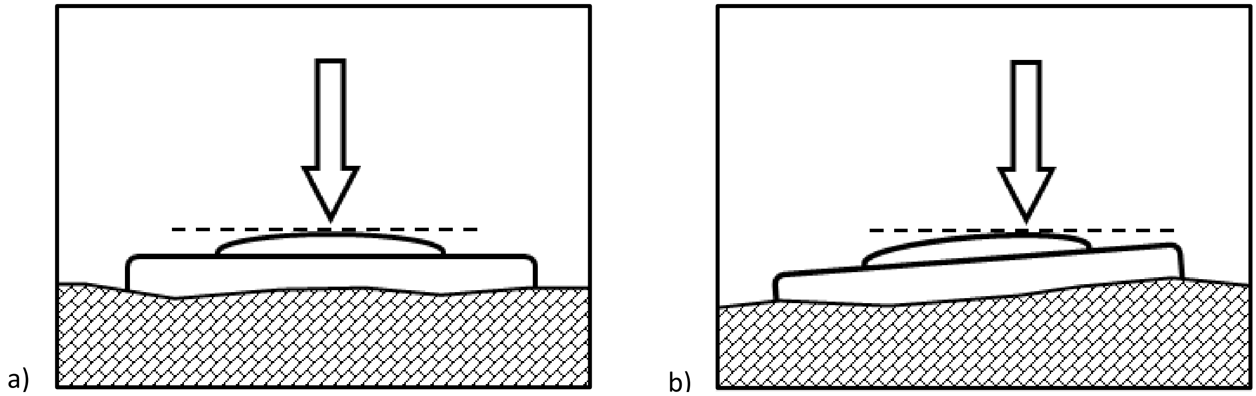

Figure 3: Benchmark caps mounted horizontally. The arrows show where the rod should be positioned when reading elevations.

3.3 Vertically mounted Benchmarks

Vertically mounted benchmarks are often set into a concrete building or bridge facility. The raised centre section protrudes far enough to allow a level rod to be placed on the edge of the crown as shown in Figure 4a, with the chisel groove forming a letter x. If the top of the benchmark is mounted under a ledge so that the edge of the crown is not accessible, a benchmark chisel can be placed in the groove and the level rod can be held on the chisel as in Figure 4b. In either case, an arrow stamped on the crowned surface is required to indicate the point to which the elevation applies, and that point must be stated in the benchmark description. The rod should only be held on one of these two locations, not on the top of the outer rim of the brass cap.

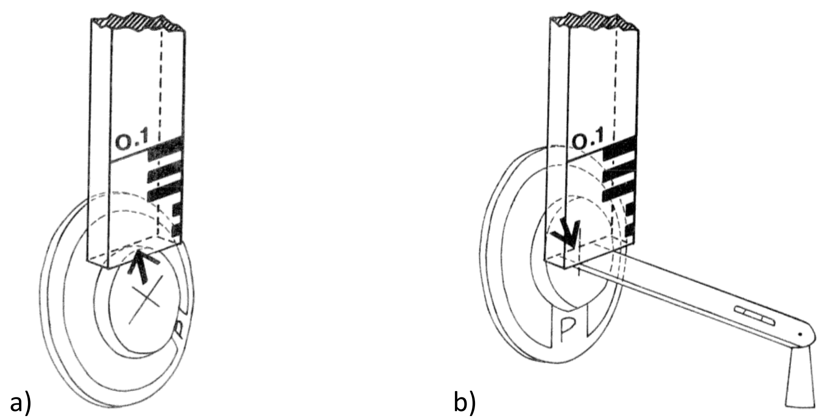

Figure 4: Demonstration of the use of benchmarks mounted in a vertical plane. Engraved arrows indicate where to place the leveling rod: (a) Place the leveling rod on the top edge of the raised center section. (b) Place a benchmark chisel in the horizontal groove, and the rod on top.

4. Monitoring Benchmark Stability

The record of surveyed elevations of all benchmarks and reference gauges used throughout a station's history is referred to as the Benchmark History. Depending on the site, this record may be a paper document, an entry within the data computation system, or some combination of the two. Analysis of this record is performed to determine if:

1. The designated primary benchmark is appropriate, i.e., if it is indeed the most stable.
2. The established elevation of a benchmark or reference gauge needs to be adjusted.
3. A new benchmark should be added to the local reference network to replace a benchmark that is unstable or has been destroyed.

Benchmark stability should be assessed after each full tie-in. When done consistently, examining the last 5-10 years of levelling data should be sufficient to draw meaningful conclusions (see Figure 5). These conclusions must be documented in the data computation system and in the Station Analysis.

4.1 Defining Stability

A benchmark is classified as stable if:

- Its surveyed elevation has fluctuated about a consistent value throughout the last three years and the deviation from the mean surveyed elevation has not exceeded the survey tolerance (concept introduced in Section 6.2) as shown in Figure 5a.

A reference gauge is classified as stable if:

- Its surveyed elevation has fluctuated about a consistent value throughout the last three years and the deviation from the mean surveyed elevation has not exceeded the survey tolerance.

A station's local reference network is classified as stable if all benchmarks in that network are stable. Having a stable local reference network will ensure that the continuity of the operating datum is maintained. A station is classified as stable if all benchmarks and reference gauges at that station are classified as stable.

A benchmark or reference gauge may be classified as unstable if:

- Its surveyed elevation differs from its established elevation by more than the survey tolerance as shown in Figure 5b. This indicates that the point was unstable in the past but does not indicate whether it will continue to be so. An event could have caused a change in elevation.
- There is a trend in the deviation of the surveyed elevation from the established elevation as shown in Figure 5c. Note that a point may be unstable even if the deviation is within the survey tolerance.

Any benchmark or reference gauge that is found to be unstable will have to be carefully monitored in future visits. Unstable benchmarks or reference gauges require more frequent levelling, and they regularly result in the application of gauge corrections when used for water level measurements. Operationally, it is more important to have a stable reference network than a stable reference gauge because gauge corrections can account for reference gauge instabilities, but these can only be defined with a stable network.

The following should also be considered when assessing benchmark stability:

- If the surveyed elevations of all secondary benchmarks indicate the same trend (i.e. evolve in the same direction by the same amount), it is likely that the primary benchmark moved, not the secondary benchmarks.
- It is important to operate stations in assumed datums to avoid integrating geodetic and large-scale geologic changes (e.g., isostatic rebound) into stage time series.

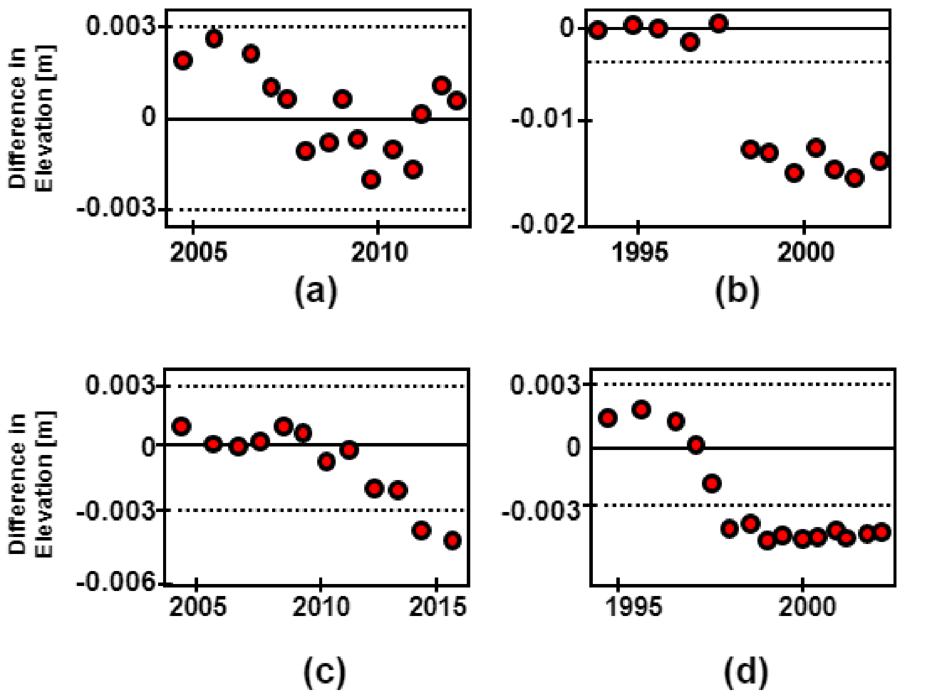

Figure 5: Difference between surveyed elevations and established elevations for three benchmarks: (a) stable benchmark; (b) benchmark whose elevation changed suddenly and appears to have stabilized; (c) currently unstable benchmark; (d) benchmarks whose elevation changed gradually then stabilized.

4.2 Frequency of Levelling

Levels must be run between all benchmarks and reference gauges at least once a year at stable sites, preferably after the spring thaw, and two or more times a year at unstable sites. If the reference gauge is unstable, consider surveying it every visit to avoid the complications associated with gauge corrections that are not applied visit to visit.

4.3 Benchmark Replacement or Change of Established Elevation

If the benchmark history reveals that:

1. A benchmark elevation has remained constant following a period of instability (see Figure 5d)
    a. the benchmark elevation should be re-established as the average value from at least three consecutive level runs covering at least 18 months.
2. A benchmark is unstable:
    a. A new benchmark should be installed, and the elevations of both benchmarks should be monitored at least twice per year, until results from at least three full tie-ins obtained over a period of at least 18 months reveal that one is no longer changing elevation.
        i. If stability of the new benchmark has been demonstrated, the old one must be removed or destroyed to avoid future confusion.
    b. If it is the primary benchmark, the role of primary should be assigned to the next most stable benchmark while maintaining the original datum (see Section 4.1). The primary benchmark references the elevations of the benchmark network and reference gauge to the operating datum. Instability of the primary benchmark can lead to errors in secondary benchmark and reference gauge elevations, and gauge height and computed discharge values. Consequently, locating the primary benchmark should be done with careful consideration.

An illustration of how to treat benchmarks after installation, and after a marked change in surveyed elevation, is offered in Figure 6. All decisions about benchmark replacement or changes to established elevations must be documented in the data computation system and in the Station Analysis. A new benchmark history report should be available in the gauge house. Note that datum continuity is essential and therefore, established elevations must only be changed after consultation with your supervisor and/or your data control supervisor.

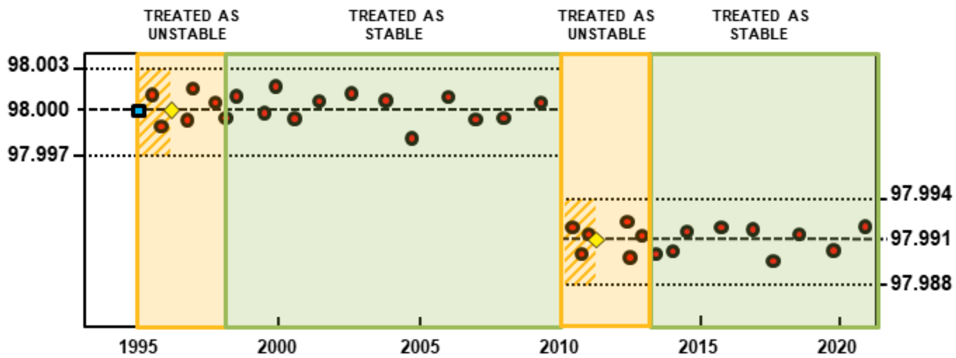

Figure 6: Green shading indicates periods when the benchmark is treated as stable, therefore only surveyed once a year. Orange shading indicates periods when it is treated as unstable and therefore surveyed at least twice a year. Orange hashed area is the 18 months following installation (blue square) or change in elevation required to establish a new elevation (yellow diamond).

5. Instrumentation

Four types of height measurement equipment are currently used by the WSC. The requirements and scenarios for their use are outlined in the following sections, along with the pros and cons of each device. All height measurement devices are mounted on tripods, and all tripods must have legs whose length can be easily adjusted and fixed. The accuracy of readings from surveyors' levels and total stations decreases with sighting distance, therefore higher accuracy measurements are obtained with shorter sightings.

5.1 Optical Surveyor's Level

The levelling traditionally performed by the WSC is known as differential levelling. Differential levelling involves measuring the vertical difference between a point of known elevation (the backsight) and a point of unknown elevation (the foresight) to determine the unknown elevation (Figure 7). A telescope with suitable magnification is used to read a graduated rod held on a point where the elevation is to be determined (the objective point). Measurements of horizontal distance and angle are not required.

Levelling with optical surveyor's levels requires graduated rods with numerical scales from which elevations are read by eye. Older levels have a manual adjustment, whereas modern levels use automatic compensators within the instrument to level the line of sight precisely after they have been levelled manually. Optical levels are accepted for use in all aspects of height measurement. They have time-tested procedures and a low equipment cost.

The following should be noted about their use:

- The distance at which readings can be obtained depends on the operator's eyesight. The recommended maximum sighting distance should be 50 metres, and ideally less than 30 m.
- They are more susceptible to human error than are digital surveyor's levels.
- They are sensitive to atmospheric refraction (i.e. heat hazes), which is particularly notable on longer distance sightings. Best results are obtained on an overcast day when atmospheric refraction is minimized.

- Sighting over water can be influenced by atmospheric refraction and light reflection (i.e. glare) off the water.
- The condition of the level and rod is critical for accuracy.
- The recommended instrumentation specification for 1 km double run levelling is 2 mm accuracy.

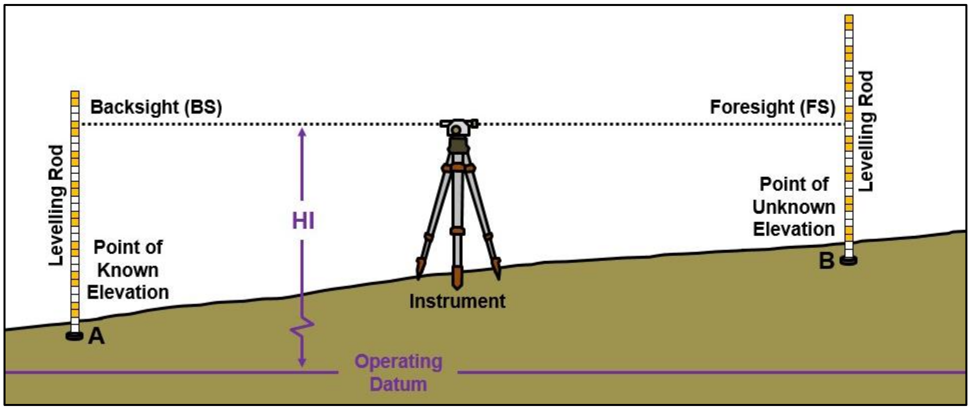

Figure 7: Illustration of instrument setup, foresight (FS) and backsight (BS) for differential leveling.

5.2 Digital Surveyor's Level

Digital levels are operated following the same procedures as optical levels (Figure 7), but they are battery operated and require bar-coded rods which are read automatically by the level. The use of digital levels is acceptable in all aspects of height measurement and may be preferable to optical levels, since measurements are quicker to perform, and they are less prone to human error in estimating and reading. The instrument can be set to automatically take a series of readings and use the mean value as the sighting, while displaying the range of measurements taken for the average.

The following should be noted about their use:

- Extreme care should be taken with them, as they can be knocked out of alignment.
- Digital files can be exported and stored for proper record keeping.
- The condition of the bar code on the rod is critical for accuracy.
- The rod waving technique does not work with digital levels – it is very important to use a calibrated rod level to keep the rod plumb.
- Construction grade laser levels are not acceptable.
- They are sensitive to atmospheric refraction, so best results are obtained on an overcast day when atmospheric refraction is minimized.
- Sighting over water can be influenced by atmospheric refraction.
- As with all electronics, there is the potential for failure, but most models can also be used as optical levels.
  - Electric contact gauges and wire weight gauge plummets can only be surveyed in optical mode.
- A clear line of site is required.
- The recommended technical specification for 1 km double run levelling is 2 mm accuracy.
- For sites that require higher accuracy (e.g. Canadian Hydrographic Service gauges), please discuss the equipment specifications with the partner prior to conducting levels.

5.3 Total Station (Trigonometric Levelling)

Total stations determine the difference in elevation using angles measured in the vertical plane (zenith or elevation/depression angle) in conjunction with the slope distance (Figure 8). No repositioning of the instrument is required to close the circuit, resulting in time saving. They are practical for use over steep slopes since there is virtually no limit to the vertical distance that can be measured in one reading. Total stations can also be used for longer sight lines than surveyor's levels, reducing the number of instrument setups and subsequently reducing measurement time. Nevertheless, the highest accuracy is obtained on lines of up to a few hundred metres. They are battery-operated and typically cost more than twenty or thirty times an optical surveyor's level.

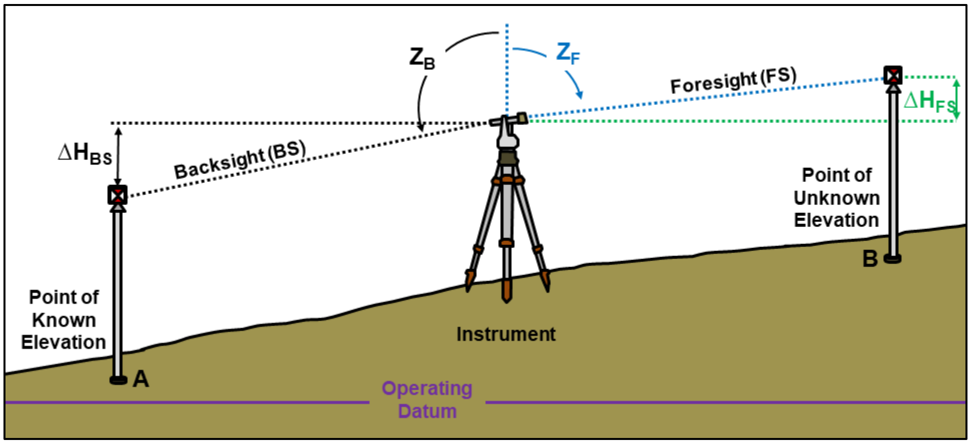

Figure 8: Example of direct sightings with a total station to prisms at points A and B.

The following should be noted about their use:

- The instrument can be set up below the points to be surveyed, offering more locations to place the tripod.
- There must be a direct line of sight between the prism and the instrument.
- The method used to measure distances is sensitive to atmospheric refraction; therefore, total stations should be used under uniform atmospheric conditions. If there are non-uniform gradients in temperature or humidity, follow manufacturer instructions.
- To perform the recommended procedures (Appendix A: Procedures Specific to Total Stations), a fixed height rod should be used since the prism target height must be maintained to correctly calculate a height difference between the backsight and foresight.
- They require annual servicing by the manufacturer which costs money and time.
- Digital files can be exported and stored for proper record keeping.
- As with surveyor's levels, accuracy decreases with sighting distance.
- They are heavier than surveyor's levels.
- It is not possible to accurately level an electric contact gauge, a wire weight gauge plummet, or a staff plate.
- The various modes and prism constants must be set correctly for usable results.
- The recommended technical specification is 1.5 mm +2 ppm accuracy for horizontal distance and 1" angular accuracy to achieve 3mm vertical accuracy for sightings up to 300m. For shorter sightings, less stringent specifications are required. Alternatively, repeated distance and angular observations (repeating all steps in Appendix A) and least-square adjustment can be used to achieve 3mm vertical accuracy.

5.4 Use of Global Navigation Satellite Systems (GNSS)

In exceptional circumstances, such as stations where benchmarks are separated by large distances (e.g., kilometres), Real-Time Kinematic (RTK) GNSS surveying may be an acceptable method for surveying benchmark and reference gauge elevations. RTK surveying uses a base station GNSS receiver to send real-time position corrections to a roving GNSS receiver and can achieve sub-centimeter accuracy relative to the base station position (i.e., in relative space). RTK surveying requires an open sky view without obstructions that may lead to errors associated with reflected satellite signals (i.e. multipath errors). For hydrometric stations where RTK surveying is used, it may be necessary to install a benchmark with a clear sky view over which the base station can be set up. It is recommended that that base station be set up at the same known location (ideally a benchmark) for each survey. RTK GNSS surveys provide the relative ellipsoidal height differences between the base station and rover. To obtain the highest level of accuracy, the relative orthometric height differences between the base station and rover is required. To determine the relative orthometric height differences, the surveyor needs to apply a geoid model to the ellipsoidal heights for the base station and rover. Normally this can be done by selecting the desired geoid model in the GNSS controller. The currently adopted geoid model in Canada is CGG2013a. Note that significant planning and data processing is required to achieve high accuracy in geodetic space (i.e., absolute space), and RTK survey results should not be interpreted as accurate geodetic positions such as those required for the Height Modernization Project. RTK GNSS surveying requires appropriate knowledge, training, and experience. Natural Resources Canada's "Guidelines for RTK/RTN GNSS Surveying" (2013) should be consulted for a basic description of the method and guidance on how to obtain accurate results. If you operate a station where RTK GNSS surveying is appropriate, consult with your supervisor and/or your data control supervisor for additional guidance. For the majority of stations, a surveyor's level is more accurate and efficient for surveying benchmark and reference gauge elevations and is the preferred equipment.

5.5 Routine Maintenance

All levelling equipment (including rod level and survey level) must be tested routinely to ensure proper adjustment and accuracy. The validation tests outlined in each instrument's operation manual (e.g. two-peg tests) must be conducted prior to full tie-ins. Therefore, they should be done at least once a year and generally in the spring. They should also be performed after any accidental rough usage. Test and calibration results should be saved and stored according to the national naming conventions.

The two-peg test is a simple and common test for surveyor's levelling equipment (see Appendix B for details). **If a two-peg test is not done prior to differential levelling, then all sighting distances from a given instrument set-up must be equal to mitigate collimation error.** Typically, modern digital instrumentation requires annual servicing by an authorized agent for each type of instrument. These should be done to the specifications outlined by the manufacturer. Survey equipment (e.g. rods and levels) should be stored and transported in an appropriate protective case. When not in use, they should be stored clean and dry. An untreated wooden rod should not continually be placed in water as the wood will swell and the painted surface will eventually flake off, limiting the useful life of the rod.

6. Error

6.1 Sources of Error

The ability to determine the correct elevation (i.e., the accuracy of levelling) depends on the quality of the instrument used and the skill and care exercised in the application of the procedures. Awareness of the factors that contribute to error and of the steps necessary to limit them can help improve the quality of levelling data. The following is a list to which some errors can be attributed, but many of these examples apply only to the use of surveyor's levels.

1. Improper Adjustment of Instrument – This condition occurs when the line of sight is not parallel to the axis of the level tube. This error can be minimized by keeping backsight and foresight distances the same. Performing the two-peg test routinely will help detect this error.
2. Parallax – If there is an apparent movement of the crosshairs on the target with a corresponding slight movement of the observer's eye, the condition of parallax exists. To reduce parallax, adjust the eyepiece of the telescope until the crosshairs appear sharp and distinct. The objective lens is then carefully focused on a target.
3. Inaccurate Reading of Rod with Optical Levels – These errors can be greatly reduced by using shorter sights and by checking each reading before recording it. The recommended maximum sighting distance is50 metres, and ideally less than 30 m.
4. Level Bubble Not Centred – If the level bubble is not centred at the time of sighting, the magnitude of the error will be proportional to the distance between the instrument and the rod. Therefore, that the greater the sighting distance, the greater the care required when levelling the instrument.
5. Settlement of Instrument Tripod – Some settlement of the tripod is likely to occur when levelling over soft, muddy, snow-covered, or thawing ground. In these instances, backsight and foresight observations should be made in quick succession to minimize any effects from the instrument settling and care should be taken not to jostle the tripod when repositioning for the foresight and backsight.
6. Improper Turning Points – Turning points are fixed points on which a foresight rod reading and then a backsight rod reading is taken in order to establish a new instrument height. If a turning point is not well-defined, it may be hard to locate on the return run. If it is not stable or does not have a rounded or pointed top, the elevation reading may not be accurate. Therefore, turning points should be well-defined, stable and rounded or pointed on top. When no natural turning point exists, portable turning points may be used.
7. Mistakes - Mistakes can be made due to miscalculation, carelessness or poor judgment. Survey results must be checked in the field before leaving the site in order to detect and eliminate errors.
8. Rod Not Plumb – A rod level can be used to keep the rod vertical. Alternatively, the rod can be waved towards and away from the objective lens while the person sighting the rod notes the smallest elevation seen, which occurs when the rod is vertical (Figure 9). When rocking the rod, it must continue to rest on the front edge of its base when tipped backwards, as can be done when the rod is on a rounded surface such as a brass cap.

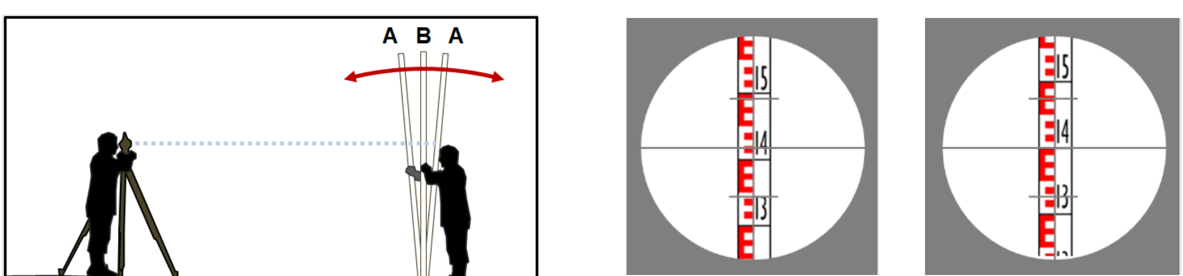

Figure 9: Depiction of waving the levelling rod, demonstrating that the smallest reading (1.400m) occurs when the rod is plumb (position B). When the rod is inclined (Position A), the reading is 1.420 m.

6.2 Closure Error and Survey Tolerance

When a level circuit is closed, the surveyed elevation of the ending location (which is also the starting location) may not equal the elevation used at the start of the circuit due to the error sources listed above. This difference in elevation is called the closure error:

$$\text{Closure Error} = \text{Elevation}_{\text{start}} - \text{Elevation}_{\text{end}}$$

The maximum allowable closure error is referred to as the survey tolerance. Closure error must be within survey tolerance to be acceptable. If this is not the case, the circuit must be rerun. For this reason, the closure error for all completed level circuits must be documented on the field note (example shown in Table 1) to enable proper quality checking of results. The survey tolerance is also used when assessing local reference network stability (Section 4.1).

For leveling circuits with three or less setups, the survey tolerance is ±0.003 m. Therefore:

- If Closure Error > ±0.003 m, the circuit should be rejected and redone until it is ≤ ±0.003 m.
- If Closure Error ≤ ±0.003 m, elevations of objective points should be recorded as surveyed on the forward run.

For leveling circuits with four or more setups, the survey tolerance is ±0.01 $\sqrt{D}$ m, where *D* is the circuit length in kilometres. For example, if a circuit with 4 or more setups is 1 km long, the survey tolerance is ±0.01 m, if it is 160 m long, the tolerance is ±0.004 m. The circuit length is the sum of all sighting distances. A rough estimate of this value can be obtained using a to scale site map in the gauge house documentation.

Therefore, for circuits with four or more setups:

- If Closure Error > ±0.01 $\sqrt{D}$ m, the circuit should be rejected and redone until it is within tolerance.
- If Closure Error ≤ ±0.003 m, elevations of objective points should be recorded as surveyed on the forward run.
- If Closure Error ≤ ±0.01 $\sqrt{D}$ m and it exceeds 0.003 m, the error should be distributed following the steps outlined below.

6.3 Distributing Closure Error

It is important to understand that error distribution **does not** compensate for errors, it simply produces a set of data for which the surveyed elevation of the last point in the circuit is the same as the elevation used at the start of the circuit. As indicated above, closure error is never distributed for circuits with three or less setups. For circuits with four or more setups, when the absolute value of the closure error is within tolerance and more than 0.003 m (i.e., ±0.003 m < Closure Error ≤ ±0.01 $\sqrt{D}$ m, where *D* is the circuit length in kilometres), error is distributed. The primary method accepted by the professional surveying community and recommended for use by the WSC is shown below. Closure error is distributed to all points in the circuit by adding the following to the surveyed elevation of each point:

$$\frac{Closure\ Error \times Setup\ Number}{number\ of\ setups}$$

An example of closure error distribution is shown in Table 1. The surveyed elevation to be recorded for each objective point is the average of the corrected elevations. The corrected elevations should be documented in the eHSN for manual entry into the data computation system.

Table 1: Demonstration of closure error distribution for a 4-setup circuit.

Station	Backsight	Height of Instrument	Foresight	Elevation	Notes	Correction	Adjusted Elevation
BM1	0.550 m	30.550 m		30.000 m	Brass Cap	0 m	
BM2	1.205 m	30.356 m	1.399 m	29.151 m	Brass Cap	-0.001 m	29.150 m
TP1	1.113 m	29.911 m	1.558 m	28.798 m	Bolt on Bridge	-0.002 m	28.796 m
BM2	1.239 m	30.388 m	0.762 m	29.149m	Brass Cap	-0.003 m	29.146 m
BM1			0.384 m	30.004 m	Brass Cap	-0.004 m	30.000 m
			Closure Error =	- 0.004 m	OK		

Four set ups and circuit length of 250 m. Survey tolerance based on distance is $\pm 0.01\sqrt{0.25\text{km}} = \pm 0.005$ m

Established elevations

BM1= 30.000 m

BM2 = 29.150 m

Average corrected surveyed elevation of BM2 = 29.148 m

7. Acceptable Levelling Circuits

A level circuit is a line of levels that starts at a point of known elevation and ends at the point of origin or at another point with a previously established elevation. A closed circuit or closed loop is a level circuit that starts and ends at the same point. The WSC uses a variety of closed loop scenarios. The choice of scenario is dictated by the distances (both horizontal and vertical) between points to be surveyed, land cover and available technology. Three acceptable scenarios for surveyor's and total station levelling are detailed below. The examples are presented as they would be completed with a surveyor's level, but they can be adapted for total stations (see Appendix A).

For all scenarios:

- Level rods should not be extended beyond 3 m unless needed. If they are extended beyond 3 m and readings are taken near the top of the rod, take extra care to ensure it is plumb, i.e., use the rod waving technique.
- When assessing the stability of the local reference network, the starting point must be the primary benchmark. Therefore, if a series of smaller loops is used, the first loop must begin on the primary benchmark.
- To obtain two independent observations of the returning point (the last objective point surveyed on the forward run of a level circuit and the first point surveyed on the return run), there needs to be a new instrument setup. This will ensure an independent return run of the level circuit. This step can be validated by confirming a difference in instrument height, ideally by more than 1 cm.

7.1 Forward and Return Runs with Two Instrument Setups

This scenario consists of a forward run to the returning point, and a return run. The objective points from the forward run are levelled in the reverse order on the return run. There are two instrument setups, one in each direction (Figure 10 and Table 2). Multiple foresights are obtained for a given instrument set-up and the additional foresights are referred to as intermediate foresights.

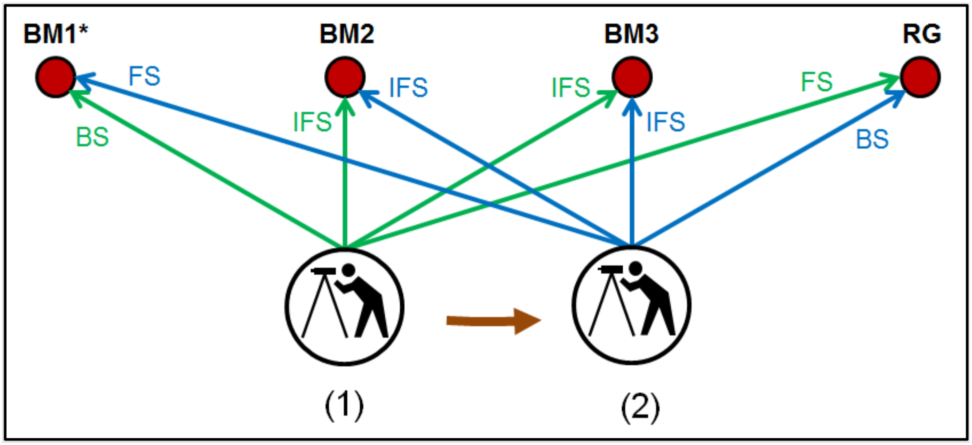

Figure 10 : Forward and return runs with two setups using intermediate foresights (IFS). The starting point is BM1 as indicated with a star. Red circles are objective points. BM stands for benchmark and RG for reference gauge. Figure is not to scale.

Table 2 : Level note corresponding to the scenario shown in Figure 10, a forward and return run with two setups.

Station	Backsight	Height of Instrument	Foresight	Elevation	Notes
BM1	2.250 m	6.563 m		4.313 m	
BM2			2.258 m	4.305 m	
BM3			1.372 m	5.191 m	
RG	1.418 m	5.980 m	2.001 m	4.562 m	Electric contact gauge
BM3			0.789 m	5.191 m	
BM2			1.673 m	4.307 m	
BM1			1.666 m	4.314 m	
			Closure error =	**-0.001 m**	ok
Two set-ups, therefore survey tolerance is ± 0.003 m					

Application

This method is best suited to sites with small spatial extent (both horizontal and vertical) that have a clear line of sight from the primary benchmark to all objective points. <u>For this method, it is especially important that the instrument be the same distance from all objective points measured from that position.</u>

Advantages:

- This method is relatively quick to perform since it only involves two instrument setups.
- Points in the circuit where errors occurred can be isolated by examining the level note. This is done by looking for discrepancies between the height difference of subsequent objective points on the forward and return runs. For example, in
- Table 2 the height difference between BM1 and BM2 is 0.008 m on the forward run and 0.007 m on the return run, so there does not appear to be any major error.

Limitations:

- If there is an error with the instrument (collimation error), the bias will not be detected on the intermediate foresights, it will only be detected once the loop is closed.
- The closure error does not account for errors in the reading of the intermediate foresights.

Survey tolerance

Since this method involves only two instrument setups, the absolute value of the closure error must be less than or equal to 0.003 m. If it exceeds 0.003 m, the circuit must be redone. Closure error is never distributed with this method. Additionally, the discrepancy between forward and return elevations for each point surveyed must be less than or equal to 0.003 m, if not the objective point in question must be re-surveyed as a circuit. Only the elevations obtained on the forward run should be documented in the Benchmark History, elevations obtained on the return run are only used for verification.

7.2 Forward and Return Runs with Four or More Setups

This method consists of a forward run and a return run, changing direction on the returning point, and moving the level after each foresight (Figure 11 and

Table 3). If turning points are required, they should be the same on both legs of the circuit. This will allow for tracking of errors since the surveyed elevation of the turning points should be the same on the forward and return runs.

Application

This method is typically used when it is not possible to sight directly between the primary benchmark and all other objective points, either due to obstruction of the line of sight or due to the spatial extent of the network.

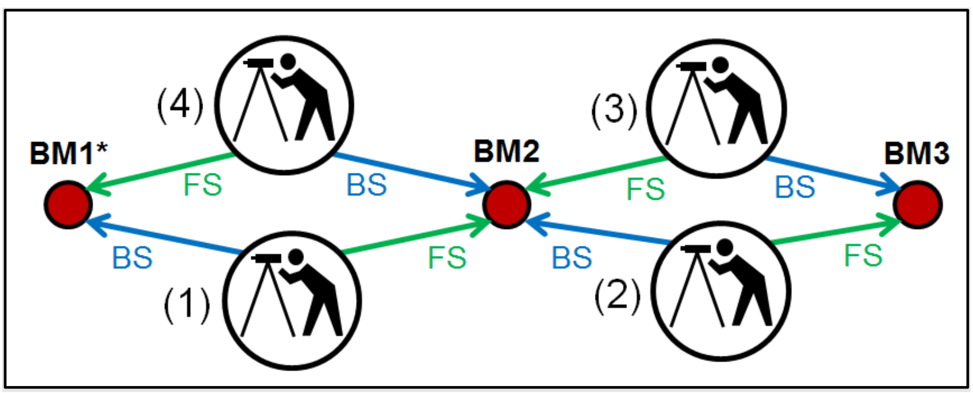

Figure 11: Forward and return runs with four setups. Red circles indicate objective points and setup numbers are given in brackets. The circuit starts and ends at BM1, as indicated by the star.

Table 3: Level note corresponding to the scenario in Figure 11, forward and return runs with four setups.

Station	Backsight	Height of Instrument	Foresight	Elevation	Notes
BM1	2.250 m	6.563 m		4.313 m	
BM2	2.192 m	6.497 m	2.258 m	4.305 m	
BM3	1.444 m	6.634 m	1.307 m	5.190 m	
BM2	2.892 m	7.196 m	2.330 m	4.304 m	
BM1			2.882 m	4.314 m	
			Closure Error =	-0.001 m	OK

Four setups, 240 m circuit length.	

Advantages:

- Ability to isolate points in the circuit where errors occurred by examining the level note. This is done by looking for discrepancies between the height difference of subsequent objective points on the forward and return runs. For example, in
- Table 3 the height difference of BM1 and BM2 is 0.008 m on the forward run and 0.010 m on the return run so does not appear to be any major errors.

Limitations:

- This method can be time consuming due to the number of setups required.
- Errors due to instrument setup propagate throughout the loop. For example, an incorrect instrument height determined on the first setup will affect the reading from the second setup since the backsight will be wrong.

Survey tolerance

Since this circuit involves four or more setups, the survey tolerance is calculated using the circuit length (Section 6.2). When the closure error exceeds the survey tolerance, the appropriate part of the circuit must be rerun. If the error is within tolerance but the absolute value is more than 0.003 m, it is distributed.

Other considerations: a series of small loops

Depending on the spatial extent and visibility of the local reference network, this scenario may take the form of a series of sequentially closed small loops. When a circuit starts on a benchmark that is not the primary benchmark, its surveyed elevation from the previous run should be used as the starting elevation. For example, if the first circuit is from BM1 to BM2 and then back to BM1, and the second circuit is from BM2 to BM3 and then back, this second circuit should begin with the surveyed elevation of BM2. For this scenario, it is important to understand how error can propagate between loops. For example, if the closure error is 0.003 m on both loops, the total closure error is 0.006 m which may exceed the survey tolerance, depending on the total distance surveyed. Since it can be tricky to track errors with a set of sequentially closed loops, this method should only be used if it has been approved by local supervisors as an acceptable solution to resolve an operational need. For this scenario, the simplest way to calculate the total closure error is to subtract the sum of the foresights from the sum of the backsights: $CE = \sum BS - \sum FS$.

7.3 Simple Loop

This method is a continuous forward run, starting and ending on the primary benchmark, moving the level after each foresight (Figure 12 and Table 4).

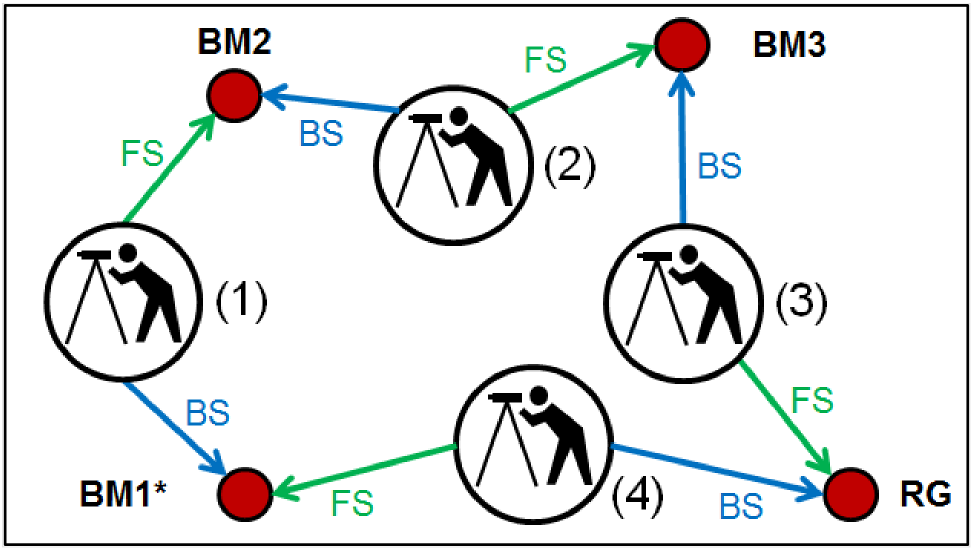

Figure 12: An example of a simple loop starting and ending on BM1, as indicated by the star. The instrument is moved after each foresight and the setup number is indicated in brackets.

Table 4: Level note corresponding to the simple loop example from Figure 12.

Station	Backsight	Height of Instrument	Foresight	Elevation	Notes
BM1	1.250 m	5.563 m		4.313 m	
BM2	1.205 m	5.509 m	1.259 m	4.304 m	
BM3	0.800 m	5.991 m	0.318 m	5.191 m	
RG	2.201 m	6.191 m	2.001 m	3.990 m	
BM1			1.880 m	4.311 m	
			Closure Error =	0.002 m	OK
Four set-ups, 450 m circuit length Survey tolerance is ±0.01√0.45km = ±0.007 m					

Application

This scenario can be used when the benchmark locations are conducive to a continuous loop run. It is not an acceptable method when obtaining the first elevation of a new benchmark or reference gauge.

Advantages:

- Relatively quick to perform as there is only one backsight and one foresight per objective point.

Limitations:

- There is not the same quality control as with the methods presented in Sections ⍰ and 7.2 since there is only ever one foresight per objective point.
- When a closure error is found, it is not possible to know where in the circuit the error was introduced.

Survey tolerance

If there are three or less setups, the ±0.003 m rule applies. If there are four or more setups, the distance rule applies. Additionally, if any point in the circuit has a surveyed elevation that differs from its established elevation by more than ±0.003 m, this difference must be confirmed by performing an additional simple loop from the primary benchmark to the point in question and back.

8. Monitoring Reference Gauge Stability

The elevation of the reference gauge is monitored in order to determine:

1. Its overall stability;
2. whether gauge corrections are required for stage records such as time series and gauge heights noted during discharge measurements.

The frequency with which the elevation of the reference gauge must be monitored depends on its documented stability (Section 4.1). At a minimum, it must be surveyed once a year. Any benchmark classified as stable following the procedures outlined in Section 4.1 can be used to monitor the elevation of the reference gauge via levelling.

8.1 Surveying the Reference Gauge Elevation

Figure 13 is a schematic demonstrating where to survey various types of reference gauges in order to obtain their elevations. These include wire weight gauges (B), staff gauges (C) and electric contact gauges (D). In each case, gauge corrections are determined by comparing the surveyed elevation of the reference gauge to its established elevation as explained in Section 8.2.

For wire weight gauges, the surveyor must determine the elevation of the bottom of the weight. To do so, the sighting should be taken within the lowest centimeter of the weight which is graduated with 2 mm markings, and the height z in Figure 13 must be subtracted from the height of the instrument. The reading output from the wire weight gauge, often on a digital screen, should correspond to this elevation. If not, a gauge correction should be considered.

For staff gauges, the surveyor must determine the elevation of the zero of the scale. To do so, a sighting can be taken on any part of the graduated plate. If the staff gauge is too far below the line of sight, a survey rod should be placed beside it. The height z in Figure 13 must be subtracted from the height of instrument.

For electric contact gauges, the surveyor must determine the elevation at which the tape is read, this is the triangular marker in Figure 13D. This can be done by sighting the bottom of the ECG plummet and adding the height z, or by sighting on the tape and calculating the difference up to the tape read marker. If the survey instrument is too high for a reading to be obtained on the ECG, a ruler or a survey rod can be placed beside the reel mounting to enable determination of the elevation of the reading/reference marker of the electric contact gauge.

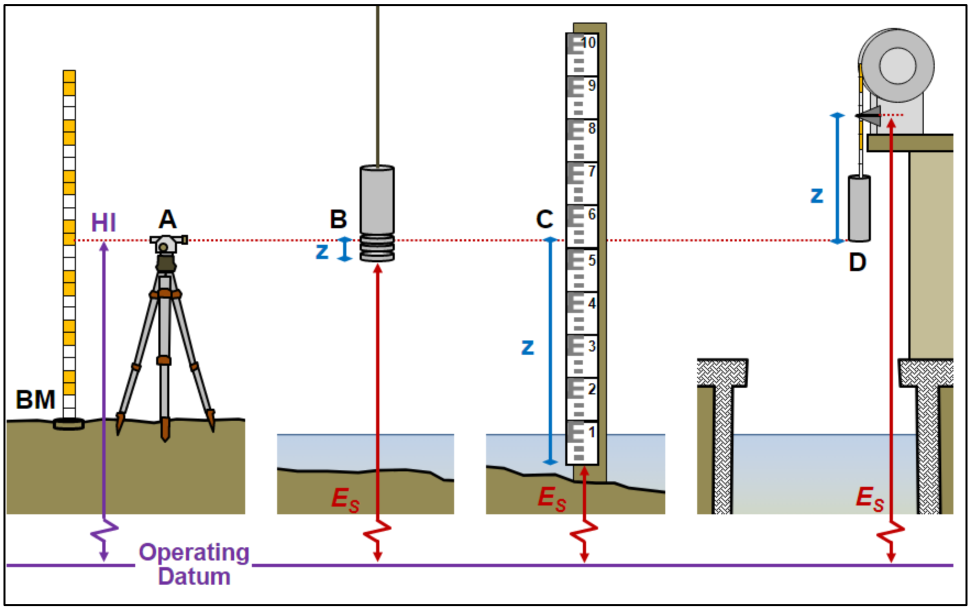

Figure 13: Demonstration of how to obtain the surveyed elevations (E_s) for the various reference gauges: a wire weight gauge (B), a staff gauge (C) and an electric contact gauge (D). The height of instrument (A), HI, was obtained using the benchmark BM.

8.2 Gauge Corrections

Gauge corrections (GC) temporarily compensate for reference gauge (Figure 14). They are computed each time that the reference gauge is surveyed by subtracting the established elevation of the reference gauge from its surveyed elevation:

Gauge Correction (GC) = Surveyed Elevation – Established Elevation

If the absolute value of GC is ≤ 0.003 m, no correction is applied. If it exceeds ±0.003 m, a gauge correction is applied to all stage data (see *qSOP-NA052 – Data Computation Manual – Stage Correction*).

Gauge corrections are applied until:

1. the elevation of the reference gauge returns to its (previously) established elevation OR
2. a new gauge correction is determined via levelling, or a new established elevation is determined by assessing the stability via the Benchmark History (see Section 4).

Gauge corrections must only be applied in the data computation system. They must not be applied in the data logger. Gauge corrections must also be kept separate from other corrections such as sensor reset corrections to ensure proper traceability and quality assurance. Sensor reset corrections account for the difference in water levels read by the reference gauge and the sensor after having accounted for gauge corrections (Figure 15). See the standard operating procedure on stage corrections for details (*qSOP-NA052*).

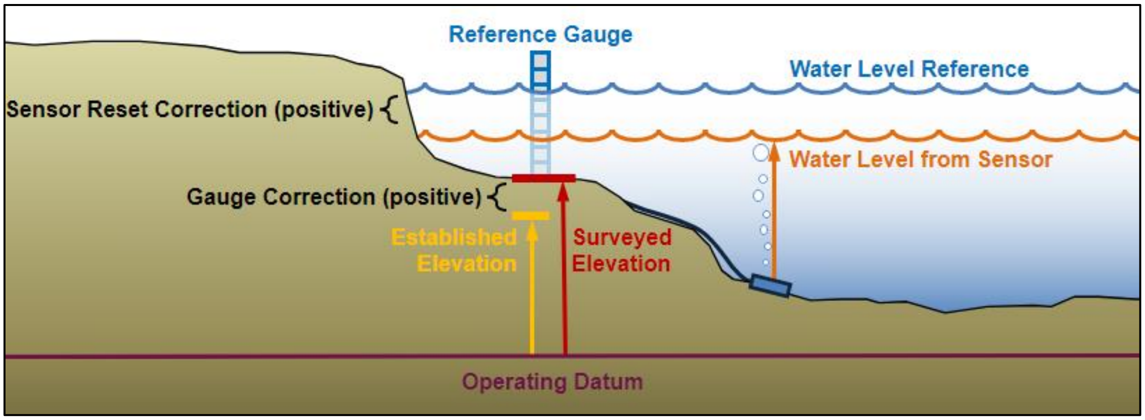

Figure 14: Information involved in the definition of gauge corrections and sensor reset corrections.

8.3 Changing the established elevation of the reference gauge

Changing the established elevation of the reference gauge should reduce or even eliminate the need for future gauge corrections. Deciding to change the established elevation of the reference gauge must be based on an assessment of stability using the Benchmark History (Section 4). When changing the established elevation of the reference gauge (Figure 15), the following steps are recommended to ensure that reliable and continuous water level data are recorded throughout the process:

Prior to the station visit:

- Define a new established elevation for the reference gauge. This value should reflect the most repeatable surveyed elevation.

During the station visit:

- Survey the reference gauge and compare this elevation to the proposed new established elevation. If they agree within ±0.003 m, proceed with the change. If not, postpone changing the established elevation until further analysis.
- Measure the water level using the reference gauge, noting the stage sensor value observed at this time. Apply a sensor reset correction if needed (see *qSOP-NA052 – Data Computation Manual – Stage Correction* for details).
- Change the established elevation of the reference gauge. This may require adjusting the instrument setup so that readings are easily compared with sensor outputs (i.e., adjusting the tape position for an electrical contact gauge).
- The reference gauge should be surveyed again to record that the gauge correction was applied.
- Measure the water level using the reference gauge, which has a new established elevation. Note the stage sensor value observed at this time. Apply a sensor reset correction once again, if needed.

After the station visit, while back in office:

- The difference between the new established elevation and the previous established elevation of the reference gauge prior to the change in established elevation is the gauge correction that is applied in the data computation system immediately prior to the change in established elevation. Re-establishing the elevation of the reference gauge eliminates the need for a gauge correction going forward.

- A sensor reset correction based on the reference gauge measurement obtained before the change of established elevation is applied to data prior to the site visit (see *qSOP-NA052 – Data Computation Manual – Stage Correction* for details).
- All relevant documentation (data computation system, station analysis) must be updated to reflect the change.

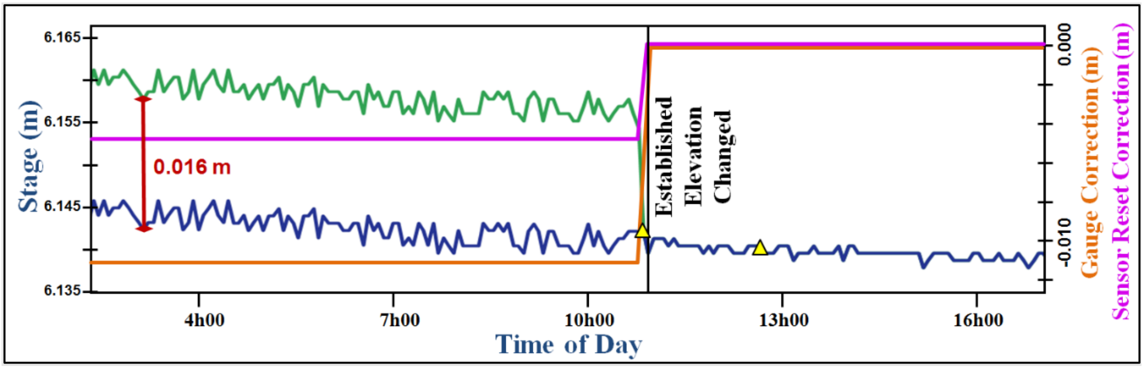

Figure 15: Example of corrections applied to stage data prior to and following a change of established elevation. The yellow triangles show reference gauge readings. Before the change of established elevation, there was a difference of 0.016 m between the raw (green) and corrected (blue) signals which corresponded to a gauge correction (GC) of -0.011 m and a sensor reset correction (SRC) of -0.005 m. The sensor was reset following the first gauge check, and the established elevation was changed and the SRC (pink) and GC were set to zero. After this change of established elevation, the raw and corrected signals match perfectly since there is zero correction (blue line is superimposed on green).

9. Surveying the water level and other landmarks

Performing a direct water level is the process of determining the water level elevation (expressed relative to the operating datum) by surveying from a point of known elevation to the water surface. In the example shown in Figure 16, the water level measured on the rod (B) is added to the surveyed elevation of point A. Important considerations for direct water level measurements can be found in Hydrometric Field Manual - Measurement of Stage (qSOP-NA008).

When the surface of the water is choppy or surging, the height of the water surface may be difficult to measure. In this case, a temporary stilling well can be constructed from a bucket with holes at the bottom (see Figure 16). This bucket will stabilize the water surface at the point where the rod is to be read. The water level fluctuations (I.e., surge) should be documented on the field note, as this will help guide future use of this value. For example, if the reading was between 0.631 m and 0.639 m on the rod, the reading would be 0.635 m with a surge of 0.004 m.

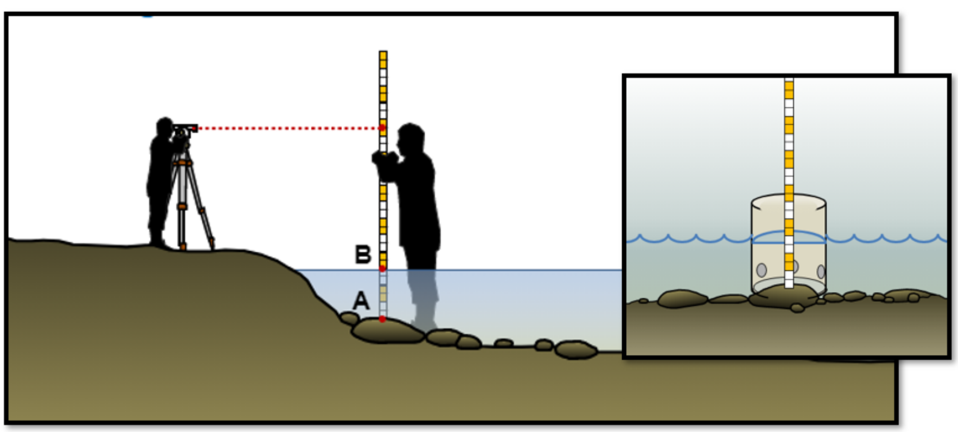

Figure 16: Demonstration of a direct water level measurement and an inset of a temporary stilling well (bucket with holes at the bottom). The surveyed water level value is determined by adding the survey rod reading at B to the surveyed elevation of point A.

Other useful information at a gauging station can be acquired from elevation surveys. Depending on its intended use, elevations can be obtained with a wide variety of tools, ranging from terrestrial levels, to GNSS, to the bottom tracking function of Acoustic Doppler Current Profilers. In particular, the elevations of the following points can be valuable:

- High water marks can be compared to recorded gauge heights (see qSOP-NA008 – Measurement of Stage).
- The elevation at which water flow overtops the riverbanks is useful for rating development, especially to define when the system might reach flood conditions.
- The elevation of zero flow can be used to define the offset of the lowest rating segment in a stage-discharge rating.
- The shape and elevation of hydraulic controls (section and channel) can help in developing the stage-discharge rating.
- Elevations of the end of an orifice line or a stilling well intake will help determine the stage at which the gauge is no longer connected with the stream. They will also assist in determining if the sensor has moved.
- At sites using alternative discharge monitoring methods, such as index velocity sites or image velocimetry, the geometry of the standard cross section must be surveyed routinely.

10. Documentation Requirements

10.1 Level Notes

The level page of the hydrometric survey note is divided into columns for recording observations and computing elevations. The *Station* column contains the name of the objective point (e.g., benchmark identification number, turning point number, type of reference gauge) and the information in each row pertains to that objective point. The eHSN has columns for time, backsight, height of instrument, foresight, surveyed elevation, comments, and established elevation. General comments about the levelling activities can be entered in the comments section at the bottom of the page. Should a paper note be completed for leveling, the final data should be entered into the eHSN and a photograph of the original paper note included as a part of the visit. An example of various level circuits, conducted with eHSN 2.3.2, are included in Figure X below. Of important note is **blue** values are calculated by the eHSN, while **black** values are entered by the user.

LEVEL NOTES

Conventional Leveling: ✓ Total Station: ❑

Station	Time	Backsight	Height of Instrument	Foresight	Elevation	Comments	Est. Elev.
**O-20-313	10:30	1.257	21.257		20	BC in Bedrock	20
O-21-305	10:43	2.718	21.242	2.733	18.524	BC for GNSS	18.525
**O-20-313	10:56			1.243	19.999		20
			Closure	0.001			
**O-20-313	11:05	2.569	22.569		20	BC in BR	20
O-20-314	11:09			1.106	21.463	BC on VL boulder	21.463
O-20-315	11:15	3.297	22.471	3.395	19.174	BC in BR	19.173
O-20-314	11:21			1.007	21.464		21.463
**O-20-313	11:26			2.469	20.002	OK	20
			Closure	-0.002			
**O-20-313	11:38	0.256	20.256		20		20
RP1	11:39	2.954	20.225	2.985	17.271	Rock in River	
**O-20-313	11:44			0.227	19.998		20
			Closure	0.002			

Level Checks Summary

Time	WL Reference Point	Elevation	Distance to Water Surface (m)	Water Level Elevation (m)	Datum	Corrected Water Level	HG	HG2	Surge	Comment
11:39	**O-20-313	17.271	0.189	17.460	0.000	17.460	17.462		0.002	inline with sensor
Comments: Cut branches to see O-21-305, marked setup location with rocks										
Surveyed By: Max Wade										

Figure 17: Example of a completed level sheet from eHSNv2.3.2, which includes three distinct level circuits.

10.2 Other Documentation Requirements

For each station, datum, benchmark and reference gauge information must be documented as follows:

In HYDEX:

- The operating datum name. Any internal communications or notes required should be included in the non-published remarks section of the operating datum.
- Datum conversions available for the station, including associated metadata (e.g., date, method of determination and uncertainty).
- A description of all benchmarks and reference gauge locations, as part of the station sketch.

In the Benchmark History, recalling that this record may be a combination of hard copy and digital documents:

- A complete list of all existing and defunct reference gauges and benchmarks with descriptions and elevations, indicating the ones that are currently used.
- A chronological listing of all benchmark activity throughout the station’s history.

In the data computation system and in the Station Analysis:

- A complete list of the current reference gauge and benchmarks
- A description of all benchmarks and reference gauge locations
- Decisions about benchmark replacement
- Decisions about changes to any established elevations of benchmarks or reference gauges

In the gauge house:

- A complete list of the current reference gauge and benchmarks
- A benchmark history containing at least five years of elevations.

References

Environment and Climate Change Canada (2017). Two Peg Test Template, qFOR-NA029-01-2017. Water Survey of Canada, National Hydrological Services, Meteorological Services of Canada.

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Environment Canada, 2012. qSOP-NA037-00-2012 - Hydrometric Manual Data Computations Beta Version.

Environment and Climate Change Canada (2022). Hydrometric Manual – Data Computations Stage Correction. qSOP-NA052-01-2022. Water Survey of Canada, National Hydrological Services, Meteorological Services of Canada.

Kenney, T.A., 2010. Levels at gaging stations: U.S. Geological Survey Techniques and Methods 3-A19.

Natural Resources Canada (2013). Guidelines for RTK/RTN GNSS Surveying in Canada. General Information Product 100-E. Earth Sciences Sector, Surveyor General Branch.

Natural Resources Canada, 1978. Specifications and Recommendations for Control Surveys and Survey Markers.

Natural Resources Canada, 2017. Height Reference System Modernization.

Oklahoma Water Resources Board Water Quality Programs Division, 2004. Standard Operating Procedure for Surveying Gaging Stations, Draft copy.

Water Resources Branch, Alberta District, 1993. Benchmark/Leveling Policy.

Appendix A: Procedures Specific to Total Stations

For sightings exceeding 300 m, special procedures must be followed. See Natural Resources Canada (1978) for details. The following steps are recommended by the WSC for sightings under 300 m.

1. Set up and level the total station. Turn on the scope and orient it to the forward position.
2. Place the target over the backsight benchmark (A) and sight on target.
3. Record vertical distance including sign (+/-) in BS column.
4. Place target over the foresight benchmark (B) and sight on target.
5. Record vertical distance including sign (+/-) in FS column.
6. Reverse the scope to the reverse face position and check that the instrument is still level. This reversing of the scope eliminates vertical axis misalignment, including vertical collimation error. Note, if surveying more than one elevation (e.g. a benchmark circuit), survey all elevations with the same face, then reverse the face position and survey all elevations with the 2nd face.
7. Point on foresight benchmark (B) and record vertical distance in BS column.
8. Point on backsight benchmark (A) and record vertical distance in FS column.

Document the circuit on the field note in the same manner as a conventional level circuit, the WSC electronic hydrometric survey note (eHSN) does the math correctly when a total station is indicated as the instrument. When entering survey values into the eHSN be careful to include the correct signs (positive for sights above the elevation of the instrument and negative for sights below the instrument.) Large differences between the first backsight and the last foresight indicate a potential collimation error and may require the instrument to be re-calibrated or serviced.

The eHSN will

1. Subtract the BS values (including signs) from the elevation to obtain the Height of Instrument value.
2. Add the FS values (including signs) to Height of Instrument to obtain elevations.

Table 5: Example eHSN input for total station levelling.

Conventional Leveling: ❑ Total Station: ✓

Station	Time	Backsight	Height of Instrument	Foresight	Elevation	Comments	Est. Elev.
**BM 9		1.799	10.063		11.862	Drill stem	11.862
BM 10				1.928	11.991	I Pin	11.991
RP1		-6.985	10.064	-6.984	3.079	Rod in River, .114 cut at 08:30	
BM 10				1.929	11.993		11.991
**BM 9				1.800	11.864		11.862
			Closure	-0.002			
BM 10		1.399	10.592		11.991	I Pin	11.991
RP2		-7.548	10.592	-7.548	3.044	.152 cut at 10:50, rod on edge of HG2 block	
BM 10				1.399	11.991		11.991
			Closure	0.0			

Appendix B: The Two-Peg Test

The two-peg test is a simple closed circuit level run used to ensure that the line of sight through the telescope of a level is horizontal. This is done by measuring the inclination of the level's line of sight, which is known as the collimation error and is expressed as vertical deviation in millimetres over a horizontal distance in metres. The WSC requires that the collimation error not exceed 0.001 m over a sighting distance of 30 m.

To begin the test, set two stakes, A and B, anywhere from 60-90 metres apart on reasonably level ground (Figure 17). Set up and level the instrument halfway between the two stakes and take rod reading **a** on stake A and reading **b** on stake B. These values are noted on the two-peg test form (Figure 18). Since the observations are made from a point that is equidistant from each stake, the difference in the reading, **b-a**, is the correct difference in elevation between the two stakes, regardless of any error in the instrument.

Next, set up and level the instrument as close as possible to stake A. Read **c** on the rod through the telescope. Move the rod to stake B and obtain reading **d**. If the instrument is in good adjustment, the difference in elevation of the two stakes as observed from stake A will be the same as when observed from midway between them, so that **d-c** will equal **b-a**. The correct reading of the rod at stake B (**e**) is equal to **b - a + c**. Therefore, the difference between this value and the actual reading at **d** is the error in the adjustment of the line of sight between the two stakes (I.e., the collimation error). An excel spreadsheet of the two-peg test form which automatically calculates collimation error can be found on the WSC Operational Library (qFOR-NA029-01-2017).

$$Collimation\ error = b - a + c - d$$

If the collimation error exceeds 0.001 m over a 30 m sighting distance, the instrument should be sent to a calibration facility for proper adjustment as per the manufacturer's instructions.

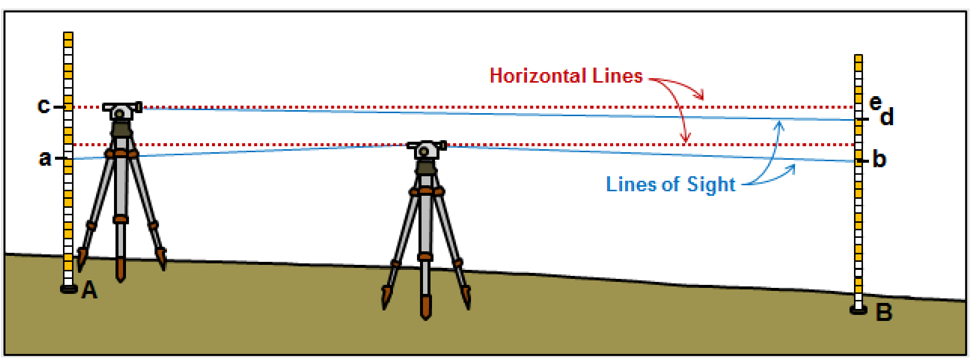


Figure 17: An illustration of the principles of the two-peg test.

Two Peg Test Form

Environment and Climate Change Canada
Water Survey of Canada

DATE: 2017/05/01

INSPECTOR: Inspector Name

LEVEL MAKE: Leica

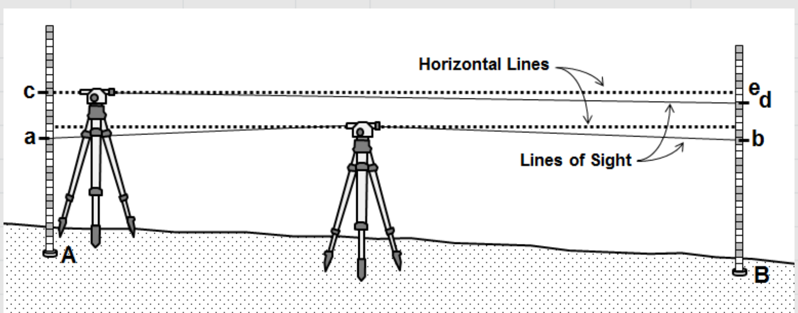
LEVEL MODEL: DNA3

LEVEL SERIAL #: 12345

LEVEL ASSIGNMENT: Tech name

Distance between rods A and B	90 m		
Shot a	0.573 m	Shot c	1.161 m
Shot b	1.35 m	Shot d	1.923 m
Difference b-a	0.777 m	Difference d-c	0.762 m
(Difference b-a)-(Difference d-c)	0.015 m		
Collimation error	0.005 m / 30 m		

less than or equal to 0.001m/30 m? No



Comments:

For Two Peg Test Procedure refer to Hydrometric Field Manual - Levelling Appendix A (qSOP-NA005-03-2017)

Figure 18: Example of a completed two-peg test form. The true difference in elevation between stakes A and B is 0.777 m and the collimation error is 0.015 m over 90 m. This exceeds the acceptable limit.

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