Sampling Method/Media: **Single Well Response Testing / Groundwater**	Title: **Standard Operating Procedure for Monitoring Well Response Testing**
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1. Introduction and Scope

This Standard Operating Procedure (SOP) provides operating guidelines and instruction for performing an in situ response test (slug or bail test) at a single monitoring well within the provincial jurisdiction of British Columbia (BC). This test method is used in conjunction with an appropriate data analysis procedure to estimate saturated hydraulic conductivity of the media in the immediate vicinity of the monitoring well screen. Hydraulic conductivity is a key parameter needed to characterize groundwater flow and is needed to develop a site's conceptual site model, as described in the Ministry of Environment and Climate Change Strategy's (ENV) Technical Guidance 8 (ENV, 2017a) document. An estimate of hydraulic conductivity is also needed for water use determinations, specifically for determining whether future drinking water use may apply (ENV, 2017b). Hydraulic conductivity estimates are also needed for groundwater modeling.

Figure 1. Slug testing setup at a monitoring well.

This SOP forms part of the British Columbia Field Sampling Manual (BCFSM). Additional information on single well response testing is provided in Part E2 – Groundwater, which must be used in conjunction with the information provided in this SOP. Further guidance regarding groundwater is provided in the Water Sustainability Act (WSA) and the Groundwater Protection Regulation (GPR) which are available at:

https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/laws-rules/groundwater-protection-regulation.

The Environmental Management Act (EMA), the Contaminated Sites Regulation (CSR) and associated guidance documents provide information specific to groundwater monitoring wells installed to investigate and remediate contaminated sites; these documents are available at:

https://www2.gov.bc.ca/gov/content/environment/air-land-water/site-remediation/contaminated-sites.

Groundwater well installations, sampling, monitoring and decommissioning conducted for regulatory purposes within the provincial jurisdiction of BC must be carried out with consideration to the WSA, the GPR, the EMA, and the CSR, all as applicable, Part E2 of the BC Field Sampling Manual, and this document.

2. Document Control

This Standard Operating Procedure (SOP) is a controlled document. Document control provides a measure of assurance that the specifications and guidance it provides are based on current information that has been scrutinized by a qualified reviewer/s. Controlled documents are reviewed within a five year life cycle. Please ensure that the revision date listed in the header of this document does not exceed five years.

3. Principle of the Measurement Method

Monitoring Well Response Testing (i.e. Slug or Bail Testing)

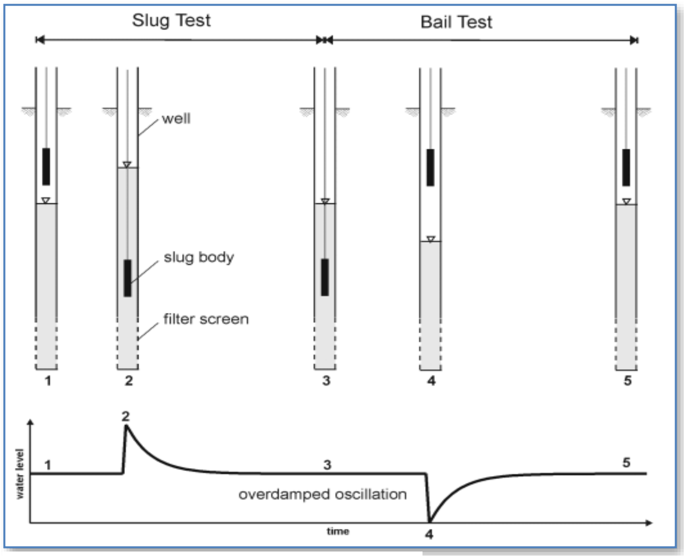

Figure 2. Examples of slug and bail tests.

In a monitoring well response test, a sudden change in pressure within a well is induced, typically by the insertion or removal of a slug or a volume of water, followed by the measurement of the rate of water level recovery to stable conditions. Water level response is a function of the hydraulic conductivity of the media surrounding the well screen, but can also be influenced by wellbore skin effects, filter pack drainage, aquifer heterogeneity, inertia (in high permeability wells), and external forces (e.g., tides or barometric air pressure). The test is relatively quick and simple to perform, and does not require the disposal of large quantities of potentially contaminated purge water. In addition, tests can be completed in aquifer materials of lower hydraulic conductivity which would not be suitable for pump testing.

4. Quality Control

- Ensure that all instruments are functioning and properly calibrated before mobilization to the site. Check once more in the field and ensure that all required information is recorded.
- All material entering the well (slugs, bailers, water level probes and transducers) must be fully decontaminated prior to use if working on a site where groundwater contamination may be present. A three-bucket rinse using a phosphate-free detergent solution, tap water and deionized water is recommended.
- Monitoring wells should be developed and stabilized prior to testing. If the water level response is very quick, repeat the test after the monitoring well has recovered to at least 99%.
- Data must be collected at sufficiently frequent intervals (pressure transducers may be required for permeable media) and/or for a sufficiently long period of time (several hours for low-permeability media).

5. Recommended Equipment and Materials

Field equipment should include the following:

- Slug Testing:
  - A slug and suspension cable made of inert, non-porous water-tight material of sufficient size to displace approximately 0.5 m of water within a well.
- Bail Testing:
  - A disposable single use bailer or a decontaminated stainless steel bailer.
  - Appropriate water collection containers (e.g., drums) if the potential exists for contaminated water.
- Pneumatic Testing:
  - A pneumatic slug testing kit with fittings suitable to seal the monitoring well for pressure application. The kit should include the pneumatic manifold, gauges, adaptors, a pressure transducer/datalogger, and a hand pump, air compressor or compressed air/nitrogen to apply either air pressure or vacuum to the well head.
- Electric water level probe to measure static water levels and water recovery during the test,

- Site plan and borehole logs if available,
- Watch, stopwatch or other device to record elapsed time during the test,
- Field book/forms to record test details and recovery measurements,
- Pressure transducer with incorporated datalogger and non-stretch cable for suspension of the pressure transducer within the monitoring well (optional; needed for wells screened in high hydraulic conductivity sands and gravels); and,
- Decontamination equipment (i.e. three bucket rinse, phosphate-free detergent, tap water and deionized water) if working on a site where contaminated groundwater is known or suspected.

6. Test Considerations

- Monitoring wells should be adequately developed prior to testing, since a poorly-developed well can result in underestimating hydraulic conductivity by up to an order of magnitude. If the well has been inactive since installation, redevelopment may be required.
- Slugs and bailers should be deployed in a controlled manner to reduce agitation and splashing. This is especially important when a transducer is used. An abrupt or uncontrolled insertion or retraction of either tool will result in “splash effects”, which can significantly impact the determination of maximum (zero-time) head displacement.
- Water should not be added to environmental monitoring wells. If water is added, take care to ensure that it does not run down the sides of the casing as this will result in a non-instantaneous water level change.
- Monitoring well response tests should not be performed on wells containing LNAPL; LNAPL will interfere with the response measurements. LNAPL bail down testing can be considered for estimating LNAPL transmissivity.
- Discuss water collection, treatment, and/or disposal requirements with your project manager prior to conducting a test where groundwater contamination suspected.
- Equipment in the well such as a foot valve and tubing, or a submersible pump must be removed prior to conducting a response test. After removal, ensure that the water level has returned to static prior to conducting the test.
- If the well is under a vacuum or has positive pressure (which can happen if the screen is submerged), remove the well cap and allow sufficient time for the water level to recover to static. Conduct several water level measurements to ensure stablility prior to the start of the test.
- If manually pumping a well to induce drawdown, it is beneficial to lower a water level probe to the desired level of drawdown before commencing the test (e.g., if 1 m of drawdown is desired, install the water level probe 1 m below the water level). The water level alarm will sound because the probe is submerged. With the water level alarm sounding proceed with rapid pumping until the alarm ceases, which will indicate the water has been drawn down by 1 m.
- Response test results for monitoring wells under the influence of external forces (i.e., tides, barometric air pressure etc.) can be corrected using water level response data from an appropriate monitoring well completed within the same test formation, but outside the radius of influence of the test well (i.e., typically more than 5 m from any test well). Using superposition any head changes at the monitoring well attributed to external forces can be applied as long as the wells are completed in the same formation. If pressure transducers monitor head changes in the monitoring well at an appropriate interval the externally forced head changes can be deducted from the K-test response. Barometric pressure influences can be removed in a similar way by using a barometric pressure transducer to measure barometric pressure, and then subtracting the barometric pressure from the pressure data recorded by transducers placed in monitoring wells (which measure both the height of the water column above the transducer and barometric pressure).

7. Test Procedure

Step 1

Determine static water level: measure and record the well’s water level and the time of this measurement before the start of testing to evaluate pre-test water level fluctuations and to determine static water level conditions. If the depth to the bottom of the well is unknown, this should be estimated using the water level tape. Ensure that groundwater returns to static conditions after the well depth is measured.

Step 2

In tidal areas, collect a minimum of two water level measurements over a 30 minute period to determine whether tidal conditions are influencing the water level in the well. If an influence is identified the measurements will also determine if the water level is rising or falling. Alternatively, in tidal areas, select an observation well that is completed in the same formation as the test wells and under the same tidal influence and equip this well with a pressure transducer recording water levels at a 15 minute frequency. The time of readings should always be recorded whether the site is tidal or not. In addition, consider conducting the test when tidally influenced water level changes in the well are minimal which occurs at high tide and low tide. Account for tidal lag, if known, when determining when high tide may be occurring in a well.

Step 3

Record all required information including well location, date, well details, and test methodology in a field book or on the attached Record of Monitoring Well Response Test Form.

Step 4

Turn on the pressure transducer (if being used): ensure the transducer is set up with a suitable measurement frequency (i.e., every 0.5 second if testing gravel/sand formation). Install the pressure transducer to a depth which is deeper than the planned slug depth or bailed water level (i.e., if water is to be removed to a depth of 15 m below top of casing (btoc), then ensure the transducer is below this depth), and is shallower than the working range of the transducer (i.e., if the transducer has a 5 m working range, do not place the transducer deeper than 4 m below the static water level – this allows for up to a 1 m rise in the water table if a slug is dropped into the well). Secure the transducer to ensure it does not move during the test. Ensure that a non-stretch cable is used to suspend the transducer (e.g. 25 lb fishing line or a cable supplied by the transducer manufacturer).

Step 5

Measure the depth to static water level at the beginning of the test. If different from the level measured in step 1, confirm the measurement and determine the reason for the fluctuation. If necessary, delay the test until the well has fully recovered to a static water level (e.g., after inserting pressure transducer or removing sampling equipment).

Step 6

At time zero, cause a rapid change in water level by inserting and quickly removing a bailer, by the addition of clean water, or the insertion of a mechanical slug. The goal of either method is to cause a "near-instantaneous" change in water level. If using a slug, ensure that the length of rope is appropriate so that the slug enters the water column and does not interfere with the transducer.

Step 7

Pumping and manual recording is adequate for lower-permeability media, while a slug combined with a pressure transducer is preferred for higher-permeability media. Pumping time should be very short relative to the well's response time. For example, two minutes of bailing versus 45 minutes or more to recover. However, two minutes of bailing is not okay for a well that recovers within 5 minutes. The amount of water level displacement should be in the range of 0.3 m to 1 m. Record the clock time at time zero. Ensure that water from the pump tubing does not drain back into the well (e.g., through the foot valve) because this will render the test invalid.

Step 8

If conducting a bail test, collect water in an appropriate container. Dispose of the water to ground surface in the vicinity of the well; however, if there is concern regarding potential contamination the bailed water must be contained until competent analytical data is available to determine its status. Water quality analysis, collection and/or disposal contingencies should be a key component of field preparation planning.

Step 9

Measure the water level as it recovers. Record the data relative to 'time zero' (i.e., the time at which the change of water level was induced. The frequency of readings is dependent on the permeability of the media being tested. During the early portion of the test, collect measurement readings as quickly as possible (i.e., at least every 15 to 30 seconds by hand, or at the datalogger's maximum rate). Later time readings can be made at increasing time intervals if the water level response is relatively slow, and other site activities such as response testing at other wells could be performed during the intervals between later stage readings. It is often beneficial to have two staff conduct the test when manual readings are recorded, especially in the early stages of the test when readings are closely spaced allowing one person to measure water levels while the other person records the water level and time. If conducting multiple response tests simultaneously, ensure enough lateral separation exists so that the tests do not interfere with one another (e.g., minimum of 5 m separation). Continue recording data until 60% to 80% of recovery has occurred. If the well is very slow to recover (i.e., greater than two hours), then record data to a minimum of 60% recovery. In very slow responding wells, collect a water level measurement at the end of the day (recording actual clock time) and collect additional measurements the following day (or days) if returning to the site. Alternatively, a pressure transducer could be left in the well and retrieved during a subsequent site visit.

Step 10

Pressure transducer data should be confirmed with manual water level measurements. Manual measurements need only be taken a few times throughout the tests duration to confirm the data produced by the pressure transducer but must also be conducted to determine when sufficient recovery has occurred. Manual water level measurements should be taken before and after the test, along with a few readings during the test. Note the time of the measurement and take care to ensure that the water level probe does not affect transducer water level measurements.

Step 11

If the well is expected to take hours or days to recover, consider installing a barometric logger so that pressure transducer measurements cab be corrected for barometric changes.

Step 12

At slug tested wells, once water levels have reached pre-test levels, the slug can be removed to induce a water level rise (rising head test). At this point, reset the stop watch and repeat step 7. Decontaminate the slug, transducer, and water level probe once the test is complete. Follow procedures outlined in the BCFSM, Part E3, Section 3.9.6.1.

Step 13

If possible, data should be plotted in the field to check the adequacy of the monitoring frequency. If the tested monitoring well recovers faster than initially anticipated, the test should be repeated with more frequent readings. Check transducer data to ensure that water levels were recorded and that the data appears valid and competent ensuring that there are no errors. Further check to ensure that the water level did not drop below the transducer [flat-line] and that bumps associated with transducer movement did not occur.

8. Common Pitfalls

- Not obtaining an accurate static water level prior to the test (i.e. removal of in-well equipment, or pressure issues, forgetting to collect this measurement),
- Do not conduct a response test during periods of heavy rainfall, due to rising water table, as well as to avoid water entering the well,
- Tidal influence may affect results,
- Test not completed to 60%-80% recovery,
- Bailer/slug deployment results in transducer movement in well or in cable entanglement,
- Insufficient frequency of manual readings,
- Cable breaks and transducer or slug loss down the well (use 25 lb non-stretch test line for transducer, and rope (not string) for slug,
- Faulty transducer, data not reviewed in field; and,
- Forgetting to start or set up transducer properly.

9. Data Analysis

The collected data may be analyzed manually, using software (i.e. Aquifer Test or AQTESOLV) or by using a suitable analytical solution with a spreadsheet. The method should be selected based on each individual monitoring wells hydrogeological condition (unconfined, confined, fracture) and the hydraulic response (i.e., filter pack dewatering, formation response, overdamped, underdamped etc.).

The following table presents the typical conditions under which a response test may require analysis and the preferred analytical solutions (available in Aquifer Test or AQTESOLV software); also included are less common but valid analytical solutions.

Aquifer Type	Preferred Solutions	Supplemental Solutions
Unconfined (overdamped)	1. Bouwer-Rice (1976) 2. Hvorslev (1951)	
Confined (overdamped)	1. Hvorslev (1951) 2. Bouwer-Rice (1976) 3. Copper-Bredehoeft-Papadopulos (CBP) (1967)	
Unconfined and Confined (underdamped)	1. Butler et al. (2003)	1. van der Kamp (1976) 2. Kipp (1985)
Fracture	1. Barker-Black (1984)	

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Approval