# UST Site 1 Final Pre-Design Investigation Water Level Data Collection Work Plan Former Tongue Point Naval Air Station Astoria, Oregon

US Army Corps of Engineers®

Kansas City District
601 East 12th Street
Kansas City, Missouri 64106

**February 2021**

# UST SITE 1 FINAL PRE-DESIGN INVESTIGATION WATER LEVEL DATA COLLECTION WORK PLAN

## TONGUE POINT CON/HTRW FORMER TONGUE POINT NAVAL AIR STATION, ASTORIA, OREGON UST SITE 1

## ENVIRONMENTAL CLEANUP SITE INFORMATION # 171

**USACE CONTRACT NO. W912DQ-18-D-3008**
**Task Order No. F3057**

***Prepared for:***
**U.S. ARMY CORPS OF ENGINEERS**
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**February 2021**

**UST SITE 1 FINAL PRE-DESIGN INVESTIGATION**
**WATER LEVEL DATA COLLECTION WORK PLAN**
**FOR THE**
**TONGUE POINT CON/HTRW FORMER TONGUE POINT**
**NAVAL AIR STATION, ASTORIA, OREGON**
**UST SITE 1**
**ENVIRONMENTAL CLEANUP SITE INFORMATION # 171**

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# Acronyms

| | |
|---|---|
| µg/L | micrograms per liter |
| API | American Petroleum Institute |
| BTOC | below top of casing |
| CDM Smith | CDM Smith Federal Programs Corporation |
| CON/HTRW | containerized hazardous, toxic, and radioactive waste |
| COVID-19 | Coronavirus Disease of 2019 |
| CQCP | Contractor Quality Control Plan |
| DTP | depth to product |
| DTW | depth to water |
| FCR | field change request |
| IDW | investigation-derived waste |
| K | hydraulic conductivity |
| LNAPL | light nonaqueous phase liquid |
| MW | monitoring well |
| OAR | Oregon Administrative Rule |
| ODEQ | Oregon Department of Environmental Quality |
| PDI | predesign investigation |
| the Plan | water levels and slug testing work plan |
| PVC | polyvinyl chloride |
| QAPP | Quality Assurance Project Plan |
| the Site | Tongue Point CON/HTRW Former Tongue Point Naval Air Station |
| SOP | standard operating procedure |
| TPJCC | Tongue Point Job Corps Center |
| USACE | U.S. Army Corps of Engineers |
| UST | underground storage tank |

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# Section 1

# Background and General Planning

This water levels and hydraulic conductivity testing work plan (the Plan) describes the procedures to be used to deploy transducers in monitoring wells to collect background water levels and perform testing to characterize the hydraulic conductivity of the water bearing zone in select wells at Underground Storage Tank (UST) Site 1 Tongue Point containerized hazardous, toxic, and radioactive waste (CON/HTRW) Former Tongue Point Naval Air Station (the Site).

The Naval Air Station Tongue Point CON/HTRW project is part of Contract No. W912DQ-18-D-3008 Task Order No. F3057 to address petroleum contamination from refueling activities conducted by the U.S. Department of Defense. The Site had a known release that has resulted in the presence of light non-aqueous phase liquid (LNAPL) that previous investigations have concluded occurs in isolated and nonmobile pockets with limited occurrence controlled by the heterogeneous, but consistently low-permeability, nature of the soils at the Site. In addition, a sheen on surface water has been observed seasonally and is controlled by sorbent booms. The observed petroleum sheen on surface water on the shoreline of UST Site 1 is prohibited by the Clean Water Act (33 United States Code 1251 et seq.) Section 311(b)(3). The discharge and presence of a sheen is a violation of federal regulations per 40 Code of Federal Regulations 110.3. These regulations are the basis for corrective action as required by Oregon's statewide water quality narrative (Oregon Administrative Rule [OAR] 340-041-0007). The source of the sheen is the subject of a predesign investigation (PDI) and design task for a corrective action to remediate the contamination and mitigate the resulting sheen on surface water. The component of the PDI planned in this document will provide data necessary to inform the design. U.S. Army Corps of Engineers (USACE) will implement the design in a future cleanup action and closure of UST Site 1 task in general accordance with the Oregon Department of Environmental Quality (ODEQ) *UST Cleanup Manual* (ODEQ 2009).

USACE has conducted multiple actions spanning more than 25 years at UST Site 1. The contents of all six UST Site 1 tanks and associated piping were pumped and cleaned in August 1990, and tank decommissioning was performed in April 1992. Two of the tanks were closed in place and the remaining four tanks were decommissioned and removed from the Site. During tank decommissioning and removal, diesel fuel was released from one of the tanks. Immediately thereafter, recovery wells were installed, and groundwater monitoring began. Monitoring wells (MW) were installed during various past events. The existing wells that remain at the Site and their installation dates are: MW-01 and MW-05, September 1991; MW-06, March 1994; and MW-08, MW-09, and MW-10, each installed in July 2001.

CDM Smith Federal Programs Corporation (CDM Smith) plans to proceed with the deployment of six transducers in existing wells and prepared this Plan, per quality assurance project plan (QAPP) objectives and field change request (FCR) No. 01, for general water level data collection and analysis. CDM Smith will proceed with slug testing of selected wells at the Site to obtain estimates of the hydraulic conductivity of the water bearing formation at the Site. CDM Smith plans to recover LNAPL (also referred to as product) from monitoring wells and measure changes in product thickness during hydraulic monitoring.

Data obtained from Plan implementation will be used to assist in the design process. Water level monitoring with transducers will be conducted to support study goal #2 identified in QAPP Worksheet #11 and FCR No. 01 (CDM Smith 2020a). Study goal #2 in QAPP Worksheet #11 included evaluating groundwater levels and groundwater gradient at the Site. During the field investigation, manual water level measurements were recorded at monitoring wells and boreholes. However, information on the variability in water level in response to precipitation, tidal effects, and seasonal water level changes has not been collected. Transducer data will supplement manual water level measurements to provide more robust characterization of water levels by assessing water level changes over time at the area planned for remediation. These data will support the overall project goal of characterizing the Site to support design of a corrective action for UST Site 1.

CDM Smith obtained eight In-Situ Level TROLL 500 datalogging pressure transducers from USACE during the August 4, 2020 site visit and kickoff meeting. The devices were checked by CDM Smith and found to be nonresponsive. After returning to the office, the transducers were reset according to manufacturer instructions and were confirmed to work properly. Vented cables, desiccant, and hardware were obtained for the initial installation/deployment. Four of the devices were deployed in MW-06, MW-08, MW-09, and MW-10 on September 10, 2020. CDM Smith planned to deploy six transducers, but the vented cable lengths for wells MW-01 and MW-05 were too short for proper deployment at those locations. Continuous water level logging at 1-hour intervals in monitoring wells MW-06, MW-08, MW-09, and MW-10 began on September 10, 2020. Subsequently, the first data download was completed on September 21, 2020 as a verification of transducer function and deployment. The transducers worked and logged data as planned.

CDM Smith purchased the vented cable lengths needed to deploy transducers in monitoring wells MW-01 and MW-05. The transducers in MW-01 and MW-05 were deployed on October 15, 2020. All six of the transducers were synchronized at the time of deployment to collect water levels continuously at 1-hour intervals as detailed in **Section 2** of this plan. Two spare transducers obtained from USACE will remain as backups for future use if needed.

The transducers will also be used to record water level data during hydraulic testing (slug testing) to be implemented in accordance with the Plan and detailed in **Section 3**.

## 1.1 Access and Coordination

Access and coordination between the Tongue Point Job Corps Center (TPJCC) and USACE is required to support this work. In general, USACE is responsible for obtaining necessary site access to execute fieldwork. CDM Smith assists USACE with obtaining access as necessary. The general routine for access and coordination with TPJCC is as follows: At least one week before onsite work, TPJCC will be notified of the areas to be accessed during field activities. Upon arrival to the Site, CDM Smith will obtain contractor badges from TPJCC to be worn by CDM Smith personnel when onsite. The TPJCC points of contact for access and security are Jeff Van Steenberg (VanSteenBerg.Jeff@jobcorps.org) and Bob McLellan (McLellan.Bob@jobcorps.org). Both can serve as the point of contact for notifications of onsite activity and to obtain the contractor badges. CDM Smith personnel will display the contractor badge at the TPJCC gate each day when arriving at the Site and will participate in any applicable Coronavirus Disease of 2019 (COVID-19) health screening performed by TPJCC. The badges will be returned at the TPJCC gate or facilities office upon the completion of onsite work but may be kept overnight by CDM Smith personnel during multiday field events.

## 1.2 Health and Safety

The work described in this Plan will be conducted in accordance with the existing accident prevention plan/site safety health plan (CDM Smith 2020b). Specifically, this work consists of nonintrusive work equivalent to groundwater sample collection (see **Activity Hazard Analysis for Groundwater Sampling in Appendix A of the Accident Prevention Plan**). Site visits to download transducer data and perform basic maintenance can be conducted by one person. The site visit to perform the slug tests will be conducted by a team of two people.

## 1.3 Management of Investigation-Derived Waste

During typical transducer maintenance and download operations, it is anticipated that insignificant amounts of nonhazardous investigation-derived waste (IDW) will be generated and will not require containerization. The transducers will generally remain deployed inside the monitoring wells, and downhole equipment such as water level meter and mechanical volumetric slugs will be decontaminated per **QAPP Worksheet 17f** (CDM Smith 2020a) between monitoring wells by wiping the meter and tape clean with paper towels and minimal amounts of distilled water and detergent (e.g., Alconox). Decontamination fluids generated during water level monitoring and slug testing are expected to be minor in volume (less than 5 gallons totaled over the approximately year-long transducer deployment) and will be discharged to the ground surface on the landscape rock located near the road at the southwest corner of UST Site 1 and left to evaporate. No other equipment will contact contaminated media. Paper towels and any personal protective equipment will be placed in a trash bag and disposed of as general refuse.

For events described in this plan relating to LNAPL recovery and removal of water from wells during redevelopment (**Section 3.1.1**), larger volumes of waste consisting of product and/or groundwater will be produced. For this waste, CDM Smith will procure 16-gallon steel drums with lids to containerize LNAPL, as needed. Effort will be made to separate LNAPL and water generated during these activities; however, product recovery and redevelopment at wells containing LNAPL may generate a mix of LNAPL and water that will be containerized together. Redevelopment water removed from the wells that do not contain LNAPL (i.e., MW-09 and MW-10) will be discharged to the ground surface on the landscape rock near the Site.

Onsite surface discharge of water generated during redevelopment (from wells not containing LNAPL) and decontamination at the Site is consistent with OAR 340-122-0040 (5) which states: “A removal or remedial action and related activities shall not result in greater environmental degradation than that existing when the removal or remedial action commenced.” Additionally, analytical results of groundwater sampled from wells not containing LNAPL (MW-09 and MW-10) show concentrations comparable with the most conservative ODEQ risk-based concentrations for residential consumption of tap water (ODEQ 2018). The applicable risk-based concentrations are 0.46 micrograms per liter (µg/L) for benzene, 110 µg/L for gasoline range organics, 100 µg/L for diesel range organics, and 370 µg/L for residual range organics. The groundwater samples collected at MW-09 and MW-10 in August 2020 show maximum detected concentrations of 0.03 µg/L for benzene, 199 µg/L for diesel range organics, and 87 µg/L for residual range organics. Gasoline range organics were not detected above the method detection limit of 50 µg/L in either sample. Though the diesel concentrations at MW-09 and MW-10 exceed the criteria for tap water, it must be emphasized that there is neither current nor planned drinking water consumption of groundwater at the Site and that any potential for exposure via this pathway can be eliminated.

Drums will be numbered and labeled with a description of the contents and stored in coordination with USACE and TPJCC. Initially, drums will be stored on the paved area off of Pier Street west of Dormitory 4, approximately 300 feet west of UST Site 1. For long-term storage pending disposal, the drums will be moved to the secure area near Hangar 2 used previously for IDW storage during the 2008 investigation.

## 1.4 Quality Control

All work performed under the Plan will conform to USACE quality assurance and quality control requirements and procedures (USACE Engineering Regulation [ER] 1110-1-12, *Engineering and Design Quality Management* [USACE 2006] and ER 1110-1-8157, *Geotechnical Data Quality Management for Hazardous Waste Remedial Activities* [USACE 2002]), the QAPP (CDM Smith 2020a), and the Final Contractor Quality Control Plan (CDM Smith 2019). Hydraulic monitoring equipment (transducers) will be operated and maintained in accordance with manufacturer recommendations in **Appendix A**.

# Section 2

# Water Level Data Collection and Evaluation

Per the QAPP objectives and FCR No. 01, this section of the Plan identifies general water level data collection techniques and includes a milestone table for identification of the wells for data collection, dates planned for downloading transducer data, and general operations and maintenance activities for the transducers and monitoring wells. A schedule of milestones for transducer deployment and data collection is provided in **Table 1**.

This section also describes the methods for the general study of water levels over time and evaluation of the tidal and seasonal influence on groundwater in shallow soil at the Site. This information may be used to evaluate the effect of fluctuations in water levels on the movement of LNAPL, spread of petroleum in smear zone, and as a potential contributing factor in the distribution of petroleum contaminants in soil and groundwater.

## 2.1 Water Level Data Collection

Water level data collection will be conducted using In-Situ Level TROLL 500 datalogging pressure transducers deployed at six monitoring wells located at and adjacent to the Site. The locations of the monitoring wells and well construction details are shown on **Figure 1**. Applicable standard operating procedures (SOPs) are included in the list on **QAPP Worksheet #21** and available in **QAPP Appendix C**. SOPs applicable to this work include **SOP No. 1-6 Groundwater Level Measurement**, **SOP No. 4-1 Field Logbook Content and Control**, and **SOP No. 4-5 Field Equipment Decontamination**.

### 2.1.1 Transducer Deployment

During deployment, the transducers are secured in place at an elevation below the anticipated lowest water level, and the dataloggers are programmed to collect data at 1-hour intervals. The transducers are suspended via a polyvinyl chloride (PVC) coupling nested upon the PVC well riser within the well vault as shown in **Figure 2**. A stainless-steel bolt was installed through a hole drilled through the PVC coupling and secured with a stainless steel nut. The transducers were then secured to the bolt via a corrosion-resistant metal loop attached to the vented cable. The bolt-hole in the PVC coupling serves as a drain if the well vault fills with water to protect the end of the vented transducer cable that is positioned above the PVC riser.

Excess vented transducer cable was coiled within the well monument and the data port attached to a cap filled with desiccant. The positions of the transducers as deployed are provided below in **Table 2**.

**Table 2 Transducer Deployment Information**

| Well Name | Cable Length (feet) | Nominal Casing Diameter (inches) | Total Well Depth (feet bgs) | Top of Screen (feet MLLW) | Bottom of Screen (feet MLLW) | 9/10/20 Water Level** (feet MLLW) | 9/10/20 Product Level (feet MLLW) | 9/10/20 Product Thickness (feet) | Transducer Depth (feet BTOC) |
|---|---|---|---|---|---|---|---|---|---|
| MW-01 | 10 | 4 | 13 | 12.92 | 2.92 | 9.31 | -- | -- | 8 |
| MW-05 | 10 | 4 | 15 | 12.79 | 2.79 | 10.67* | -- | -- | 8 |
| MW-06 | 20 | 2 | 18 | 8.13 | -1.87 | 6.48 | 7.01 | 0.53 | 15 |
| MW-08 | 15 | 2 | 13 | 12.87 | 2.87 | 7.93 | 8.68 | 0.75 | 12 |
| MW-09 | 8 | 2 | 13 | 12.46 | 2.46 | 9.15 | -- | -- | 8 |
| MW-10 | 8 | 2 | 13 | 12.86 | 2.86 | 9.35 | -- | -- | 8 |

*Measured on August 17, 2020.

**Water levels listed here for wells containing product have not been corrected to account for the weight of product where applicable.

bgs: below ground surface; MLLW: mean lower-low water; BTOC: below top of casing

Approximately 1 month following the deployment of transducers in MW-06, MW-08, MW-09, and MW-10, the materials and equipment (PVC coupling, bolts, transducers, vented cables, and desiccant caps) for deployment in MW-01 and MW-05 were requisitioned and compiled, and installation was scheduled for October 15, 2020. During this visit, the transducers were deployed in MW-01 and MW-05 by suspending them from the bolt on the PVC coupling attached to the well riser at least 8 feet below top of casing (BTOC), as shown on **Figure 2**. At MW-05, there was not enough space to install a PVC coupling inside the well vault; therefore, the bolt nests in two notches cut into the top of the well head.

The transducers were configured to output depth to water data in feet BTOC referenced using a water level meter at the time of setup. Care was taken to confirm that the depth to water stabilized following the displacement of the groundwater caused by the submersion of the transducers. Logging was set at 1-hour intervals and all transducers at the Site were synchronized to log depth to water BTOC in each well at the same time (e.g., at the top of each hour). After deployment, two spare transducers remain for future use as needed.

## 2.1.2 Maintenance, Risk Management, and Data Downloads

At approximately monthly intervals, data will be downloaded, and monitoring equipment will be checked for proper functionality. Because of the seasonally high rainfall at the Site, measures will be employed to manage risks to the equipment from surface water infiltration. This process for downloading data and checking equipment at each location is outlined below.

### 2.1.2.1 Maintenance and Risk Management

Maintenance and risk management measures will be employed both during the initial deployment and during subsequent monthly visits. For optimal functionality, the vented cables attached to each transducer must be protected from water. This will be accomplished via well monument improvements and maintenance, secure positioning of the vented cable, and protective desiccant-filled caps on the vented cables. Each of the existing wells has surface completions flush with or slightly below the ground surface. Infiltration of seasonal precipitation caused accumulation of water within the below grade surface completions (well vaults). Based on discussions with USACE, all well vaults, with the exception of MW-01, MW-05, and MW-06, will become completely flooded throughout the rainy season.

Well vaults will be maintained and inspected onsite by CDM Smith. A basic maintenance activity involves bailing or purging accumulated surface water from inside the well vault. Basic improvements to be made would include replacing rubber gaskets, tapping new threads, and installing new well bolts for sealing the well lid. The drilling subcontractor (Holt Services), who worked earlier on the PDI, has the expertise, supplies, tools, and availability to complete these improvements during the onsite work for hydraulic testing (**Section 3.2**).

If the seal on the well monuments remains an issue, the well monument could potentially experience infiltration of surface water. Therefore, the vented cables are positioned such that they are protected from accumulations of water in the well monument. In this fashion, if water collects within the well monument, it will drain through the bolt-hole in the PVC coupling or well riser before inundation of the end of the vented cable can occur. Though the introduction of surface water to the well is usually undesirable, there is no surface contamination at the Site and leaving the well riser open for drainage will protect the vented cable while allowing for drainage of potential surface water infiltration. Although managing infiltration risk by allowing inflow to the well will influence the water level being recorded, the change is expected to be minor, manageable, and correlated with the precipitation records. If the precautions described above to manage infiltration are ineffective, the consequences could be faulty readings (see **Section 2.1.2.2**) and potential damage to the transducer. In this situation, either of the backup or spare transducers obtained from USACE would be deployed to replace the faulty device.

The maintenance of the desiccant-filled caps on the end of each vented cable is the final line of defense from moisture. The desiccant will be inspected monthly during site visits to download data. CDM Smith has procured the desiccant to replace the spent desiccant when necessary. The desiccant-filled caps used during the initial deployment were smaller than those typically used during longer transducer deployments and CDM Smith will assess whether the existing caps need to be replaced with larger caps designed for longer deployments. Field observations of the desiccant caps would show evidence of excessive moisture, i.e., that the desiccant is almost completely used as indicated by a change in the color of the desiccant from blue (fresh) to pink to clear (spent). If field observations in November 2020 indicate that larger caps would be preferrable to the smaller caps initially deployed, CDM Smith will procure replacement caps to be deployed during the hydraulic testing event in December 2020.

#### 2.1.2.2 Data Downloads

For detailed information on the operation of In-Situ Level TROLL 500 datalogging pressure transducers or Win-Situ software, refer to the In-Situ Operator's Manual in **Appendix A**. The general sequence for downloading transducer data is as follows:

1. Using a USB TROLL Com Communication Device cable, connect the datalogger to a laptop with WinSitu software and open a connection with the datalogger. View output for depth to water to verify that the transducer is functional and for comparison with manual water level readings.

2. Concurrent with or shortly after Step #1, measure and record depth to water from the reference location at the top of the inner casing with a clean water level meter using the procedures described in **SOP No. 1-6 (see QAPP Appendix C).** Care will be taken to obtain a stabilized depth to water measurement as per the SOP. After measuring depth to water, decontaminate the water level meter with a paper towel, distilled water, and Alconox.

3. Using WinSitu software, download and export data that have been acquired since the previous download. Verify that the data were logged over the entire period and that no erroneous readings are observed. If there are gaps in the data or error readings, consult the product manual (**Appendix A**) for potential solutions and troubleshooting tips. Evidence of water infiltration to the vented cable may be apparent as a sinusoidal curve with a diurnal cycle in the water level data. This is caused by the daily changes in temperature causing expansion of moisture within the cable, which exerts a pressure within the vented cable. This pressure signal is superimposed upon any signal from water level fluctuation. A diurnal cycle would be distinguishable from a tidal cycle by the cycle's frequency. A diurnal cycle occurs once daily, whereas a tidal cycle occurs twice daily. After data have been downloaded, verify that configuration settings are correct and the datalogger is acquiring data, then disconnect from WinSitu.

## 2.2 Data Evaluation

Water level data will be uploaded to a database and evaluated to assist in the PDI evaluation and remedial design process. This evaluation will consider precipitation, tide elevations, and surface water elevations adjacent to the site over the period analyzed when developing and reporting findings, conclusions, and recommendations. Tidal and seasonal variations in water levels may have an effect on the movement of LNAPL, spread of the petroleum smear zone, and distribution of petroleum contamination in soil and groundwater.

The data acquired will be plotted over time with precipitation data and stage height data from the Columbia River that document tidal and other changes in surface water elevation. The stage height of the Columbia River adjacent to the site is influenced by the tide and other factors, including the timing of water releases from upstream reservoirs and basin-wide precipitation. Microsoft Excel or Golden Software's Grapher software may be used to plot time-series water elevation data. The data collected will be converted to and plotted in elevation units of feet with a datum of mean lower-low water. Elevation conversion will be accomplished using up-to-date TOC elevations collected during the PDI land survey. An example plot of water elevations in wells compared with Columbia River stage height over time is shown on **Figure 3** for data collected between September 10 and November 18, 2020. Maps of groundwater flow at any hour during the transducer deployment may also be prepared using the data. Water level data will be used to provide an estimate of vadose zone soil thickness and volume that will be used to support future identification and screening of remedial technology during the predesign process. In addition, as described in Section 3.1.1.1, the elevation of top of well screens will be evaluated relative to fluid levels as one part of assessing the mobility of the LNAPL.

Stage height data for the Columbia River adjacent to Tongue Point will be acquired from the National Oceanic and Atmospheric Administration monitoring station located approximately 0.25 miles from the Site at the U.S. Coast Guard Base at Tongue Point (Station ID: 9439040) for comparison with monitoring well groundwater elevations. To evaluate groundwater level responses to rainfall events, daily precipitation data will be acquired from the Port of Astoria Airport Station WBAN 94224 and presented graphically as shown on **Figure 3**.

# Section 3

# Hydraulic Testing and Analysis

Hydraulic testing (also known as slug testing) will be performed to support **study goal #4** identified in **QAPP Worksheet #11**. Study goal #4 in QAPP Worksheet #11 included characterization of subsurface conditions to support potential excavation system design and dewatering requirements. Slug testing will be used to obtain an estimate of hydraulic conductivity (K) at the Site, which will support evaluation of pumping requirements for a potential dewatering system during excavation.

## 3.1 Preparation

Slug testing preparation will involve limited redevelopment and assessing monitoring wells for selection for hydraulic testing.

### 3.1.1 Well Preassessment

During the November 2020 event to download transducer data, CDM Smith will conduct a preliminary assessment of hydraulic conditions at each monitoring well. This assessment will consist of LNAPL recovery at MW-06 and MW-08 and limited redevelopment of each UST Site 1 monitoring well (MW-06, MW-08, MW-09, and MW-10.)

#### 3.1.1.1 Light Nonaqueous Phase Liquid Recovery

Removing LNAPL from the wells and monitoring LNAPL recovery will provide useful information on the mobility of LNAPL in the water bearing zone.

To maximize LNAPL recovery while minimizing disturbance to the water bearing zone that may also contain LNAPL, a peristaltic pump and/or disposable bailer will be used to recover product from the top of the water column in both MW-06 and MW-08. Before recovery, the fluid elevation and product thickness will be measured using an oil-water interface probe and compared to the elevation of the top of the well screen to assess if the wells are receptive to LNAPL recovery. If the well does not have sufficient LNAPL recovery from the previous visit, or if the screen length above fluid level is less than approximately 1 to 2 feet, the well will not be subjected to a recovery test. LNAPL will be removed, but recovery will not be monitored onsite.

If using a peristaltic pump, plastic tubing will then be cut to length so that it will draw from the product layer sitting atop the water in each well during purging. The purged product will be discharged into a bucket and containerized in an IDW drum. The oil-water interface probe will be used during and after purging to monitor the change in product thickness. Longer-term changes in product thickness will be assessed monthly during visits to download and maintain the transducers. If practicable, the monthly visits could include additional efforts to recover product and document changes in product thickness.

The American Petroleum Institute (API) provides a user guide for the performance and analysis of LNAPL baildown tests to estimate the transmissivity of LNAPL (provided in **Appendix C**). This test procedure involves rapid removal of LNAPL from a well (e.g., using a peristaltic pump) and monitoring depth to water (DTW) and depth to product (DTP) over time using an oil-water interface probe. In wells where LNAPL recovers too quickly for near-simultaneous manual measurements of DTW and DTP, a transducer may be used to monitor the DTW, thereby simplifying the manual measurements to DTP only. Generally, 20 to 30 measurements of recovery over time are needed to perform the transmissivity analysis. Such a test is planned to be performed during one of the monthly transducer maintenance and data download events.

#### 3.1.1.2 Well Redevelopment

Well redevelopment will be scheduled for approximately 1 week before slug testing. Well redevelopment will help reduce low bias in the estimation of K values potentially related to drilling effects, such as a well skin effect, and potential biofouling of the well screen and filter pack.

Redevelopment will not require a drilling subcontractor and can be accomplished by CDM Smith staff using a stainless-steel bailer. The transducers will be removed from the wells before bailer insertion. At minimum, the well screen will be surged using the bailer and then bailed to clean out the suspended fines and other fouling agents. Serial bailing to draw groundwater through the sand pack and into the well will be performed if sufficient groundwater recharge is observed during bailing. Measurements of DTW and volume purged over time will be recorded during serial bailing.

To assist in the selection of wells for possible slug testing, a groundwater recharge test will be performed at each monitoring well immediately following redevelopment. Each test will use a bailer to draw down the water in each monitoring well to the maximum extent feasible. The transducer will then be redeployed to monitor groundwater recharge to the well. Data will be downloaded from the transducers the day following redevelopment to assess initial recovery as a proxy for recovery following a slug test.

### 3.1.2 Well Selection

Select monitoring wells will be identified to perform slug testing to obtain data necessary to provide the best available estimate of the hydraulic conductivity (K) for the shallow water bearing soils in the area of planned remediation. The results of well redevelopment and the groundwater recharge test described above will inform well selection. A well will be considered acceptable for slug testing if redevelopment shows the well to be clear of sediment or other fouling agents and the rate of groundwater recharge is responsive enough to conduct slug testing in a reasonable timeframe (e.g., over a 2-day field event). Preliminarily, these wells will consist of MW-06, MW-08, MW-09, and MW-10, with MW-01 used as a background observation well. The rationale for selection of each of the wells is as follows:

**MW-06**: MW-06 is representative of areas where LNAPL has historically been observed but where recent LNAPL recovery indicates limited LNAPL availability to the well screen.

**MW-08**: MW-08 is representative of areas with observed LNAPL that would presumably be excavated and is on the edge of the formerly excavated area.

**MW-09**: MW-09 is representative of areas within the former excavation and backfill material.

**MW-10**: MW-10 is representative of areas within the former excavation and backfill material that may have low hydraulic conductivity based on observed drawdown during low-flow sampling in August 2020.

To the extent feasible, the testing will be sequenced to proceed starting from wells with assumed low contamination concentrations and finish at wells with higher concentrations.

## 3.2 Slug Testing

This section describes the field methods that will be used to perform a series of rising head slug tests to collect data for analysis, which will provide an estimation of the range of K values by lithology in the saturated interval beneath the Site. In general, the field methods and data analysis will follow the procedures outlined in Midwest GeoSciences Group's *Field Guide for Slug Testing and Data Analysis* and CDM Smith's **Technical SOP for Hydraulic Conductivity Testing**, which are provided in **Appendix B**.

Water level data during slug testing will be collected using a transducer set to log water levels at 0.5-second or shorter intervals. The shortest measurement interval recordable by the Level TROLL 500 transducers currently deployed is 0.5 second, which would not be fast enough to record a slug test in a high K formation. Therefore, a Level TROLL 700 transducer, which can log as frequently as four measurements per second, will be rented for use during slug testing. The Level TROLL 700 can also use a logarithmic logging interval, which is desirable for testing wells with low K (e.g. MW-10).

The Solid H(o) Slug by Midwest GeoSciences Group will be procured (see information sheet included in **Appendix B**). It is designed to yield a pre-estimated initial displacement in 2-inch diameter wells. Slugs for at least two different initial displacements will be procured. At least three rising and three falling head tests will be performed at each well with at least two different initial displacements (e.g., 12 inches and 18 inches) for a total of at least six tests per well.

Slug test analysis parameters, including the depth to water and well depth, will be recorded in the field before starting testing at each location. Other data required for slug test analysis, such as the well screened interval and total depth, will be taken from lithologic and well construction logs. The well depth measured in the field will be compared to the well depth reported in the well construction diagram. A field data collection sheet for slug testing is included in **Appendix B**.

MW-01 will serve as a background observation well with its transducer reprogrammed to record data at 1-minute intervals throughout the slug testing event. This will document any transient changes to the water bearing zone that could affect the data recorded during the slug testing. Before slug test initiation, a transducer will be lowered into the well (if not already in place) and placed far enough below the water level so that it will not be affected by the movement of the slug. After the transducer is in place, the transducer will be allowed to equilibrate to the water temperature for at least 10 minutes before starting any tests. The slug will be lowered into the well and positioned immediately above the water level. The field team will start data collection using the pressure transducer before inserting or withdrawing the slug to ensure that the data includes the pretest static water level. To start the falling head test, the slug will be lowered into the water in one smooth, quick motion to create a near instantaneous change in the water level in the well. The change in water level will be recorded until the water level recovers, as feasible, to at least 95% of the static pretest level. Following recovery, data collection on the transducer will be stopped and a new test will be started. The rising head test will then be initiated by raising the slug in one smooth, quick motion out of the water while continuing to collect water level data with the transducer. The test will be complete once the water level recovers, as feasible, to 95% of the static, pretest static water level.

Slug test data collected will be analyzed using coincident plots in Microsoft Excel to select representative tests for further analysis using AQTESOLV hydraulic analysis software to provide the best available estimates for a range of K values according to the methods outlined in the field guide and per Butler's *The Design, Performance and Analysis of Slug Tests* (Butler 1998).

# Section 4
# Reporting

This section summarizes how the activities and data collected in Sections 1 through 3 will be evaluated and reported. The anticipated schedule for reporting is shown on **Table 1**.

Results of the evaluation completed by execution of Sections 1 through 3 of the Plan will be presented in an interim report that will include a preliminary presentation of water level data, tidal study, seasonal water level study, and slug test data and analysis. The interim report will be included in the preliminary draft of the Corrective Action Plan (Task 7), which includes the predesign data collection and maps/cross sections, and an engineering evaluation to identify and screen remedial technologies. After all data have been collected and evaluated, a final report will be included in an Appendix to the Draft Design Report (Task 9) in September 2021. This will include raw data files made available as an electronic attachment.

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# Section 5

# References

American Petroleum Institute. 1989. A guide to the assessment and remediation of underground petroleum releases, Publ. 1628, API, Washington, DC, 81 pp.

Butler, J.J., Jr., 1998. The Design, Performance, and Analysis of Slug Tests, Lewis Publishers, Boca Raton. 252pp.

CDM Smith Federal Programs Corporations (CDM Smith). 2020a. Quality Assurance Project Plan for Tongue Point CON/HTRW Former Tongue Point Naval Air Station Data Gaps Investigation at UST Site 1. June 30.

CDM Smith. 2020b. Accident Prevention Plan. Tongue Point CON/HTRW Former Tongue Point Naval Air Station Astoria, Oregon. May.

CDM Smith. 2019. Final Contractor Quality Control Plan (CQCP). Tongue Point CON/HTRW Former Tongue Point Naval Air Station Astoria, Oregon. November 4.

Hudak, P.F., K.M. Clements, and H.A. Loaiciga. 1993. Water table correction factors applied to gasoline contamination, J. Environ. Eng., 119(3): 578-584.

Midwest Geosciences Group. 2010. Field Guide for Slug Testing and Data Analysis. Published with permission from the Kansas Geological Survey.

Oregon Department of Environmental Quality (ODEQ). 2018. Risk-Based Concentrations for Individual Chemicals, May 2018 Revision. Accessed December 2020, https://www.oregon.gov/deq/FilterDocs/RBDMTable.pdf.
For UST at: https://www.oregon.gov/deq/FilterDocs/RBCtanksHOT.pdf

Oregon Department of Environmental Quality (ODEQ). 2009. UST Cleanup Manual Cleanup Rules for Leaking Petroleum UST Systems OAR 340-122-0205 through 340-122-0360 and Associated Guidance Documents. Originally published December 2000, editorial updates. January 2008 and May 2009.

USACE. 2006. Engineering and Design – Quality Management. ER 1110-1-12. July 21.

USACE. 2002. Geotechnical Data Quality Management for Hazardous Waste Remedial Activities. ER 1110-1-8157. October 1.

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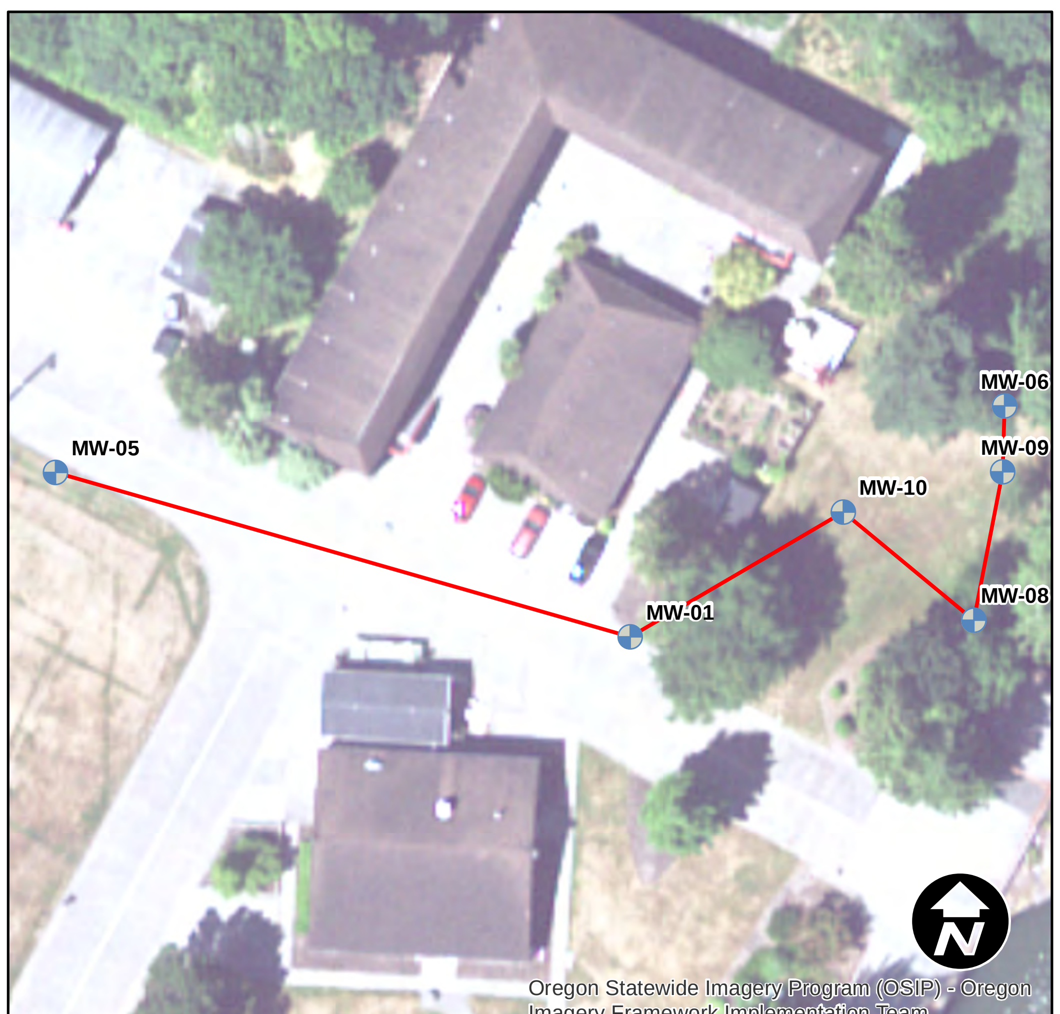
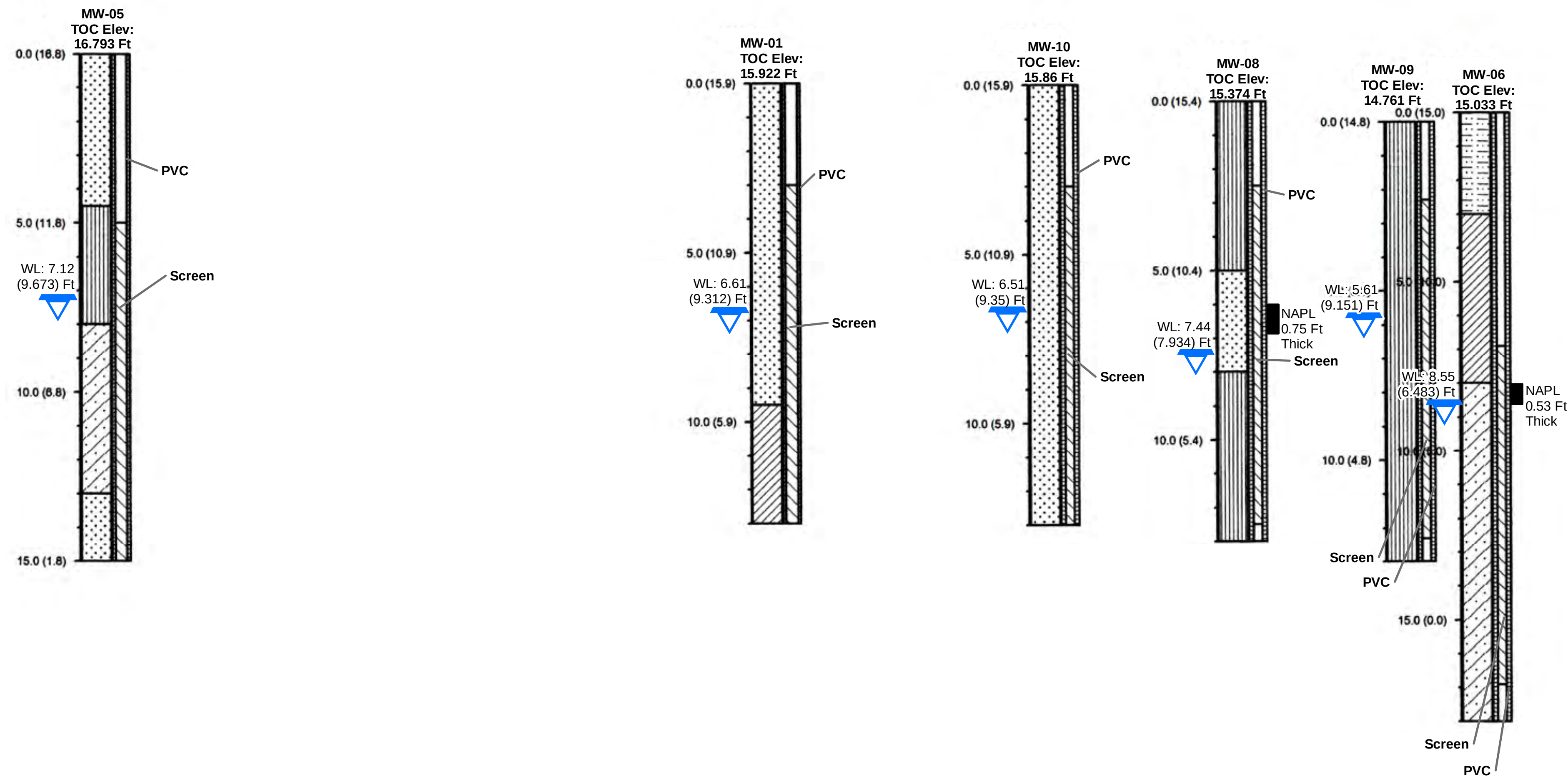
# Figures

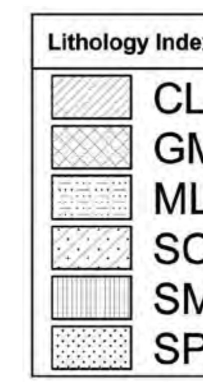

Water Level: Depth ft = WL: 8.55
Water Level Elevation = (6.483) Ft

0.0 (16.8) = Depth Ft (Elevation Ft)

Water Level Dates:

MW-05 - Measured 8/17/2020
MW-01, MW-06, MW-08, MW-09, & MW-10 - Measured 9/10/2020

TOC Elevations are at MLLW.




**CL** - Clay; clay, silt, sand mixtures, may contain trace organics, wood, plant or shell debris

**GM** - Silty gravel; gravel, sand and silt mixtures

**ML** - Silt sand; sand, gravel mixtures,minor fines

**SC** - Clayey sand; sand, clay, gravel mixtures

**SM** - Silt; silt, clay, sand mixtures, may contain trace organics, wood, plant or shell debris

**SP** - Poorly graded sand; sand-gravel mixtures, with little to no fines

U.S. ARMY
CORPS OF ENGINEERS
KANSAS CITY DISTRICT
KANSAS CITY, MISSOURI

**Hydraulic Monitoring Wells**
Former Tongue Point Naval Air Station
Astoria, Oregon

Figure 1

Document Path: D:\Projects\TP\MXD\Figur_1_TPWellCrossSection_20201013.mxd

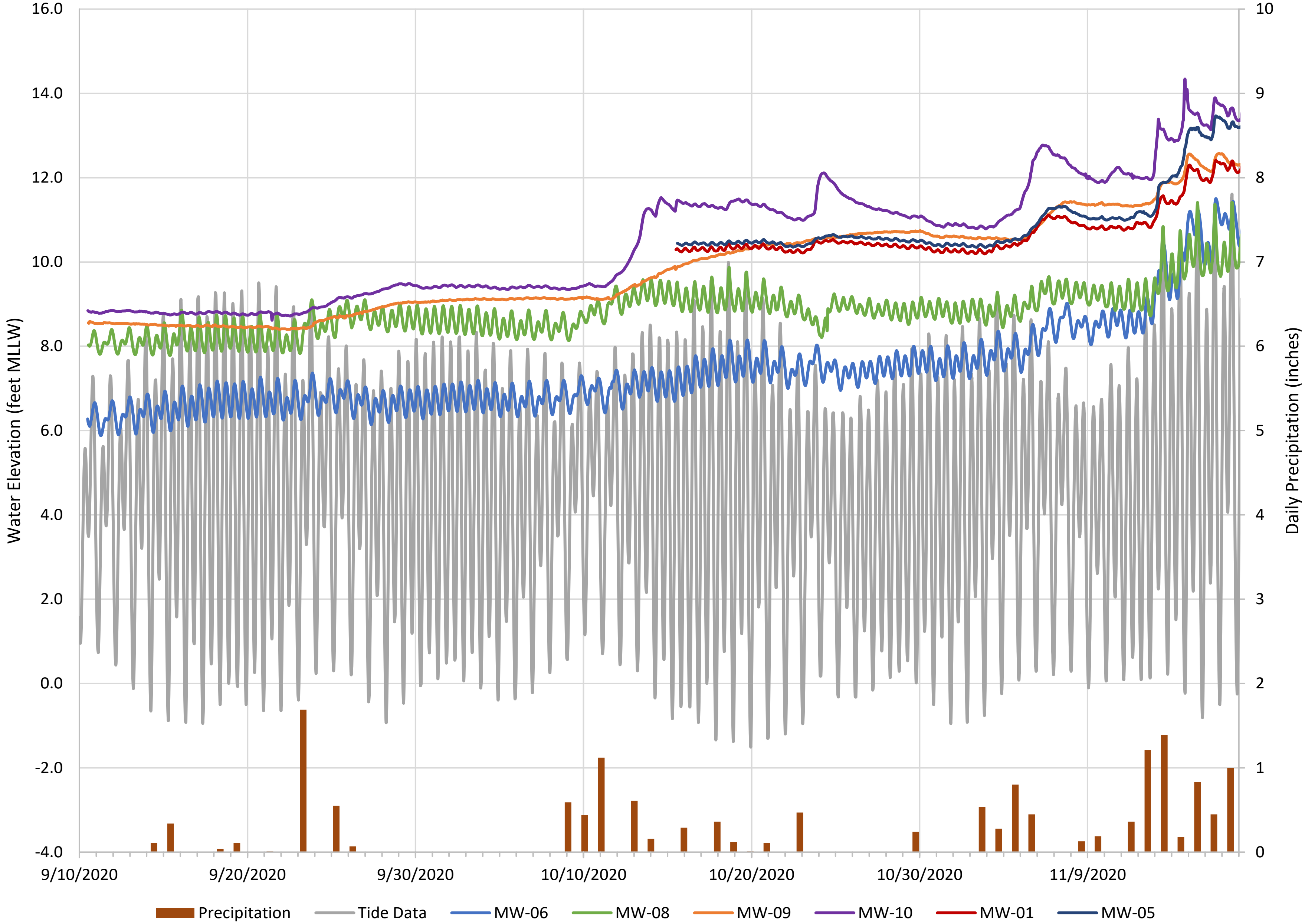
MW-06

MW-05

MW-01

Notes: - Photographs show PVC coupling at MW-06 and MW-01 and transducer cable suspended from the bolt attached to the PVC coupling.
- The desiccant cartridge and transducer cables can be seen in the photos

| U.S. Army Corps of Engineers<br>Kansas City District<br>Kansas City, Missouri | Former Tongue Point Naval Air Station<br>Astoria, Oregon | Figure 2<br>**Transducer Installation Photographs** |
|---|---|---|




Notes: - Elevations referenced to the mean lower low water (MLLW) tidal datum
- Water elevations at MW-06 and MW-08 are adjusted groundwater elevations calculated using the specific gravity of diesel fuel (0.827) to correct for the presence of LNAPL
- Tide data obtained from NOAA tide station 9439040 in Astoria, Oregon

| U.S. Army Corps of Engineers<br>Kansas City District<br>Kansas City, Missouri | Former Tongue Point Naval Air Station<br>Astoria, Oregon | Figure 3<br>**UST Site No. 1 Water Elevations and Precipitation** |
|---|---|---|

# Tables

**Table 1 - Schedule of Milestones**

Tongue Point Naval Air Station UST Site No. 1

Astoria, Oregon

| Task | Planned Start Date | Planned Completion Date | Frequency of Events | Comment |
|---|---|---|---|---|
| Transducer Deployment | 9/10/2020 | 9/15/2021 | 1 | Initial transducers were deployed in MW-06, MW-08, MW-09 and MW-10 per FCR NO. 01. Planned to continue logging until 9/15/2021 |
| Work Plan | 10/19/2020 | 12/11/2020 | 1 | Workplan to be completed per the QAPP, FCR No. 01, and planning memorandum. |
| Purchase Vented Cables | 9/22/2020 | 10/6/2020 | 1 | Received 2 vented cables |
| Deploy Transducers in MW-01 and MW-05 | 10/15/2020 | 9/15/2021 | 1 | Transducers were deployed in MW-01 and MW-05 as scheduled. Continue logging until 9/15/2021. |
| Download Transducer Data and Transducer Maintenance/Measure Product Thickness/Inspect Well Condition | 10/15/2020 | 9/15/2021 | 1 per month | Includes downloading transducer data, replacing desiccant as needed, measuring product thickness in MW-06 and MW-08 and inspecting well boxes for surface water infiltration with repairs as necessary. |
| Well Redevelopment | 11/18/2020 | 11/19/2020 | 1 | Wells selected for slug testing my be redeveloped prior to slug testing. Well redevelopment will be performed by CDM Smith using a bailer, or perstaltic pump. |
| Perform Maintenance on Existing Monitoring Wells | 12/2/2020 | 12/3/2020 | 1 | Intended to minimize surface water infiltration of well boxes. Includes replacing bolts, well monument gaskets other needed repairs as needed to be performed by Holt Services (drilling subcontractor). |
| Slug Testing Data Collection | 12/2/2020 | 12/3/2020 | 1 | Slug testing will be performed using manual method with transducer logging at 0.5-second interval or faster. |
| Slug Testing Data Analysis | 12/7/2020 | 12/17/2020 | 1 | Data will be analyzed using software to produce the best available estimate for K. |
| Interim Report (Task 7) | 12/17/2020 | 12/23/2020 | 1 | Interim report will include preliminary presentation of water level data, tidal study, seasonal vadose thickness study and slug test analysis. Interim Report will be included in the preliminary draft of the corrective action plan which includes the pre-design data collection and maps/cross-sections and an engineering evaluation to identify and screen remedial technologies. |
| Final Report (Task 9) | 9/15/2021 | 10/15/2021 | 1 | To be included as an Appendix to the draft design report after all data have been collected. |

# Appendix A

# In-Situ Operator's Manual

Innovations in Water Monitoring

# Operator's Manual

## *Level TROLL® 400, 500, 700, 700H Instruments*




0052212 | 2019-05-06

**Mailing and Shipping Address:**

In-Situ
221 East Lincoln Avenue
Fort Collins, CO 80524
U.S.A.

| | |
|---|---|
| **Phone:** | 970-498-1500 (international & domestic) |
| **Fax:** | 970-498-1598 |
| **Internet:** | *www.in-situ.com* |
| **Support:** | 800-446-7488 (U.S.A. & Canada) |



The presence of the Waste Electrical and Electronic Equipment (WEEE) marking on the product indicates that the device is not to be disposed via the municipal waste collection system of any member state of the European Union.

For products under the requirement of WEEE directive, please contact your distributor or local In-Situ office for the proper decontamination information and take back program, which will facilitate the proper collection, treatment, recovery, recycling, and safe disposal of the device.

0052212 | 2019-05-06

## Table of Contents

## *Introduction*

The Level TROLL Instrument is a compact, modular system for measuring level and temperature in natural groundwater, surface water, industrial waters, and other installations.

### Scope

This document is intended to describe the characteristics, operation, calibration, and maintenance of the instrument. Communication registers and SDI-12 programming information can be found in the Modbus and SDI-12 Reference Guides on the In-Situ website.

### Serial Number Location

The serial number is engraved on the instrument housing. It is also programmed into the instrument and is displayed when the instrument is connected to a computer running Win-Situ Software.

### Certification

See the Declarations of conformity at end of this manual.

### Unpacking and Inspection

Your instrument was carefully inspected before shipping. Check for any physical damage sustained during shipment. Notify In-Situ and file a claim with the carriers involved if there is any shipping damage. Accessories may be shipped separately and should also be inspected for physical damage and the fulfillment of your order.

> ⚠ Please save packing materials for future storage and shipping. The shipping boxes have been performance-tested and provide protection for the instrument and its accessories.

### Warranty

See the product specification tables for warranty information.

### Contact Information


| **Mailing and Shipping Address:** | **Phone:** | 970-498-1500 (international & domestic) |
|---|---|---|
| In-Situ<br>221 East Lincoln Avenue<br>Fort Collins, CO 80524<br>U.S.A. | **Fax:** | 970-498-1598 |
| | **Internet:** | *www.in-situ.com* |
| | **Support:** | 800-446-7488 (U.S.A. & Canada) |

## *Product Specifications*

### Level TROLL 400 Instrument

| General | Level TROLL 400 |
|---|---|
| Temperature ranges[1] | Operational: -20-80° C (-4-176° F)<br>Storage: -40-80° C (-40-176° F)<br>Calibrated: -5-50° C (23-122° F) |
| Diameter | 1.83 cm (0.72 in.) |
| Length | 21.6 cm (8.5 in.) |
| Weight | 124 g (0.27 lb) |
| Materials | Titanium body; Delrin nose cone |
| Output options | Modbus/RS485, SDI-12, 4-20 mA |
| Battery type & life[2] | 3.6 V lithium; 10 years or 2M readings |
| External power | 8-36 VDC |
| Memory<br>Data records[3]<br>Data logs | 2.0 MB<br>130,000<br>50 |
| Log types | Linear, Fast Linear, and Event |
| Fastest logging rate & Modbus rate | 2 per second |
| Fastest SDI-12 & 4-20 mA output rate | 1 per second |
| Real-time clock | Accurate to 1 second/24-hr period |
| Sensor Type/Material | Piezoresistive; titanium |
| Calibrated Range (Usable Depth) | *Absolute (non-vented)*<br>30 psia (11 m, 35 ft)<br>100 psia (60 m, 197 ft)<br>300 psia (200 m, 658 ft)<br>500 psia (341 m, 1120 ft) |
| Burst pressure | Max. 2x range; burst > 3x range |
| Accuracy (FS)[4] | ±0.05% from -5° to 50° C |
| Long-term stability | < 0.1% FS |
| Resolution | ±0.005% FS or better |
| Units of measure | Pressure: psi, kPa, bar, mbar, mmHg, inHg, $cmH_2O$, $inH_2O$<br>Level: in, ft, mm, cm, m |
| Temperature Sensor | |
| Accuracy & resolution | ±0.1° C; 0.01° C or better |
| Units of measure | Celsius or Fahrenheit |
| Warranty | 3 years<br>Extended warranties are available for all instruments—call for details |

| | |
|---|---|
| Footnotes | [1] Temperature range for non-freezing liquids<br>[2] Typical battery life when used within the factory-calibrated temperature range<br>[3] 1 data record = date/time plus 2 parameters logged (no wrapping) from device within the factory-calibrated temperature range<br><br>[4] Across factory-calibrated pressure and temperature ranges. Defined as greater than 98% of all readings fall within spec across full temperature and pressure<br><br>Specifications are subject to change without notice.<br>Delrin is a registered trademark of E.I. du Pont de Nemours and Company. |

## Level TROLL 500 Instrument

| General | Level TROLL 500 |
|---|---|
| Temperature ranges[1] | Operational: -20-80° C (-4-176° F)<br>Storage: -40-80° C (-40-176° F)<br>Calibrated: -5-50° C (23-122° F) |
| Diameter | 1.83 cm (0.72 in.) |
| Length | 21.6 cm (8.5 in.) |
| Weight | 124 g (0.27 lb) |
| Materials | Titanium body; Delrin nose cone |
| Output options | Modbus/RS485, SDI-12, 4-20 mA |
| Battery type & life[2] | 3.6 V lithium; 10 years or 2M readings |
| External power | 8-36 VDC |
| Memory<br>Data records[3]<br>Data logs | 2.0 MB<br>130,000<br>50 |
| Log types | Linear, Fast Linear, and Event |
| Fastest logging rate & Modbus rate | 2 per second |
| Fastest SDI-12 & 4-20 mA output rate | 1 per second |
| Real-time clock | Accurate to 1 second/24-hr period |
| Sensor Type/Material | Piezoresistive; titanium |
| Calibrated Range<br>(Usable Depth) | *Gauged (vented)*<br>5 psig (3.5 m, 11.5 ft)<br>15 psig (11 m, 35 ft)<br>30 psig (21 m, 69 ft)<br>100 psig (70 m, 231 ft)<br>300 psig (210 m, 692 ft)<br>500 psig (351 m, 1153 ft) |
| Burst pressure | Max. 2x range; burst > 3x range |
| Accuracy (FS)[4] | ±0.05% from -5° to 50° C |
| Resolution | ±0.005% FS or better |
| Long-term stability | < 0.1% FS |
| Units of measure | Pressure: psi, kPa, bar, mbar, mmHg, inHg, $cmH_2O$, $inH_2O$<br>Level: in, ft, mm, cm, m |
| Temperature Sensor | |
| Accuracy & resolution | ±0.1° C; 0.01° C or better |
| Units of measure | Celsius or Fahrenheit |

| | |
|---|---|
| Warranty | 3 years<br>Extended warranties are available for all instruments—call for details |
| Footnotes | See See page 8. |

## Level TROLL 700 Instrument

| General | Level TROLL 700 |
|---|---|
| Temperature ranges[1] | Operational: -20-80° C (-4-176° F)<br>Storage: -40-80° C (-40-176° F)<br>Calibrated: -5-50° C (23-122° F) |
| Diameter | 1.83 cm (0.72 in.) |
| Length | 21.6 cm (8.5 in.) |
| Weight | 124 g (0.27 lb) |
| Materials | Titanium body; Delrin nose cone |
| Output options | Modbus/RS485, SDI-12, 4-20 mA |
| Battery type & life[2] | 3.6 V lithium; 10 years or 2M readings |
| External power | 8-36 VDC |
| Memory<br>Data records[3]<br>Data logs | 4.0 MB<br>260,000<br>50 |
| Log types | Linear, Fast Linear, Linear Average, Event, Step Linear, True Logarithmic |
| Fastest logging rate & Modbus rate | 4 per second |
| Fastest SDI-12 & 4-20 mA output rate | 1 per second |
| Real-time clock | Accurate to 1 second/24-hr period |
| Sensor Type/Material | Piezoresistive; titanium |
| Calibrated Range<br>(Usable Depth) | *Absolute (non-vented)*<br>30 psia (11 m, 35 ft)<br>100 psia (60 m, 197 ft)<br>300 psia (200 m, 658 ft)<br>500 psia (341 m, 1120 ft)<br>1000 psia (693 m, 2273 ft)<br><br>*Gauged (vented)*<br>5 psig (3.5 m, 11.5 ft)<br>15 psig (11 m, 35 ft)<br>30 psig (21 m, 69 ft)<br>100 psig (70 m, 231 ft)<br>300 psig (210 m, 692 ft)<br>500 psig (351 m, 1153 ft) |
| Burst pressure | Max. 2x range; burst > 3x range |
| Accuracy (FS)[4] | ±0.05% from -5° to 50° C |
| Resolution | ±0.005% FS or better |
| Long-term stability | < 0.1% FS |
| Units of measure | Pressure: psi, kPa, bar, mbar, mmHg, inHg, cm$H_2O$, in$H_2O$<br>Level: in, ft, mm, cm, m |
| Temperature Sensor | |
| Accuracy & resolution | ±0.1° C; 0.01° C or better |
| Units of measure | Celsius or Fahrenheit |
| Warranty | 3 years<br>Extended warranties are available for all instruments—call for details |
| Footnotes | See See page 8. |

### Level TROLL 700H Instrument

Comply with the Office of Surface Water by using the most accurate pressure transducer available. The Level TROLL 700H meets the surface-water specification of ±0.01 foot.

For accuracy under all operating conditions, instruments are calibrated over the full pressure and temperature range. Each instrument includes a serialized, NIST-traceable calibration report.

| General | Level TROLL 700H |
|---|---|
| Temperature ranges[1] | Operational: -20-80° C (-4-176° F)<br>Storage: -40-80° C (-40-176° F)<br>Calibrated: 0-40° C (32-104° F) |
| Diameter | 1.83 cm (0.72 in.) |
| Length | 21.6 cm (8.5 in.) |
| Weight | 124 g (0.27 lb) |
| Materials | Titanium body; Delrin nose cone |
| Output options | Modbus/RS485, SDI-12, 4-20 mA |
| Battery type & life[2] | 3.6 V lithium; 10 years or 2M readings |
| External power | 8-36 VDC |
| Memory<br>Data records[3]<br>Data logs | 4.0 MB<br>260,000<br>50 |
| Log types | Linear, Fast Linear, Linear Average, Event, Step Linear, True Logarithmic |
| Fastest logging rate & Modbus rate | 4 per second |
| Fastest SDI-12 & 4-20 mA output rate | 1 per second |
| Real-time clock | Accurate to 1 second/24-hr period |
| Pressure Sensor Type/Material | Piezoresistive; titanium |
| Calibrated Range<br>(Usable Depth) | *Gauged (vented)*<br>15 psig (11 m, 35 ft) |
| Burst pressure | Max. 2x range; burst > 3x range |
| Accuracy[5] | ±0.01 foot up to 15 ft and ±0.1% of reading > 15 ft |
| Resolution | ±0.005% FS or better |
| Units of measure | Pressure: psi, kPa, bar, mbar, mmHg, inHg, $cmH_2O$, $inH_2O$<br>Level: mm, cm, m, in, ft, |
| Temperature Sensor | |
| Accuracy & resolution | ±0.1° C; 0.01° C or better |
| Units of measure | Celsius or Fahrenheit |
| Warranty | 3 years<br>Extended warranties are available for all instruments—call for details |
| Footnotes | See See page 8. |

## BaroTROLL Instrument...

The titanium BaroTROLL measures and logs barometric pressure and temperature. Use the BaroTROLL in conjunction with non-vented In-Situ Instruments.

Win-Situ BaroMerge Software simplifies post-correction of water level data by automatically subtracting barometric readings from data collected by a non-vented instrument to compensate for changes in pressure due to barometric fluctuations.

| General | BaroTROLL |
|---|---|
| Temperature ranges[1] | Operational: -20-80° C (-4-176° F)<br>Storage: -40-80° C (-40-176° F)<br>Calibrated: -5-50° C (23-122° F) |
| Diameter | 1.83 cm (0.72 in.) |
| Length | 21.6 cm (8.5 in.) |
| Weight | 124 g (0.27 lb) |
| Materials | Titanium body; Delrin nose cone |
| Output options | Modbus/RS485, SDI-12, 4-20 mA |
| Battery type & life[2] | 3.6 V lithium; 10 years or 2M readings |
| External power | 8-36 VDC |
| Memory<br>Data records[3]<br>Data logs | 1.0 MB<br>60,000<br>2 |
| Log types | Linear |
| Fastest logging rate | 1 per minute |
| Fastest output rate | Modbus: 2 per second<br>SDI-12 & 4-20 mA: 1 per second |
| Real-time clock | Accurate to 1 second/24-hr period |
| Sensor Type/Material | Piezoresistive; titanium |
| Calibrated Range<br>(Usable Range) | 30 psia (usable up to 16.5 psi, 1.14 bar) |
| Burst pressure | Vacuum/over-pressure above 16.5 psi damages sensor |
| Accuracy | ±0.05% FS from -5 to 50° C |
| Long-term stability | <0.1% FS |
| Resolution | ±0.005% FS or better |
| Units of measure | Pressure: psi, kPa, bar, mbar, mmHg, inHg, $cmH_2O$, $inH_2O$ |
| Temperature Sensor | |
| Accuracy | ±0.1° C |
| Resolution | 0.01° C or better |
| Units of measure | Celsius or Fahrenheit |
| Warranty | 3 years<br>Extended warranties are available for all instruments—call for details |
| Footnotes | See See page 8. |

## RuggedCable System

| General | RuggedCable System |
|---|---|
| Operating temp. range | -25° to 80° C (-13° to 176° F) |
| Jacket options | TPU (thermoplastic polyurethane)<br>Tefzel (ETFE fluoropolymer; generic equivalent to Teflon) |
| Vent options | Non-vented (absolute)<br>Vented (gauged) with desiccant (used to mitigate moisture/humidity) |
| Conductors | 6 conductors, 24 AWG, polypropylene insulation |
| Cable diameter | TPU: 6.7 mm (0.265 in.)<br>Tefzel: 6.35 mm (0.25 in.) |
| Connector diameter | 18. 5 mm (0.73 in.) |
| Weight | Non-vented, TPU: 16 kg/300 m (35.6 lbs/1,000 ft)<br>Non-vented, Tefzel: 14 kg/300 m (32 lbs/1,000 ft)<br>Vented, TPU: 14 kg/300 m (32 lbs/1,000 ft)<br>Vented, Tefzel: 14 kg/300 m (32 lbs/1,000 ft) |
| Minimum bend radius | 2X cable diameter (13.5 mm; 0.54 in.) |
| Break strength | 127 kg (280 lbs) |
| Maximum cable length | 1,219 m (4,000 ft) for RS485 |
| Desiccant pack (required for vented systems) | Large and extra large desiccant packs available with titanium, ABS, or stripped-and-tinned termination. |
| Warranty | 2 years |
| | Specifications are subject to change without notice. |

## Suspension Wire

| General | Suspension Wire |
|---|---|
| Material | 304 stainless steel, 7 x 7 strand |
| Coating | 15 mil polyester elastomer insulation |
| Weight | 0.28 kg / 30 m (0.60 lb / 100 ft) |
| Break strength | 122 kg (270 lb) with proper clip tightening |
| | Specifications are subject to change without notice. |

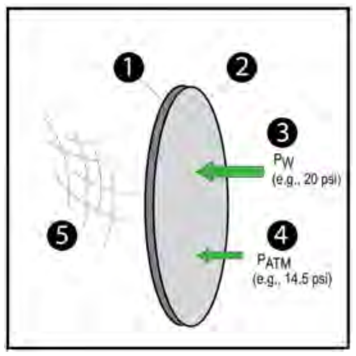
## *About the Pressure/Level Sensor*

A pressure transducer senses changes in pressure, measured in force per square unit of surface area, exerted by water or other fluid on an internal media-isolated strain gauge. In-Situ offers instruments with either absolute (non-vented) or gauged (vented) pressure sensors.

> ⚠ The "Absolute vs. Gauged: Comparing Absolute and Gauged Pressure Sensors" technical note describes the difference between absolute and gauged pressure sensors and explains the proper use of each type of sensor in different applications.

### Absolute Pressure Sensor

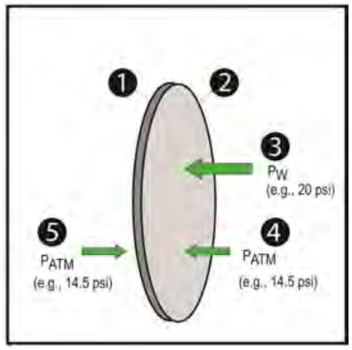
An absolute or non-vented pressure sensor measures all pressure forces detected by the strain gauge, including atmospheric pressure ($P_{ATM}$). The unit of measure is PSIA (pounds per square inch absolute), measured with respect to zero pressure. The back of an absolute pressure sensor is sealed from the atmosphere. Therefore, the front of the absolute pressure sensor responds to both atmospheric pressure and the pressure head of water above the sensor.




| | Absolute Sensor |
|---|---|
| 1 | Sensor back |
| 2 | Sensor front |
| 3 | Water pressure, $P_W$ (e.g., 20 PSI) |
| 4 | Atmospheric pressure $P_{ATM}$ (e.g., 14.5 PSI) |
| 5 | Vacuum |

### Gauged Pressure Sensor

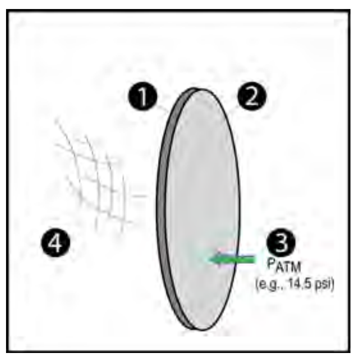
A gauged or vented pressure sensor eliminates the effects of atmospheric pressure because the vent tube in the cable allows atmospheric pressure to be applied to the back of the sensor. The unit of measure is PSIG (pounds per square inch gauge), measured with respect to atmospheric pressure.




| | Gauged Pressure Sensor |
|---|---|
| 1 | Sensor back |
| 2 | Sensor front |
| 3 | Water pressure, $P_W$ (e.g., 20 PSI) |
| 4 | Atmospheric pressure $P_{ATM}$ (e.g., 14.5 PSI) |
| 5 | Atmospheric pressure $P_{ATM}$ (e.g., 14.5 PSI) |

### BaroTROLL Atmospheric Pressure Sensor

Barometric pressure applies a direct stress upon open wells and surface water. Locally, barometric effects can change significantly from location to location as a result of topographical and micro-meteorological changes. Therefore, it is important to compensate for the barometric pressure changes when monitoring water elevation.

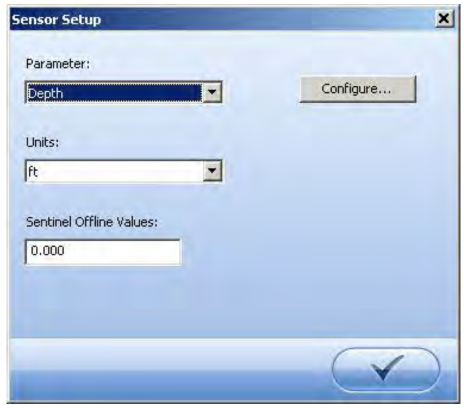



| | BaroTROLL Sensor |
|---|---|
| 1 | Sensor back |
| 2 | Sensor front |
| 3 | Atmospheric pressure $P_{ATM}$ (e.g., 14.5 PSI) |
| 4 | Vacuum |

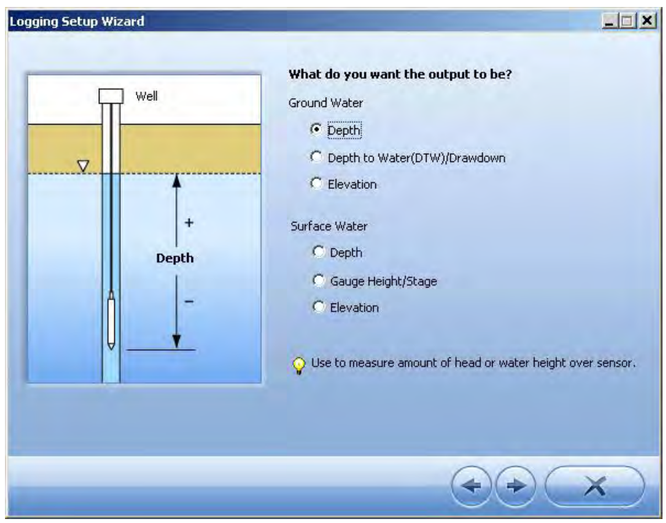
### Configuring Depth and Level for PLC or Data Logger

When you configure level using the **Sensors** tab, the settings are stored in the instrument and are available for use in Modbus, SDI-12, or 4-20 mA analog communication. A different configuration can be selected when you set up a log.

1. Connect the instrument to the software.
2. Click the **Sensors** tab .
3. Select the level/pressure sensor and click the **Configure**  button. The Sensor Setup window appears.




4. In the **Sensor Setup** window, select the Level parameter, then click **Configure** The Level Setup Wizard opens.




5. In the Level Setup Wizard, select the options you want. For more information, view the Help in the Win-Situ 5 Software.

## System Components

### Instrument

The Level TROLL Instrument is completely sealed and contains no user-serviceable parts. The instrument includes pressure and temperature sensors, a real-time clock, microprocessor, sealed lithium battery, data logger, and memory. Options include a vented or non-vented pressure sensor in a variety of ranges.

### RuggedCable System

RuggedCable Systems are custom-built, durable, direct-read cables that include the following items.

- Titanium twist-lock connectors for quick, reliable connections to the instrument, desiccant, and communication cable
- Metal shield beneath the cable jacket to prevent electrical interferences
- Kellems grip for secure instrument deployment
- Small desiccant for vented systems (for storage only)

> ⚠ Non-vented cables are marked with VF, which means vent free.

#### Vented or Non-Vented Cable

Vented cable is used with vented pressure sensors to produce gauged measurements. The cable vent tube ensures that atmospheric pressure is applied to the back of the sensor diaphragm.

Non-vented cable is used with non-vented instruments for absolute measurements. Compensate absolute measurements by using a BaroTROLL Instrument and Win-Situ Baro Merge Software.

> ⚠ Vented cable is shipped with a small desiccant to protect against condensation. Larger desiccants are necessary for deployment.

#### Jacket Options

Tefzel (vented) or thermoplastic polyurethane (TPU, vented or non-vented)

#### Customizable Cable Lengths

Cables can be ordered up to 1,219 m (4,000 ft).

#### Cable Termination

Cables can be ordered with a twist-lock termination (female connector) on both ends that connect to the instrument, the TROLL Com Communication Device, desiccant, and other accessories.

Cables can also be ordered with stripped-and-tinned termination for wiring to a data logger or controller using SDI-12, analog (4-20 mA), or Modbus communication protocol.

| | |
|---|---|
| 1 | RuggedCable System with female to female connectors |
| 2 | Stripped-and-tinned RuggedCable System with female connector |
| 3 | Stripped-and-tinned RuggedCable System with male connector (short length that converts a cable with a twist-lock connector to a stripped-and-tinned cable) |

## Suspension Wire

Polyurethane-coated stainless steel suspension cable can be used to deploy instruments with non-vented pressure sensors such as the Level TROLL 400 Instrument, the non-vented Level TROLL 700 Instrument, and the BaroTROLL Instrument. Suspension wire is appropriate to use when direct communication with the instrument is not necessary during deployment.

| Description | Part Number |
|---|---|
| Suspension Wire - 300 feet | 0066450 |
| Suspension Wire - 150 feet | 0066460 |
| Suspension Wire - 50 feet | 0066470 |

## Communication Cables

The TROLL Com Communication Device provides an interface between the instrument and a desktop/laptop PC for calibrating and programming the instrument and for profiling and downloading data. The TROLL Com Communication Device is offered in either a cable-connect or direct-connect configuration including a 0.9 m (3 ft) vented polyurethane cable, external power input jack, and vent with replaceable membrane.

### Description

The *Wireless TROLL Com* enables wireless communication between a Bluetooth 2.0-enabled Android or Windows device and an instrument deployed on a cable. You can also use the Wireless TROLL Com as a replacement for a standard wired TROLL Communication Device.

The *Wireless Rugged TROLL Com* permits wireless transmission between a Bluetooth 2.0-enabled device and a Rugged TROLL data logger. You must use a Direct Read Rugged TROLL cable with the Wireless Rugged TROLL Com.


| | |
|---|---|
| 1 | Dust cover for the USB connection |
| 2 | Connection status<br>**Red (flashing)** = The communication device, instrument, and Bluetooth-enabled device are not connected.<br>**Red (continuous)** = The communication device and instrument are connected, but the communication device is not connected to the Bluetooth-enabled device.<br>-OR-<br>The communication device is connected via USB cable.<br>**Green (flashing)** = The communication device is connected to the Bluetooth-enabled device, but is not connected to the instrument.<br>**Green (continuous)** = The communication device, instrument, and Bluetooth-enabled device are connected. |
| 3 | On/Off button |
| 4 | Battery charge status:<br> 100% -90%<br> 90% - 75%<br> 75% - 50%<br> 50% - 25%<br> Less than 25% |
| 5 | Cable connector to the instrument |
| 6 | Lanyard connector |
| 7 | Serial number |
| 8 | USB connection to a power source for charging the internal battery or wired connection to a computer |

### Contents

- Wireless TROLL Com
- USB cable
- AC wall charger (U.S.A. only, universal charger sold separately)
- Lanyard

### Charging the Communication Device

1. Remove the protective cover from the USB slot.
2. Connect the USB cable to the device.
3. Plug the USB cable into the wall charger or a powered USB port such as a computer that has a charger plugged in.
4. The device lights will turn on and blink according to charge level.

A fully-charged communication device will run for up to 40-50 continuous hours.

### Battery Tips

The communication device uses an internal, rechargeable Lithium-ion (Li-ion) battery to supply power. While these batteries last for years with minimal decrease in performance, there are a few tips to prolong the life of the battery.

- Avoid full discharges and charge the battery more often between uses.
- Avoid storing the communication device in a high temperature (above 86° F / 30° C) area.

### Connecting to a Wireless TROLL Com

A Wireless TROLL Com can be used to connect the instrument to software if the sonde is deployed on a cable.

1. Turn on the Wireless TROLL Com.
2. Make sure the cable is connected to the instrument as well as the communication device.
3. Go to Bluetooth settings on your mobile device or computer.
4. From the Bluetooth section, search for devices.
5. Tap or click the serial number of the communication device to pair the device with the phone or computer. The serial number is located under the USB flap.

#### Connecting to VuSitu

1. Open the VuSitu Mobile App. If you have correctly paired your Wireless TROLL Com with your wireless device, and the instrument is available, the software will connect and display readings.

> ✔ If the Searching screen continues to show, tap "Choose another device" and select the device you are trying to connect to.

#### Connecting to Win-Situ 5

1. Open Win-Situ 5 Software.
2. When prompted, "Connect to device now?" click **No**.
3. Plug the USB charging cable into the computer and Wireless TROLL Com.
4. Click **Preferences**, then click **Comm Settings**.
5. Select the correct Com port used by the charging cable, then select the communication settings for the instrument you are connecting. The following default communication settings are most common for In-Situ instruments:
    - Baud: 19200
    - Data Bits: 8
    - Parity Bits: Even
    - Stop Bits: 1
    - Device Address: 1
    - Mode: Modbus-RTU

   If you cannot connect using these settings, click the "Search for Devices" or "Reset All Devices" button.
6. Click the checkmark, then click the Connect button in the lower right hand corner.

## Power Options

### Internal Power—Batteries

Internal batteries are not user-replaceable. The approximate percentage of the power remaining in an internal battery is displayed on the Home Screen when an instrument is connected to Win-Situ Software.

The instrument is powered by 3.6 VDC, supplied by a sealed, non-replaceable AA lithium battery. Battery life depends on sampling speed. The battery typically lasts for 10 years or 2,000,000 readings, whichever occurs first.

When an instrument is wired to a data logger or PLC controller, power to the instrument is supplied by the data logger or controller.

### AC Adapter

The AC adapter provides 24 VDC, 0.75 A, AC input 100-250 V and includes a North American power cord. The TROLL Com Communication Device includes an external power input port for connection to the AC adapter.

| Description | Part Number |
|---|---|
| AC Adapter 24 VDC | 0052440 |

Use only In-Situ Inc.'s AC adapter. Damage to the instrument caused by the use of third-party converters is not covered by the warranty.

### External Power—External Battery Packs

External battery packs can significantly increase the life of an instrument, either for long-term deployments or to preserve an aging instrument.

### TROLL Battery Pack

The sealed, submersible TROLL Battery Pack supplements internal battery power when an instrument is used for fast, frequent sampling or during long-term deployments. When this power source is connected, the instrument will use the external battery source first and switch to the internal batteries when external battery power is depleted. Total battery life depends on the sampling speed.

| Description | Part Number |
|---|---|
| TROLL Battery Pack | 0051450 |

The sealed, submersible TROLL Battery Pack supplies 14.4 V. When this power source is connected, the Level TROLL will use the external battery source first and switch to the internal batteries when external battery power is depleted.

| | |
|---|---|
| 0.5 second sampling interval | 1.2 months |
| 1 second sampling interval | 2.3 months |
| 1 minute (or longer) sampling interval | 1 year |

### TROLL Replaceable Battery Pack

The TROLL Replaceable Battery Pack supplements internal battery power when a Level TROLL or Aqua TROLL 100 or 200 Instrument is used for frequent, fast sampling or during long-term deployments. When this power source is connected, the TROLL instrument will use the external battery source first and switch to the internal batteries when external battery power is depleted. Battery life depends on sampling rate. This battery pack allows for 1.5 V UM-3 or size AA batteries (8) that are replaced by the user.

> ✔ The TROLL Replaceable Battery Pack is not submersible.


| Description | Part Number |
| --- | --- |
| TROLL Replaceable Battery Pack | 0090000 |

### Estimated Battery Lifetime

| ***TROLL Battery Pack*** | **Level TROLL Family** |
| --- | --- |
| 15 minute logging rate* | 1.1 years |
| 1 hour logging rate* | 1.1 years |

*Logging with all sensors. Actual battery lifetime varies based on site conditions.

| ***TROLL Replaceable Battery Pack*** | **Level TROLL Family** |
| --- | --- |
| 15 minute logging rate* | 1.6 years |
| 1 hour logging rate* | 1.7 years |

*Logging with all sensors. Actual battery lifetime varies based on site conditions.

## Installation Accessories

### NPT Adapter

The 0.25 in. NPT adapter allows instrument installation in piping.

| Part Number | Image | Description |
|---|---|---|
| 0051470 |  | NPT Adapter |

### Cable Extender

The cable extender connects two lengths of RuggedCable System to meet varying installation needs.

| Description | Image | Part Number |
|---|---|---|
| Cable Extender |  | 0051490 |

### Twist-Lock Hanger

The Twist-Lock Hanger is used with a suspension wire to install a non-vented instrument when the user does not require direct communication.

| Part Number | Image | Description |
|---|---|---|
| 0051480 |  | Twist-Lock Hanger, titanium for Level TROLL 400, 700, 700H, BaroTROLL |

**Bulkhead Connector**

The panel-mounted bulkhead connector provides connection between RuggedCable System and a controller panel.

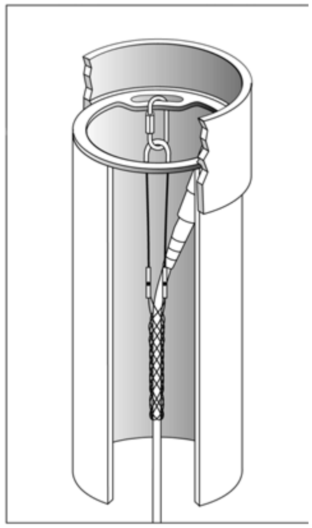
| Part Number | Image | Description |
|---|---|---|
| 0053240 |  | Bulkhead Connector |

**Locking Well Cap**

| Description | Part Number |
|---|---|
| Locking Well Cap, 2" | 0020360 |
| Locking Well Cap, 2" vented | 0020370 |
| Locking Well Cap, 4" | 0020380 |
| Locking Well Cap, 4" vented | 0020390 |

### Well Dock Installation Ring

The well dock installation ring provides installation support for 2", 4", and 6" well casings.



| Description | Part Number |
|---|---|
| Well Dock Installation Ring 2" | 0004690 |
| Well Dock Installation Ring 4" | 0004700 |
| Well Dock Installation Ring 6" | 0020650 |

## *Software*

TheLevel TROLL can be programmed using the VuSitu Mobile App for Android, or using Win-Situ 5 Software.

### About VuSitu

VuSitu is the mobile user interface and control application for In-Situ water quality instruments. You can use VuSitu on mobile devices with Android operating system 4.4, *Bluetooth* 2.0 and newer. Download the latest version of the app from the Google Play Store at play.google.com.

VuSitu allows you to accomplish the following tasks.

- View live readings that update every 10 seconds
- Change parameters and units
- Set up a data log
- Record data
- Email data in spreadsheet format
- Download data to mobile device
- Transfer data from mobile device to a computer

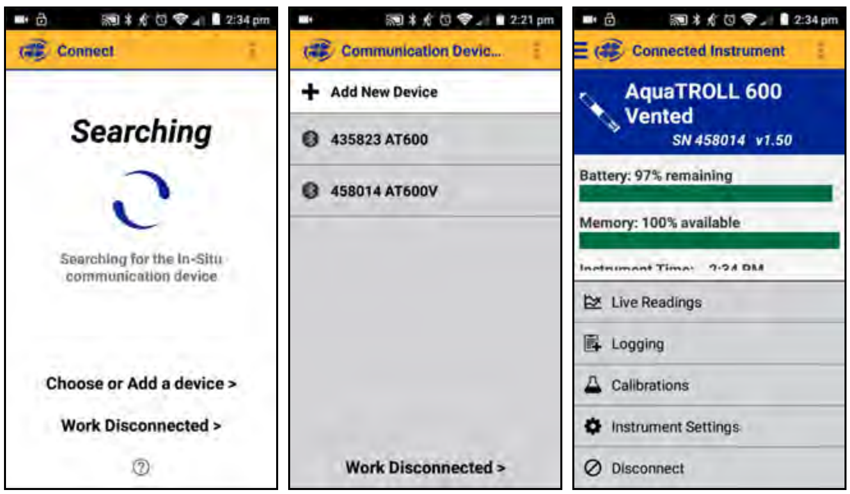
- Organize data by Location
- Calibrate Sensors and View Reports

### Connecting Your Instrument to VuSitu

To use VuSitu, you will need a Bluetooth-enabled mobile device, a Wireless TROLL Com and a deployment cable.

Attach one end of the cable to the Wireless TROLL Com and secure the other end to the instrument. Press the power button on the Wireless TROLL Com and open the VuSitu mobile app on your phone or tablet.

VuSitu will automatically search for Bluetooth devices nearby, but you will need to select the correct instrument when connecting for the first time. Select **Choose or Add a Device**. You should see the serial number of the instrument you wish to pair. Tap the serial number to connect. Tap the **Back** button on your device to view the Connected Instrument screen.



### Selecting with Long-press and Swipe

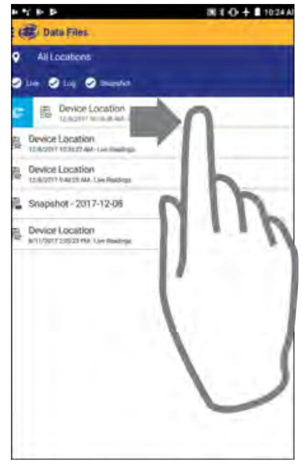
**Long Press**

Press and hold any item in a list of files. You can now select multiple files.

**Swipe Left**

Press an item and swipe left to reveal the delete and share icons.

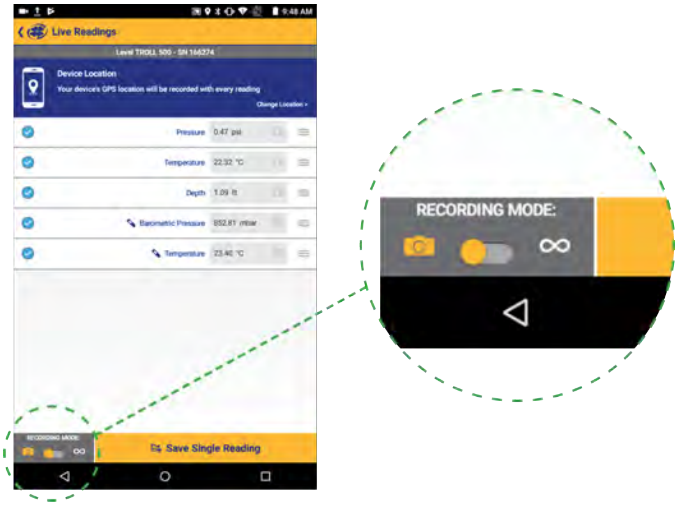
**Swipe Right**

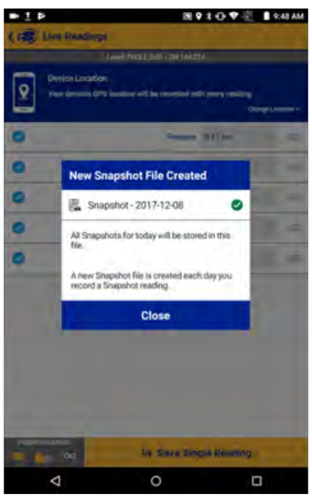


Press any item in a list and swipe right to reveal the sharing icon.

## Taking live readings in VuSitu

### *Snapshot Mode*

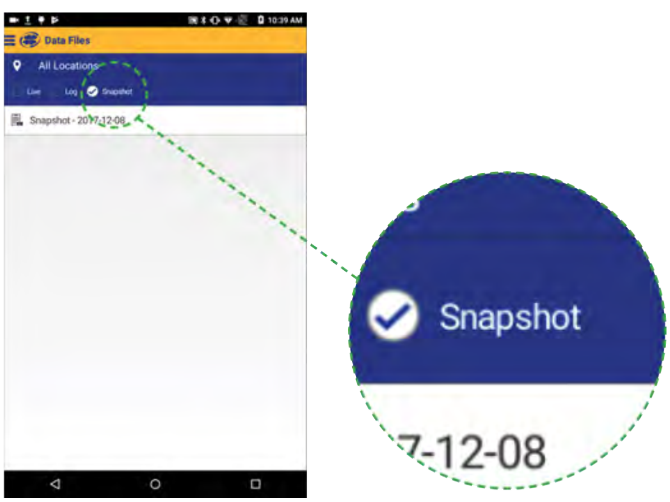


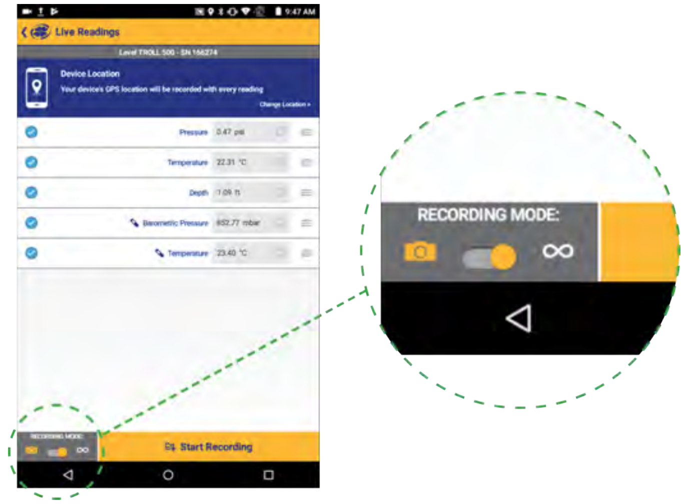

Take a single reading and save to Snapshot file.

View Snapshot file from Menu > Data Files.

Check Snapshot option.




### *Live Readings Mode*

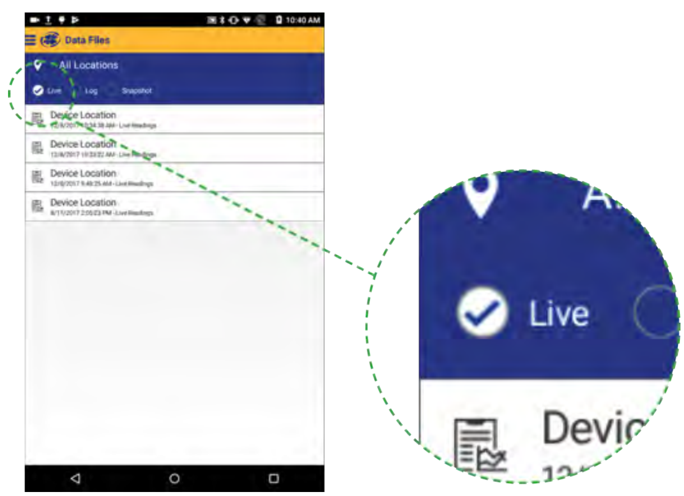




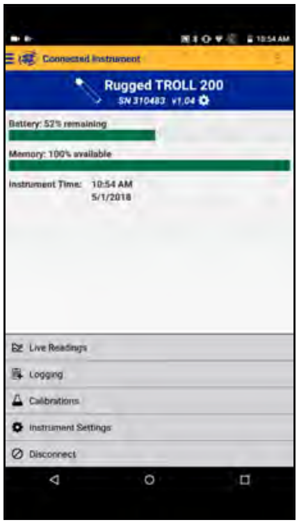
Take readings at two-second intervals.

View readings from Menu > Data Files.

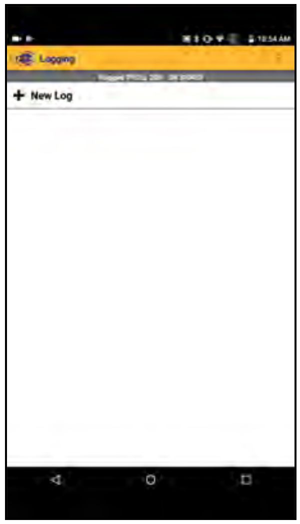
Check Live option.



## Setting Up a Log

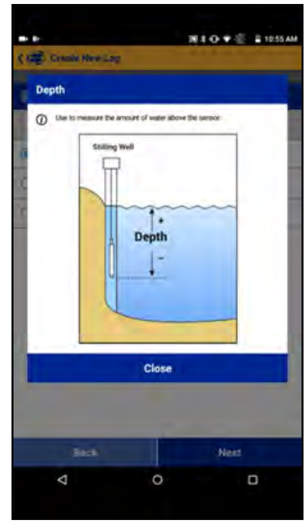



From the Connected Instrument screen, select **Logging**.




Tap **New Log** and follow the prompts to create a name, select a location and choose the parameters you wish to monitor.


Select a level mode in step 4. Tap the blue circle to the right of each option for an explanation of how the mode works.

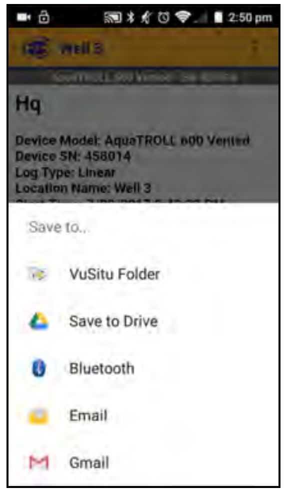



For Depth to Water and Surface Elevation modes, enter a level reference. See "About the Level Reference" on page 54 of this manual for complete information about level modes and level references.

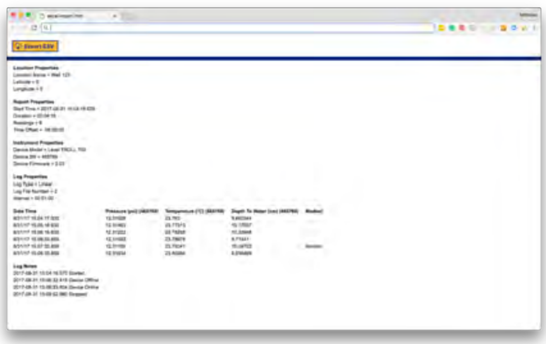
## Downloading and sharing your data.

You can download VuSitu data as an HTML file and share it via email, SMS or a cloud storage service such as Google Drive. To download a log, select it from the Downloaded Data screen and tap **Save to**.


Choose one of the download options from the menu. You can transfer a data file from your mobile device to a PC via Bluetooth, email it to yourself or any valid email address, save the file to the VuSitu folder on your device or upload it to Google Drive.




View your data in any web browser by double-clicking the file. You can then export a CSV file by clicking the **Export a CSV** link at the top of the page.



## *Getting Started*

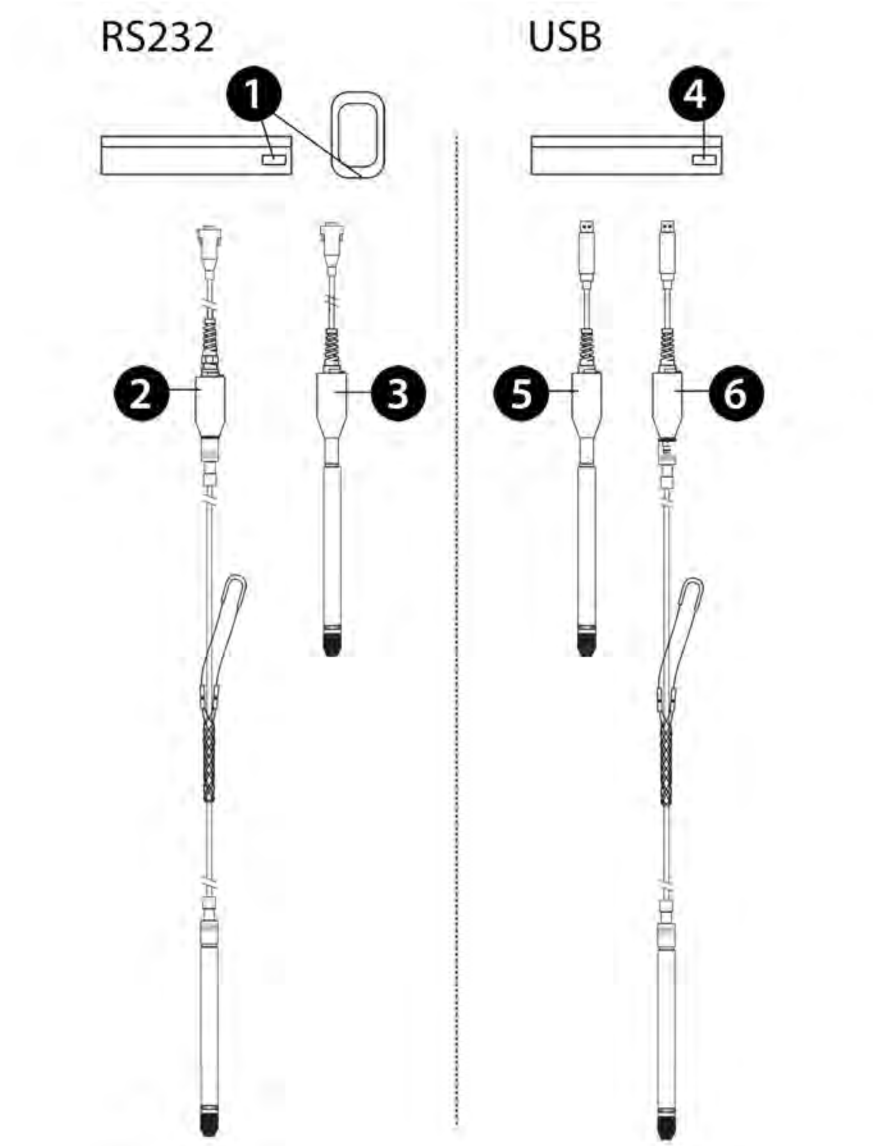
This section provides an overview of the initial steps necessary to prepare the instrument to log data.

- Select the appropriate TROLL Com Communication Device. This determines the hardware connections, and may influence the software installation. The drawing on the following page shows the function of the different TROLL Com Communication Device models.
- Install the software.
- Connect the hardware.
- Open the software and establish communication with the instrument.

### Select a TROLL Com Communication Device

The subsequent figure shows the function and connection features of the TROLL Com Communication Device models.

- A Direct-Connect TROLL Com might be preferred for programming an instrument that will be deployed on a suspension cable.
- A RuggedCable System and a Cable-Connect TROLL Com are required if you intend to communicate with the instrument while it is deployed. However, you can program the instrument with any TROLL Com.
- A Wireless TROLL Com will allow you to connect to the VuSitu mobile app, which you can use to configure and deploy your instrument.




| | |
|---|---|
| 1 | Cable-Connect TROLL Com Communication Device, serial connection, for field use |
| 2 | Direct-Connect TROLL Com Communication Device, serial connection, programming only, not submersible |
| 3 | USB port on a PC/laptop |
| 4 | Direct-Connect TROLL Com Communication Device, USB connection, programming only, not submersible |
| 5 | Cable-Connect TROLL Com Communication Device, USB connection, for field use |

## Connecting RuggedCable

### Connect the Instrument to the RuggedCable

1. Remove the protective caps from the instrument and cable. Ensure that the O-ring on the instrument connector is clean. Apply a small amount of vacuum grease to the o-ring.
2. Position the instrument and cable flat edges so they will connect properly. Insert the instrument connector firmly into the cable connector.

3. Hold the textured section of the sleeve in one hand and the instrument in the other. Push and twist until you hear a click. The click ensures the cable and instrument are securely attached.

### Connect TROLL Com Communication Device to the RuggedCable System

1. If a desiccant is present, remove the desiccant from the cable. Twist the desiccant and cable sleeve in opposite directions to unlock the desiccant from the cable.
2. Position the TROLL Com and cable flat edges so they will connect properly. Push and twist until you hear a click.

## Install the Software

### Win-Situ 5 Software

Install Win-Situ 5 Software from the In-Situ website. Click the Win-Situ 5 link, and follow the instructions to install Win-Situ 5 to your local hard drive.

### USB TROLL Com Drivers

If you are using a USB TROLL Com Communication Device, be sure to select the option "Install USB TROLL Com Drivers" during the Win-Situ 5 installation. Two drivers will be loaded to your hard drive, one for the USB TROLL Com, one for the USB TROLL Com serial port.

## Field Deployment

### Program the Instrument

In order to set up a log or download data, you must connect the instrument to a computer running Win-Situ 5 software or to a mobile device with the VuSitu app. See page 52.

### Position the Instrument

Place the instrument at the desired depth. Position the instrument below the lowest anticipated water level, but not so low that the pressure sensor range might be exceeded at the highest anticipated water level. Refer to the tables below to determine usable depth.

⚠ A BaroTROLL Instrument can be deployed with a non-vented instrument to compensate level data for changes in atmospheric pressure. Make sure the clocks on both instruments are synchronized, and install the BaroTROLL in a location that will never be submerged in water. See page 41.

Non-Vented Level TROLL Instrument

| Range | Effective Range | | Usable Depth | |
|---|---|---|---|---|
| PSIA | PSIA | kPA | Meters | Feet |
| 30 | 15.5 | 106.9 | 11 | 35 |
| 100 | 85.5 | 589.5 | 60 | 197 |
| 300 | 285.5 | 1968 | 200 | 658 |
| 500 | 485.5 | 3347 | 341 | 1120 |
| 1000 | 985.5 | 6795 | 693 | 2273 |

* Effective range for psia sensors is limited by an estimated 14.5 PSI atmospheric pressure at sea level.

Vented Level TROLL Instrument

| Range | | Usable Depth | |
|---|---|---|---|
| PSIG | kPA | Meters | Feet |
| 5 | 34.5 | 3.5 | 11.5 |
| 15 | 103.4 | 11 | 35 |
| 30 | 206.8 | 21 | 69 |

| Range | | Usable Depth | |
|---|---|---|---|
| 100 | 689.5 | 70 | 231 |
| 300 | 2068 | 210 | 692 |
| 500 | 3447 | 351 | 1153 |

## Verify Instrument Depth

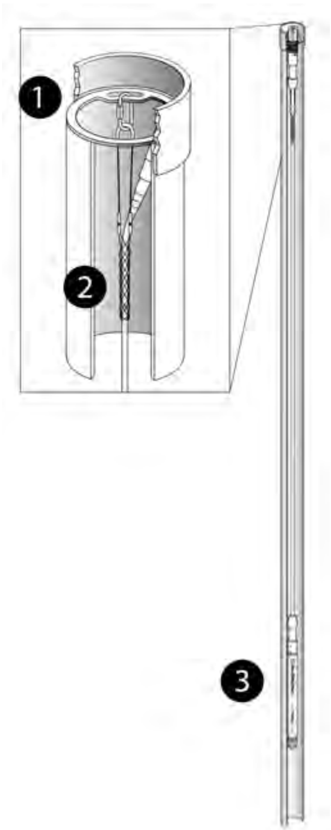
After you have installed the instrument, it is possible to connect the instrument to a computer or mobile device, open the software, and take a reading to verify the installation position. If the reading confirms that the instrument is in the correct position, you can secure it as described below.

During log setup there was an option to "Remind Me Later" for setting a level reference. If you set the log to remind you later, ensure that the instrument is submerged and set the level reference when prompted. See page 54.

## Secure the Cable

The RuggedCable System includes a Kellems grip near the up-hole end. You can compress the wire mesh and slide the grip to the desired location on the cable. Pull on the grip to tighten it on the cable.

Use the loop on the Kellems grip to anchor the cable to a convenient stationary object such as the In-Situ well dock installation ring. To install the Kellems grip to the installation ring, insert the loop into the locking clip on the well dock and position the assembly at the top of a well casing.




| | |
|---|---|
| 1 | Well Dock Installation Ring |
| 2 | Kellems Grip |
| 3 | Instrument Installed in Well |

## Install the Desiccant

> ⚠ Vented cable must be protected with a desiccant pack that is properly sized for site conditions.

### Desiccant

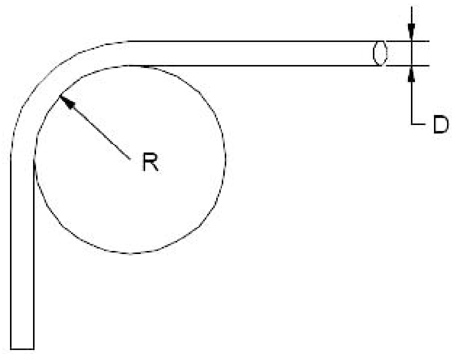
Desiccant protects cables, connections, and internal components from condensation, which can cause irreparable damage and loss of data. Indicating desiccant changes from blue to pink as it becomes saturated with moisture.

*Desiccant stages (from left)*
*New, nearly expired (replace now), expired*

It is **extremely important** to use a properly-sized desiccant for your deployment and to **change desiccant often**. Desiccant should be changed before the entire volume has turned pink, and you should use enough desiccant to effectively keep your equipment dry until your next scheduled maintenance. Desiccant longevity is dependent on site conditions and can vary from one site to the next.

### Installation Guidelines

- Never let the instrument fall freely down a well. Doing so will damage the sensor.
- After you have installed the instrument, verify the water level reading. Move the instrument and take another reading to ensure that the instrument shows reasonable change. The instrument could be wedged against the well casing with a loop of cable hanging below. An instrument in such a position could become dislodged and move while it is logging data, which would record a false change in the water level.
- For accurate measurements, the instrument should remain immobile while it is logging data.
- Make sure that the uphole cable end is protected. The vented cable must be protected with a desiccant, and the non-vented cable must be protected with a dust cap. The uphole cable end must be positioned above the highest anticipated water level. Avoid placing this end in a location that might flood.
- Do not deploy instruments in such a way that ice may form on or near the sensor or cable connections. Ice formation is a powerful expansive force that can over-pressurize the sensor or otherwise cause damage. Damage associated with ice formation is not covered by the instrument warranty.
- Do not allow vented cable to bend enough to obstruct the internal vent tube. The recommended bend radius is 13.5 mm (0.54 in), which is twice the cable diameter.




| | |
|---|---|
| R | Bend radius 13.5 mm (0.54 in) |
| D | Cable diameter |

**Stabilization Time**

After you have installed the instrument, allow it to stabilize to the environment for about 10 minutes before logging data. The T95 response time for temperature is less than 9 minutes.

A generous stabilization time is always desirable, especially in long-term deployments. Even though the cable is shielded, temperature stabilization, stretching, and relaxing can cause changes to readings.

> ⚠ If you intend to monitor water levels to the instrument's stringent accuracy specifications, allow up to 60 minutes for the probe and cable to stabilize to the environment.

## BaroTROLL Instrument Installation

The BaroTROLL Instrument is designed to log barometric pressure from 0 to 16.5 PSIA (1.14 bar, 33.59 inHg) at the surface near a submerged non-vented Level TROLL Instrument or Aqua TROLL 200 Instrument. BaroTROLL data may then be used to correct the water level data for barometric pressure fluctuations. See page 15.


#### Programming the Baro TROLL Instrument

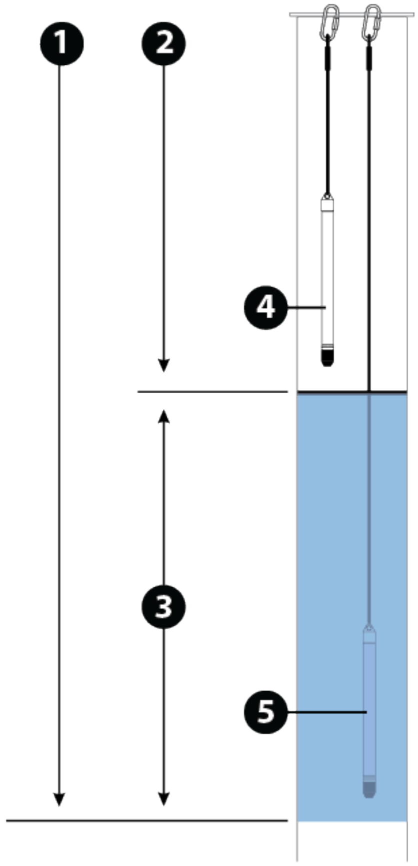
Connect the BaroTROLL to Win-Situ 5 software or the VuSitu mobile app and sync the clock.See page 53.

Set up a log with the same start time and sample interval as you set up in the non-vented level instrument. See page 53.

#### Installation

After the BaroTROLL Instrument is programmed, install it in a protected location above the water level near the submerged water level instrument. One installation configuration option is shown below using a twist-lock hanger and a suspension wire.

> ⚠ To prevent flooding of the BaroTROLL electronics, attach the twist-lock hanger before you install the BaroTROLL. Do not submerge the Baro TROLL Instrument.



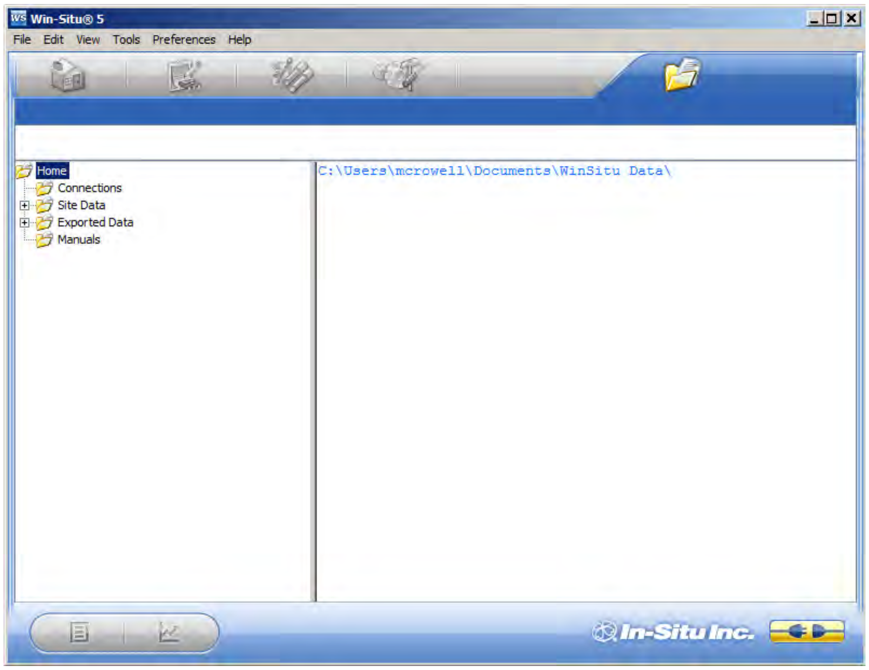

| | |
|---|---|
| 1 | Atmospheric pressure + water pressure (as measured by a non-vented pressure sensor) |
| 2 | Atmospheric pressure (as measured by the BaroTROLL) |
| 3 | Water pressure (as measured by a vented pressure sensor, or by subtracting BaroTROLL data from non-vented pressure sensor data) |
| 4 | BaroTROLL Instrument (Do not submerge.) |
| 5 | Non-vented Level TROLL Instrument |

> ⚠ To merge atmospheric pressure data with water level data, See page 58.

## Win-Situ Overview

### Data Tab

When you open Win-Situ 5 Software, the **Data** tab appears. The left side of the screen contains a file tree where you can view previously downloaded site data as well as data you have exported to Microsoft Office Excel. The links on the right side of the screen show where downloaded data are stored on your computer. The disconnected plug icon in the lower-right corner of the screen indicates that the software is not yet communicating with an instrument.

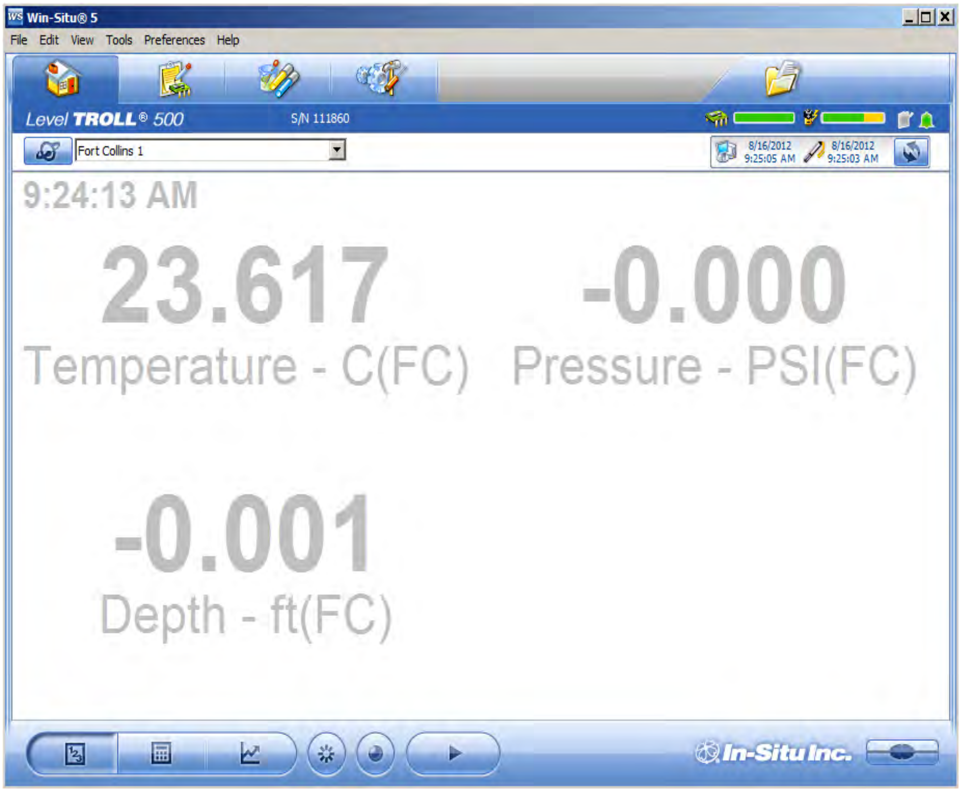



| Screen Element | Definition |
|---|---|
|  | The disconnected plug indicates the instrument is not communicating with the software. Click to establish communication with a connected instrument. |
|  | The connected plug indicates the instrument is communicating with the software. Click to disconnect the software from the instrument. |
|  | The **Home** tab displays real-time readings from the instrument. When connection to the instrument is first established, the software displays one reading of all available parameters in light gray. You must click the **Play** button  at the bottom of the screen to view real-time readings. |
|  | The **Logging** tab displays a list of logs stored in the connected instrument. When you click the **Logging** tab, it can take a moment for the software to retrieve information from the instrument. (Not applicable for the RDO PRO-X and the Aqua TROLL 400.) |

| Screen Element | Definition |
|---|---|
|  | The **Sensors** tab lists the sensors in the connected instrument, along with their serial numbers and the dates of factory calibration and user calibration. Use the buttons in this tab to calibrate sensors that support user calibration and configure sensors that are supported by the instrument. |
|  | The **Device Setup** tab allows access to instrument information and settings such as instrument name, serial number, firmware version, communication settings, diagnostics, and factory reset options. |

## Home Tab

The **Home** tab displays real-time readings from a connected instrument. When you first establish communication, the software displays one reading of all available parameters in light gray.



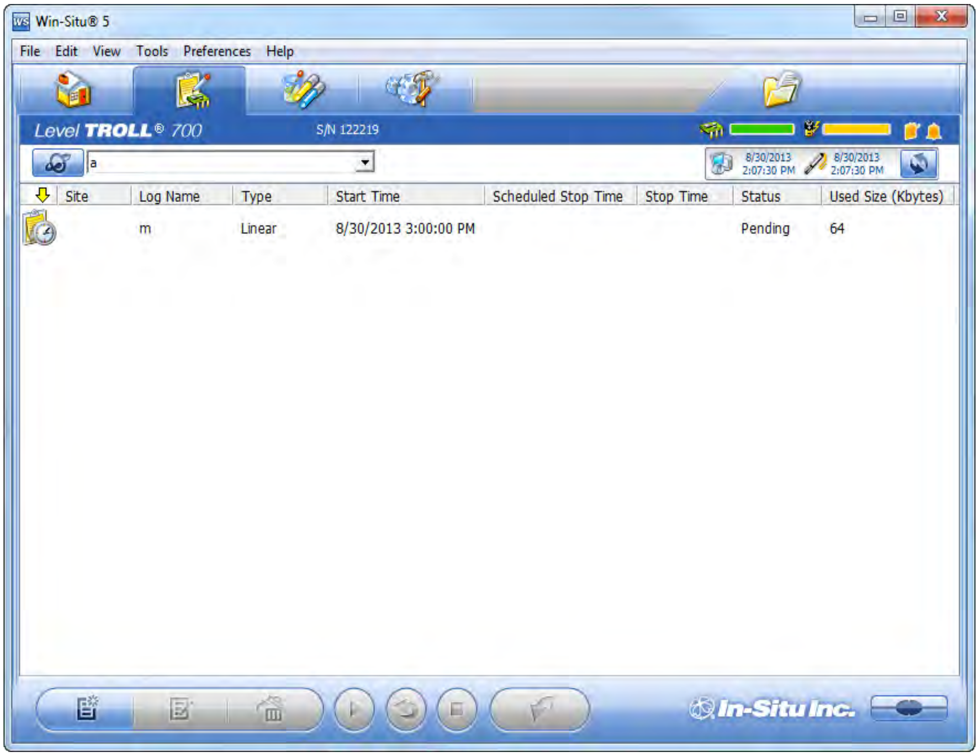

| Screen Element | Definition |
|---|---|
|  | The **Sites** button allows you to add, edit, or delete a site. Click the drop-down arrow next to the button to view the list of sites. |
|  | The **Device Memory** gauge turns yellow when the internal memory is used. Note: Non-logging instruments do not have internal memory, however, the gauge shows 100 percent green when power is applied. |
|  | The **Device Battery** gauge turns yellow as the battery is depleted. This example shows 80 percent of the battery remaining (green) and 20 percent used (yellow). Note: Non-logging instruments do not have internal batteries, however, the gauge shows 100 percent green when power is applied. |

| Screen Element | Definition |
|---|---|
|  | The **Logging Status** icon:<br>Green—The instrument is actively logging data.<br>Gray—The instrument has no logs pending or running. Non-logging instruments always show a gray status icon.<br>Yellow—The instrument has log data that was collected according to specific instructions in the "Pending" or "Suspended" state. |
|  | The **Alarm** icon provides additional instrument status information.<br>Green—No alarms or warnings<br>Yellow—One or more warnings<br>Red—One or more alarms<br>Move the cursor over the alarm icon to view a description. Click the **Device Setup** tab for detailed information on the alarm or warning.<br>Note: Disregard the **Device Reset** alarm for non-logging instruments such as the RDO PRO Probe or the Aqua TROLL 400. |
|   | **System Time** is displayed on the left. **Device Time** is displayed on the right. Clocks are updated once every two seconds. When the **Device Time** is displayed in red, it differs from the current **System Time**, and should be synchronized. |
|  | The **Time Sync** button is used to write the current PC time to the instrument. If you need to set the instrument clock to a time other than the system (PC) time, use the **Set Clock** button on the **Device Setup** tab. |
|  | **Meter View** shows the last known parameter values, displayed with current units and time stamp. Readings are sized to occupy the entire screen. This is the default display in the **Home** tab. If the type is black, the readings are updating in real time. |
|  | **List View** is a running list of the most recent records. New readings are continuously added to the top of the list and old readings scroll off the bottom. |
|  | **Graph View** shows a real-time trend graph of the selected parameters. |

| Screen Element | Definition |
| --- | --- |
|  | The **Snapshot** button records one set of readings. |
|  | The **Record** button logs data to a CSV file that can be opened in a spreadsheet program. This is not the same as recording data in a log on the instrument. |

## Logging Tab

The **Logging** tab displays a list of logs in the instrument. When you click the **Logging** tab, it may take a moment for the software to retrieve information from the instrument.




### Log Information

Columns across the **Logging** screen show information about the logs in the instrument.

- **Symbol**—This is a graphic representation of the information in the **Status** column.
- **Site**—The site that was specified when the log was configured.
- **Log Name**—The name that was entered when the log was configured.
- **Type**—The logging method that was selected when the log was configured.
- **Start Time**—For a Pending log, the scheduled start time is shown. For a Ready log that has not yet started, this column displays “Manual.” For a Running or Stopped log, the actual start time is shown.
- **Scheduled Stop Time**—For a log with a scheduled stop, the scheduled stop time is shown. For a log without a scheduled stop time, this column is blank.
- **Stop Time**—For a Pending or Ready log, this column is blank. For a Running log, the time of the last data point is shown. For a Stopped log, the actual stop time is shown.
- **Status**—Each log has a specific status. See **Log Status** for details.
- **Used Size**—Kilobytes of instrument memory allocated for this log. For a Pending or Ready log, the current size of the log configuration is shown. For a Completed log, the size of the entire log file is shown. For a Running log, the current size of the log up to the last data point is shown.

### Log Status

The status of each log in the instrument is displayed in the Logging tab by a symbol beside the log name, and in the Status column.

 **Ready**—Manual Start log is ready to start.

**Pending**—Scheduled start log is ready to start at its programmed time, or when you click the **Start** button.

**Running**—The log is actively logging data.

**Suspended**—The log has been paused (stopped temporarily).

**Stopped**—The log has been stopped, either manually or on a schedule.

**Deleted**—The log has been marked for deletion and will be deleted from the instrument when memory is needed. The software manages this automatically.

**Invalid**—The log as programmed cannot be run.

> ✔ **Ready**, **Pending**, **Running**, and **Suspended** logs are considered active. Only one log can be active in the instrument.

### Log Control Buttons

You can control the status of a log by selecting the log and clicking the appropriate button in the **Logging** tab control panel:

The **Start** button starts a **Ready** or **Pending** log, or resumes a **Suspended** log.

The **Pause** button pauses a **Running** log allowing you the option to resume it.

The **Restart** button restarts the selected **Running** log from the beginning. This can be useful during aquifer testing using a logarithmic data collection schedule.

The **Stop** button permanently stops the selected **Running** log.

### Log Operations

Use the buttons in the control panel to perform the following actions:

Create a new log.

The **New** button is disabled if a Ready, Pending, Running, or Suspended log is on the instrument. When the instrument contains its maximum number of logs, the New button is unavailable.

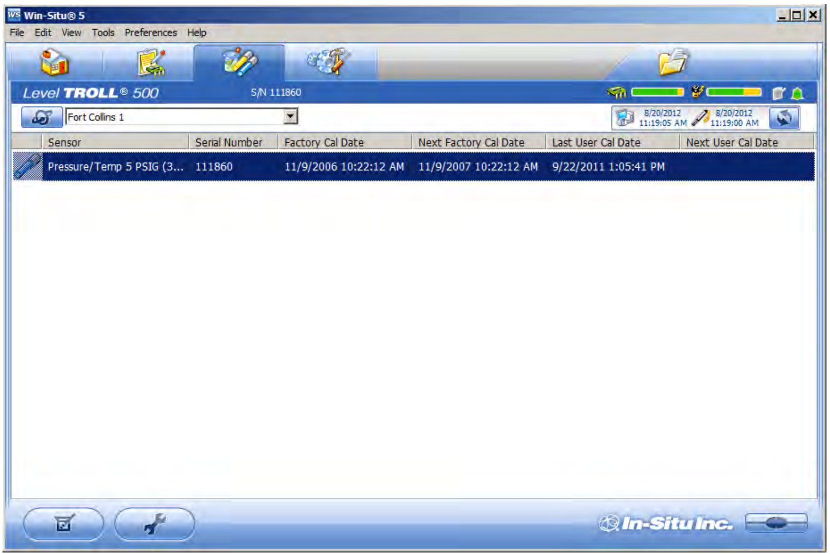
**Edit** (or review) the log configuration for a Ready, Pending, or Invalid log.

**Delete** the log. (Note that you must delete a log twice before it is permanently removed.)

**Download** the log to a PC.

## Sensors Tab

The **Sensors** tab lists the sensors in the instrument, along with their serial numbers and calibration dates. Use the buttons in this tab to calibrate and configure sensors.




### Calibrate

Use the **Calibration** button to calibrate sensors or to adjust a level reference that is currently stored on the instrument. The **Calibrate** button is not available when the instrument does not support calibration (e.g. BaroTROLL Instrument).

1. With the instrument connected to the software, select the **Sensors** tab.
2. Select the parameter you intend to calibrate.
3. Click the **Calibrate** button .

### Configure

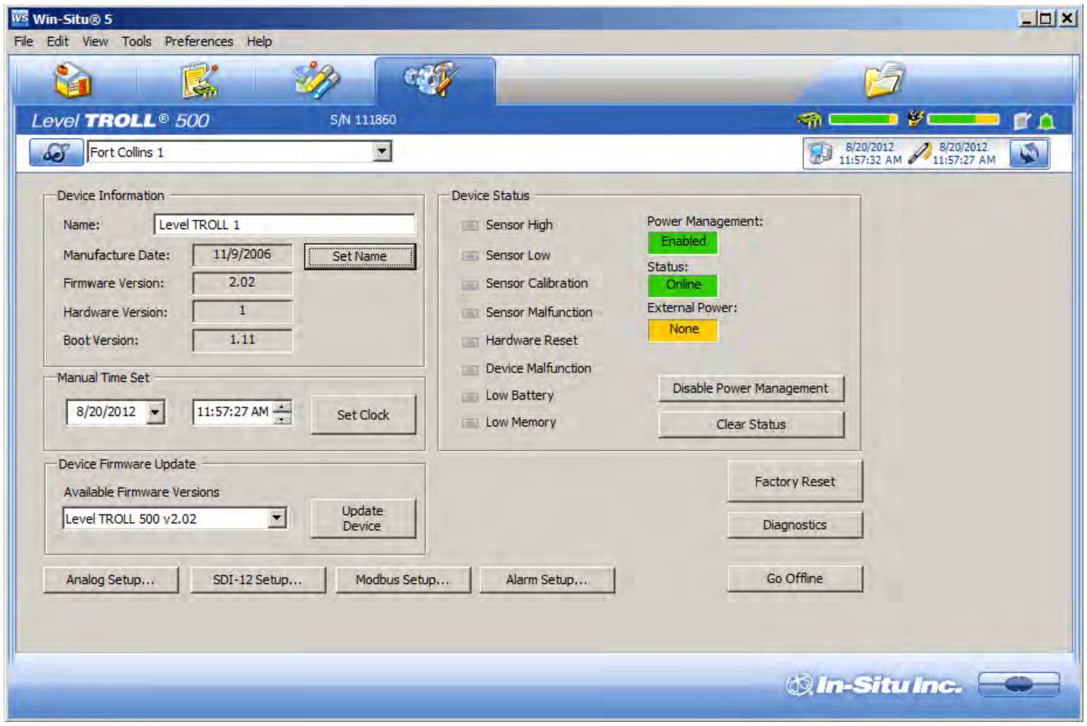
Use the **Configure** button to select parameter units and to configure parameters that support configuration. Examples include Level/Depth, Specific Conductivity, and Total Dissolved Solids. Parameters cannot be configured while the instrument is showing live data on the **Home** screen or while the instrument contains an active log.

1. With the instrument connected to the software, select the **Sensors** tab.
2. Select the parameter you intend to configure.
3. Click the **Configure** button .

> ✔ When you configure the Level parameter using the **Sensors** tab, the settings are stored in the instrument and are available for use in Modbus, SDI-12, or analog communication (if available). If desired, a different configuration can be selected when setting up a log.

## Device Setup Tab

In general, you should not use the **Device Setup** tab unless you are corresponding with the In-Situ technical support team. However, you can use this screen to set up communication protocols if you are connecting the instrument to a PLC or data logger.




✔ See the online Help for more details.

## *Using Win-Situ 5 Software*

### Connecting an Instrument to the Software

When you open Win-Situ 5 Software, you are asked if you want to connect to your device. Click **Yes**. Synchronize the instrument clock to the PC clock. 

The software displays an error message if a connection cannot be established.

### Selecting the Correct COM Port

If you are using a USB TROLL Com, select the correct COM port by following the steps below. If you are using a serial TROLL Com, the Win-Situ Software should default to the correct COM port, which is usually COM 1.

**Steps for Windows 8.1 and Windows 10 systems.**

1. Right-click the **Start** button.
2. Click **Device Manager**.
3. Click the arrow next to **Ports (COM and LPT)**, and locate the USB Serial Port listing. The number listed next to this entry is your COM port address.

**Steps for Windows 8 systems.**

1. Right-click the **Start** screen.
2. Select **All Apps**.
3. Click **Control Panel**.
4. Open the **Device Manager**.
5. Click the arrow next to **Ports (Com and LPT)**, and locate the USB Serial Port listing. The number listed next to this entry is your COM port address.

**Steps for Windows 7 systems.**

1. Click the **Start** button, and open the **Control Panel**.
2. Click **Hardware and Sound**, and open the **Device Manager**.
3. Click the arrow next to **Ports (COM and LPT)**, and locate the USB Serial Port listing. The number listed next to this entry is your COM port address.

**Steps for Windows XP systems.**

1. Click the **Start** button, and open the **Control Panel**.
2. Double-click the **System** icon. Click the **Hardware** tab, and open the **Device Manager**.
3. Click the plus sign next to **Ports (COM and LPT)**, and locate the USB Serial Port listing. The number listed next to this entry is your COM port address.

> ✔ **The following steps apply for all Windows operating systems.**

1. Once you have determined the correct COM port address in your operating system, reopen Win-Situ 5 Software.
2. Close any open windows in Win-Situ Software.
3. Click **Preferences**.
4. Click **Comm Settings**, and then click the **Port Number** menu.

5. Scroll down to find the correct COM port address. Click the **check mark** to accept the changes.
6. Click the yellow **Connect** button in the lower right corner to establish a connection to the instrument.

### Setting the Instrument Time

The instrument time and the current PC time are shown at the top of the screen when an instrument is connected to the software.


The PC time appears on the left, the instrument time on the right. Both clocks are updated at 0.5 Hz (once every two seconds). The device time is displayed in red if it differs by more than a few seconds from the current PC time. Data logging schedules depend on a correct instrument time.

To synchronize the instrument time to the current PC time, click the **Clock Sync** button . Win-Situ writes the current PC time to the instrument.

### Adding a New Site

To add a new site to the site database in your working directory do one of the following:

On the **Data** tab, click the **Site Data** folder, select **File**> **New** > **Site**.

or

On the **Home** tab, click the **Site** button to display the site list, then click **New** . Enter a name for the site. This is the only required field.

Click **Save** to save the new site. The new site will appear in the **Site Data** folder, and Win-Situ will add it to the site database in the working directory on your computer. It is now available to select for any instrument log.

### Log Setup

The Log Setup Wizard presents sequential screens to help you supply all the information necessary to set up a data log in the instrument.

To access the Log Setup Wizard the instrument must be connected to the software.

1. Click the **Logging** tab .
2. Click the **New** button .

> ✔ The **New** button may be disabled or may show a warning if an active log already exists on the instrument, or if the instrument is polling live data (see the **Home** screen), or if the device already contains its maximum number of logs.

3. Select the **Site** where the set of data will be logged and supply a name for the log.
4. Click the **right arrow** to continue after each step.
5. Select the parameters you intend to measure, choose the measurement units, and specify the order in which the selected parameters will be logged.
6. Select the logging method you intend to use. See page 54.
7. Select the log interval. A log interval is how often a measurement will be taken and stored.
8. Select the start condition, stop condition, and specify how to handle full device memory.

9. If you selected **Level** or **Depth** as a parameter to measure, specify how you intend to log this parameter. See page 54.
10. The final screen summarizes the log setup. Click the **check mark** to write this information to the instrument.

## Logging Method Descriptions

The following is a list of log types and their descriptions. The log types that are available on an instrument vary depending upon the capabilities of the instrument.

### Logging Methods for Long-Term Monitoring

#### Linear

Linear log type measures and records at a user-defined fixed interval of one minute or more. This method is used for long-term studies, landfill monitoring, stream gauging, tidal studies, and background monitoring prior to aquifer testing. Intervals are measured in days, hours, or minutes.

#### Linear Average

Linear Average log type can smooth out anomalous highs and lows that may occur in a data set, for example, when a water wave passes over the instrument. Each stored measurement is the average of several rapid measurements. This method is used for long-term studies, stream gauging, tidal and open-water studies where trends are more important than accuracy. Intervals are measured in days, hours, minutes, or seconds.

#### Event

Linear Event log type combines basic fixed-interval logging of specified parameters with the ability to log data at a faster interval when a single-parameter event condition is present.

### Logging Methods for Aquifer Testing

#### True Logarithmic

True Logarithmic log type captures early-time water-level data during aquifer testing. Measurements are very closely spaced at the start of the test (4 measurements per second) and move further apart on a logarithmically decaying schedule as the test progresses. There are 40 measurements per log decade. This log type is commonly used for rapid step-drawdown pump tests, constant-rate pump tests, and slug tests.

#### Fast Linear

Fast Linear log type measures and records at a user-defined fixed interval of one minute or less. The interval is small (seconds, milliseconds), and the test is usually of short duration due to the volume of data logged and the impact of very fast sampling on battery life.

#### Step Linear

Step Linear log type measures and records data according to a number of user-defined elapsed time intervals or "steps" within a schedule. Both the elapsed time and the number of measurements within each step can vary. After completing the elapsed time for each step, the schedule will automatically move to the next step. Up to 10 separate steps can be defined.

## About the Level Reference

A Level Reference, also called an offset, is a user-specified starting point for logged Level readings.

Depth mode does not require that you enter a Level Reference.

The Level Reference can be any value you choose. Here are some examples:

- **Elevation**—If you calculate the water level above mean sea level (MSL) and enter this as the Level Reference, then elevations above MSL will be logged.

- **Depth to Water**—If you measure the depth to the water surface (DTW) from the top of the well casing and enter this as the Level Reference, then DTW (also called drawdown) values will be logged.
- **Zero**—A Level Reference of 0 effectively sets the probe to zero at the start of the log. Changes, both positive and negative, from the starting water level, will be logged.

Once you have determined the value of your Level Reference, the software gives you three options for entering it. These control when the level reference is applied.

- **New Reference**—This option is designed to be used with an active software connection when the device is installed in the water.

> **A new level reference must be entered while the device's pressure sensor is submerged in its final position in the water.** This is because the current probe reading is set equal to the Level Reference to create the offset that takes effect at the start of the data log. The log header will show the probe reading at the time you entered the Level Reference.

During log setup, the software presents two additional options for entering the Level Reference:

- **Set first logged reading**—Use this option when the instrument will be deployed on wire rather than cable because you will not be able to communicate with the instrument when it is submerged.
- **Remind me to set reference later**—Use this option to defer the entry of the Level Reference during log setup and set a reminder to enter it when the device is submerged in its final position.

## Starting a Log

Every log is programmed for either a manual or a scheduled start. A log with a manual start time is displayed in the Logging screen with **Ready** in the **Status** column. A log with a scheduled start time is displayed with **Pending** in the **Status** column.

### Starting a Pending Log

A **Pending** log automatically starts at the scheduled time without any user intervention.

> A scheduled log with **Pending** status can be manually started at any time before its scheduled start.

### Starting a Manual Log

With the instrument connected to the software, select the **Logging** tab.

Select the Ready log you want to start.

Click the **Start Log** button . The log starts and the symbol changes. The **Status** column displays **Running**.

## Suspending (Pausing) a Log

A running log may be temporarily paused. For example, you might want to reposition an instrument, calibrate a sensor, or clean a sensor and later resume the log. A log can be suspended and resumed three times.

1. With the instrument connected to the software, select the **Logging** tab .
2. Select the log you intend to suspend.
3. Click the **Suspend** button . **Suspended** appears in the **Status** column.

### Resuming a Suspended Log

1. To resume logging after a log has been suspended, select the **Logging** tab.
2. Select the **Suspended** log.
3. Click the **Start Log** button . Logging resumes. **Running** appears in the **Status** column. The data file will show the time when the log was suspended and the time when it restarted.

### Stopping a Log

A log can be manually stopped at any time, even if a stop time has been previously scheduled. If you did not specify a stop condition when you defined the log, the log will run until the instrument is out of memory or battery power, or until you manually stop it.

> ✔ A log that has been stopped cannot be resumed. If you intend to resume a log later, you should suspend a log rather than stop it.

1. To manually stop a log, the instrument must be connected to the software.
2. Select the **Logging** tab .
3. Select the running log you intend to stop.
4. Click the **Stop Log** button .

### Downloading Data to a PC

This procedure copies the data log from the instrument to a PC. It does not remove the data log from the instrument. After a log is downloaded, it can be exported to a CSV file format that can be used by spreadsheet programs. The time shown in the log name is the time the log was downloaded.

1. With an instrument connected, select the **Logging** tab .
2. Select the log you intend to download.
3. Choose a Running, Suspended, Stopped, or Deleted log.
4. Click the **Download**  button.
5. In the next screen, select one of the three download options.
   - All data
   - New data (data logged since the last download)
   - Time interval to download

> ✔ New data is downloaded by default to a new log file. To append new data to the last download of this log, be sure the option "Append logs on download" is selected in the **General Settings** dialog (**Preferences** > **General Settings**).

2. The log is copied to the connected PC into your Win-Situ working directory folder. View or change the working directory using **File** > **Settings**.
3. At the end of the download, Win-Situ gives you the option of viewing the data.
   - Select **Yes** and the log is displayed in the **Data** screen.

- Select **No** and the **Logging** screen appears. You can view the data at any time by selecting it in the **Data** tab.

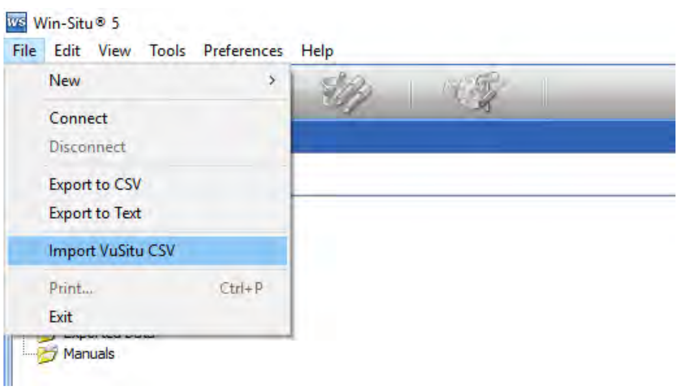
## Viewing Logged Data

1. To view the data stored in the instrument, you must first download the data. A connection to an instrument is not needed after the data log has been downloaded.
2. Select the **Data** tab .
3. On the left side of the screen, select the log you want to view. To expand a folder shown in the navigation tree, double-click the folder. The content of the data log is displayed on the right side of the screen in text or graph format.

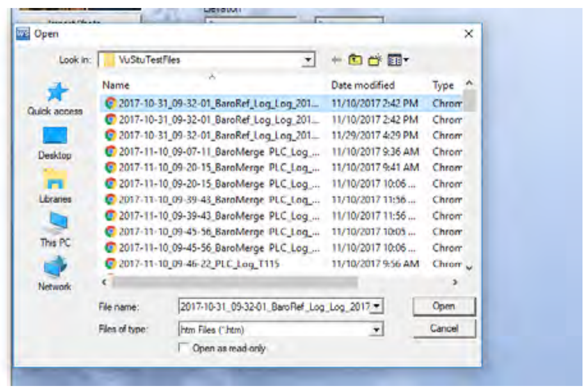
> To switch between view formats, click the **Text** or the **Graph** button in the control panel. To customize the text or graph view, select **Preferences** > **Graph Settings** or **Preferences** > **Data View Settings**. These options apply to all downloaded data until you change the options.

## Importing VuSitu Data to Win-Situ

You can import data files from VuSitu into Win-Situ 5 from the File menu.

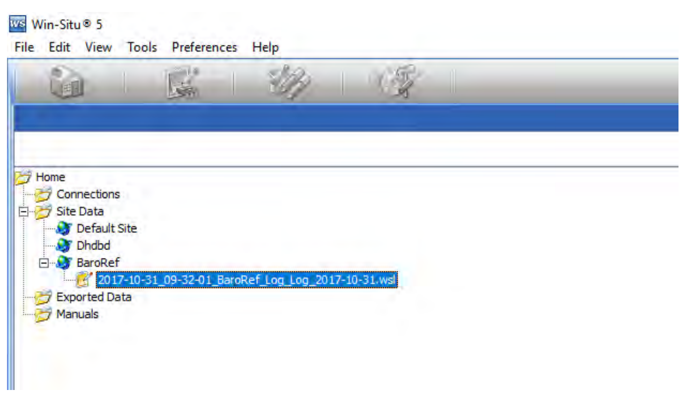



A. Click **File** > **Import VuSitu CSV** in the menu bar at the top of the screen.




B. Select the file you wish to import and click **Open**.


C. Select **OK** at the prompt.




D. Click on the file name to view it.

## Using BaroMerge Software

BaroMerge Software is used to post-correct absolute (non-vented) level sensor data to eliminate barometric pressure effects from the measurements. BaroMerge Software can be accessed through the Win-Situ 5 Software **Tools** menu. BaroMerge provides three options to correct data.

- **Fixed Correction**—A single offset value is applied to all selected log data. Use this option if you know the barometric pressure of the site during the log, and know that it did not change.
- **Manual Entry**—Specify two or more correction values to apply to the log data. Use this option if you wish to manually enter a data set of barometric pressure values.
- **BaroTROLL log file**—Absolute level sensor data points are individually corrected to reflect barometric pressure changes that were logged by a BaroTROLL instrument during the approximate time period.


## BaroMerge Input—BaroTROLL File

Log files that contain absolute data can be barometrically compensated using values logged by the In-Situ Inc. BaroTROLL Instrument. Select this method when you have access to a BaroTROLL log file covering approximately the same time period as the data file you intend to correct.

To use this correction method, you need the name of the BaroTROLL log file and the name(s) of the absolute log file(s) you want to correct.

1. From the **Tools** menu in Win-Situ 5 Software, select **Win-Situ BaroMerge**.


2. Select the "Use a BaroTROLL file:" option.
3. Click the browse button to the right of the file field.
4. Select a BaroTROLL file and click the **check mark**.
5. Values from the BaroTROLL file will be displayed in the next window. You can edit these values if necessary.
6. Click the **right arrow** button.
7. Select the log file(s) you intend to correct and click the **check mark**.
8. Compensated data files can be viewed or exported from the **Data** tab.

## BaroMerge Output

Your original log file is not changed. A new, corrected log file with the same name and path is created. The original ".wsl" extension is replaced by "-Baro Merge.wsl".

### Disconnecting an Instrument from the Software

Click the plug icon  in the lower-right corner of the screen to disconnect the instrument from the software.

Disconnect the instrument from the communication device. Attach a desiccant pack if you are using a vented cable.

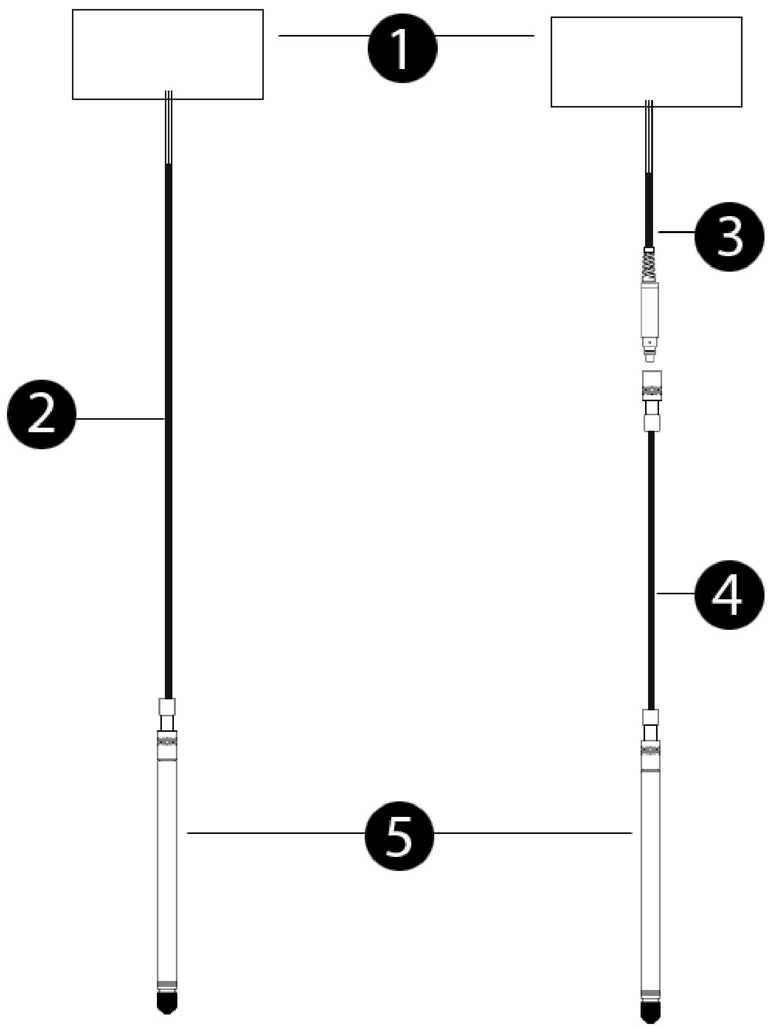
## *Connect to a Data Logger or PLC Controller*

The instrument can be connected to a data logger or controller via a stripped-and-tinned RuggedCable System for communication using one of the following protocols.

- Analog (4-20 mA)
- SDI-12
- RS485 Modbus
- RS232 Modbus (with a customer-supplied converter)

Stripped-and-tinned RuggedCable System includes a female connector on one end that connects to the instrument. The uphole end terminates in stripped-and-tinned wires for connection to a PLC controller or data logger.

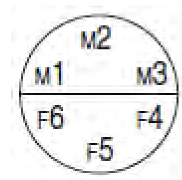
A shorter length Stripped-and-tinned RuggedCable System with a male connector is available to convert a female to female RuggedCable System to a stripped-and-tinned configuration.



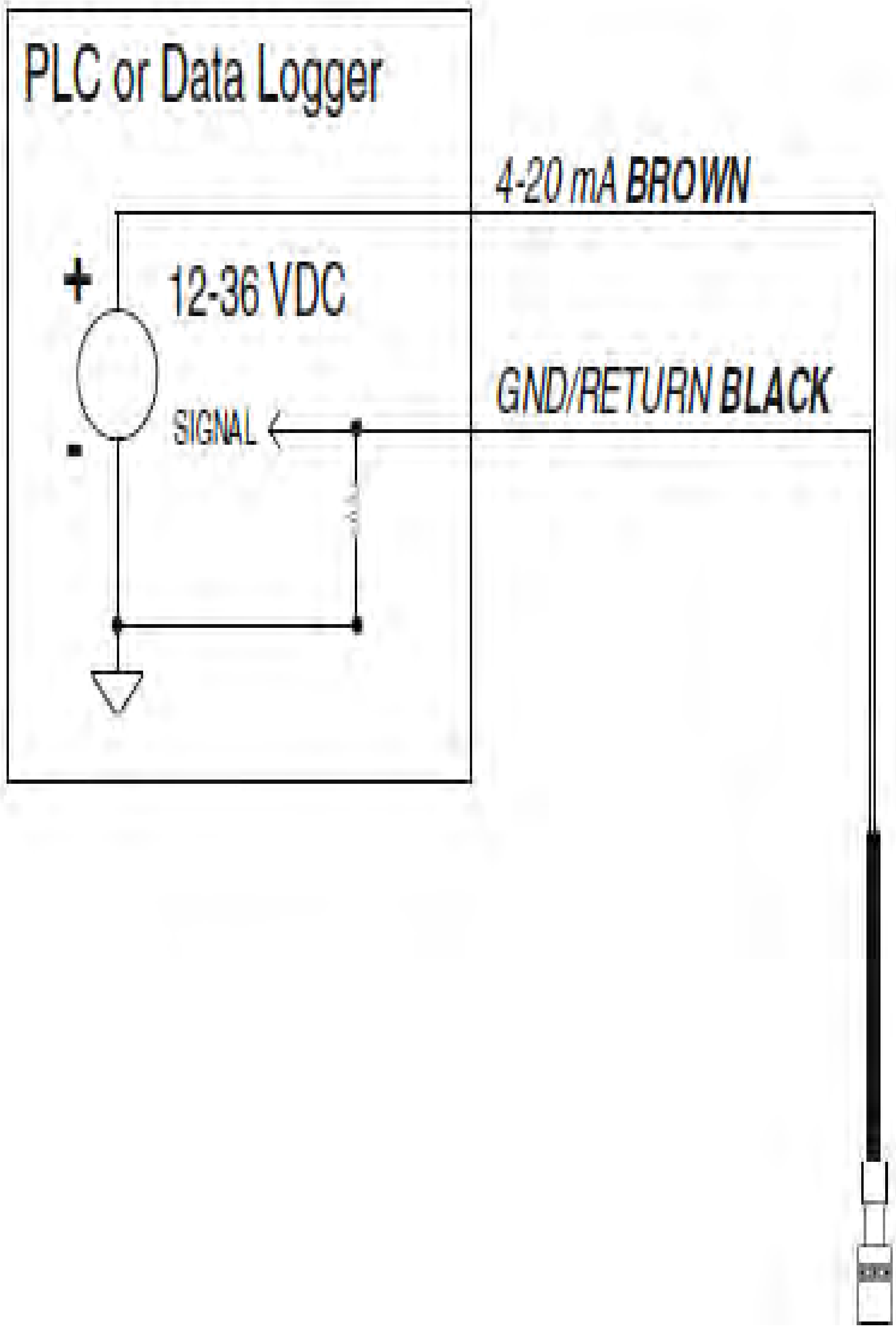
| | |
|---|---|
| 1 | PLC or Data Logger |
| 2 | Stripped-and-tinned RuggedCable System with female connector |
| 3 | Short stripped-and-tinned RuggedCable System with male connector |
| 4 | RuggedCable System with female to female twist-lock connector |
| 5 | Instrument |

## Wiring

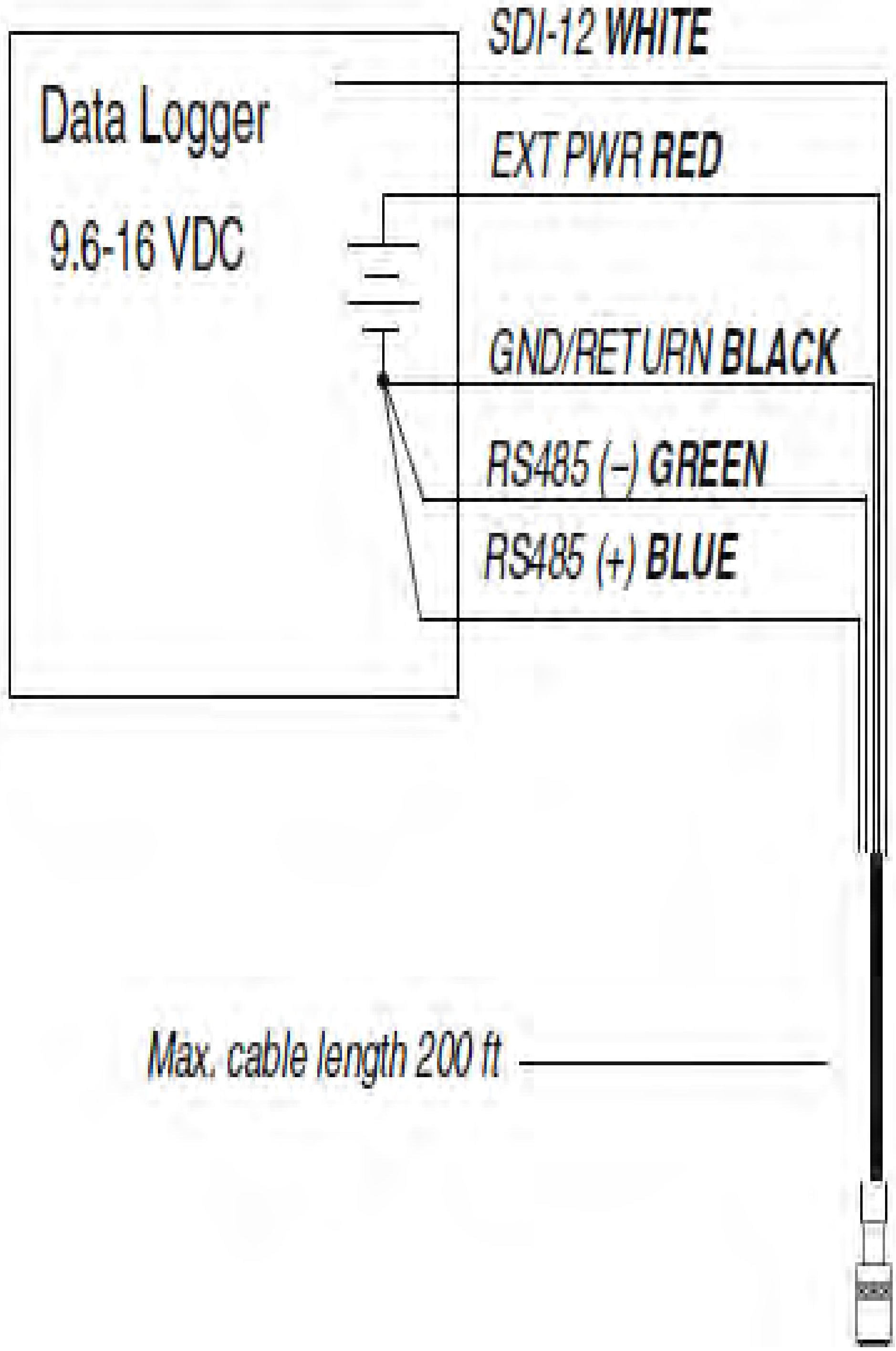
Refer to the diagrams on the following pages for wiring information. Make sure that you trim and insulate unused wires. The shield must be wired to a chassis ground or earth ground.

| Signal | Color | Pin | |
|---|---|---|---|
| Gnd/Return | Black | 6 |   |
| Ext Power | Red | 5 | |
| 4-20 mA | Brown | 4 | |
| RS485(-) | Green | 3 | |
| RS485(+) | Blue | 2 | |
| SDI-12 | White | 1 | |

**Analog (4-20 mA) 2 Wire**

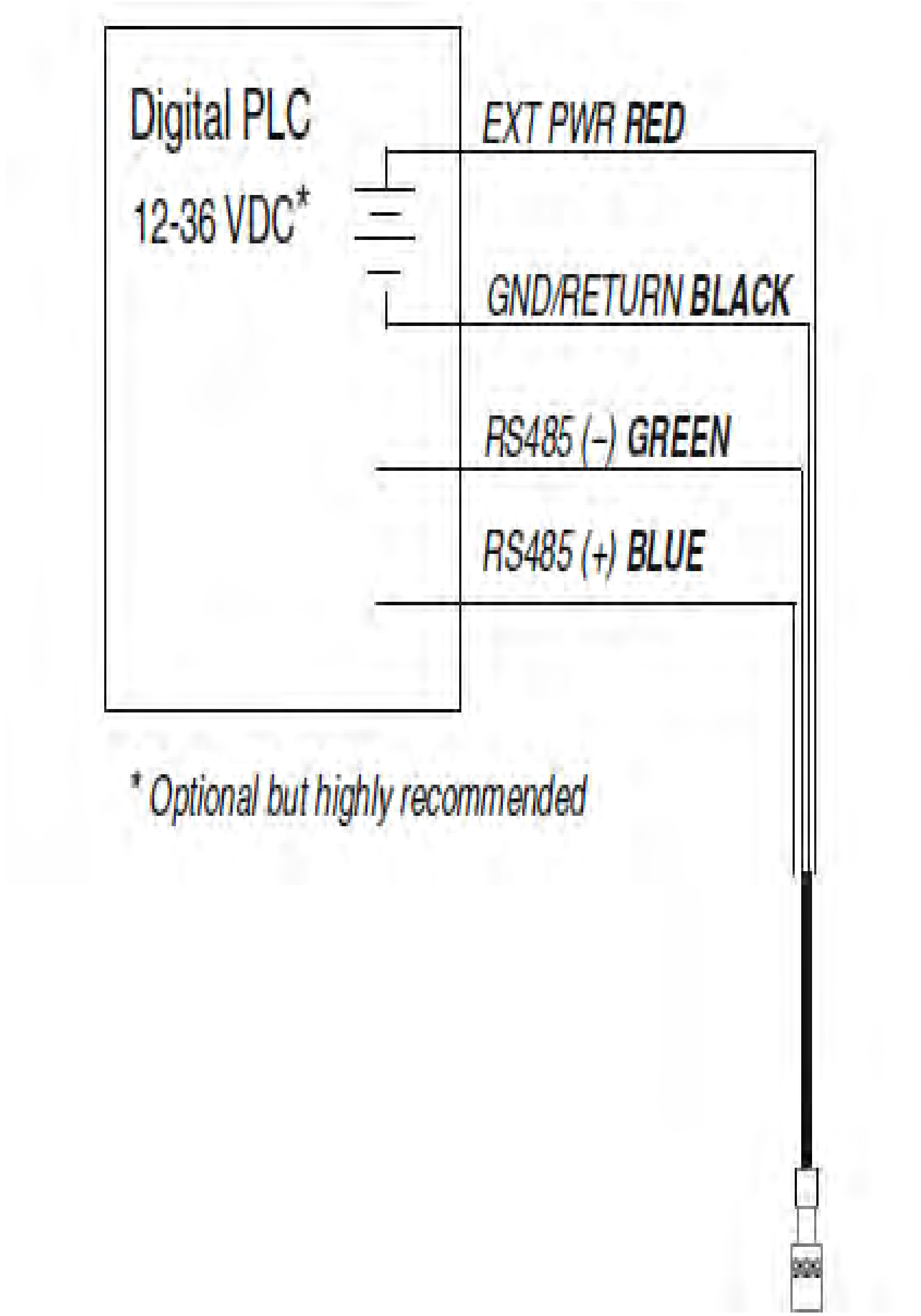


**SDI-12 3 Wire**

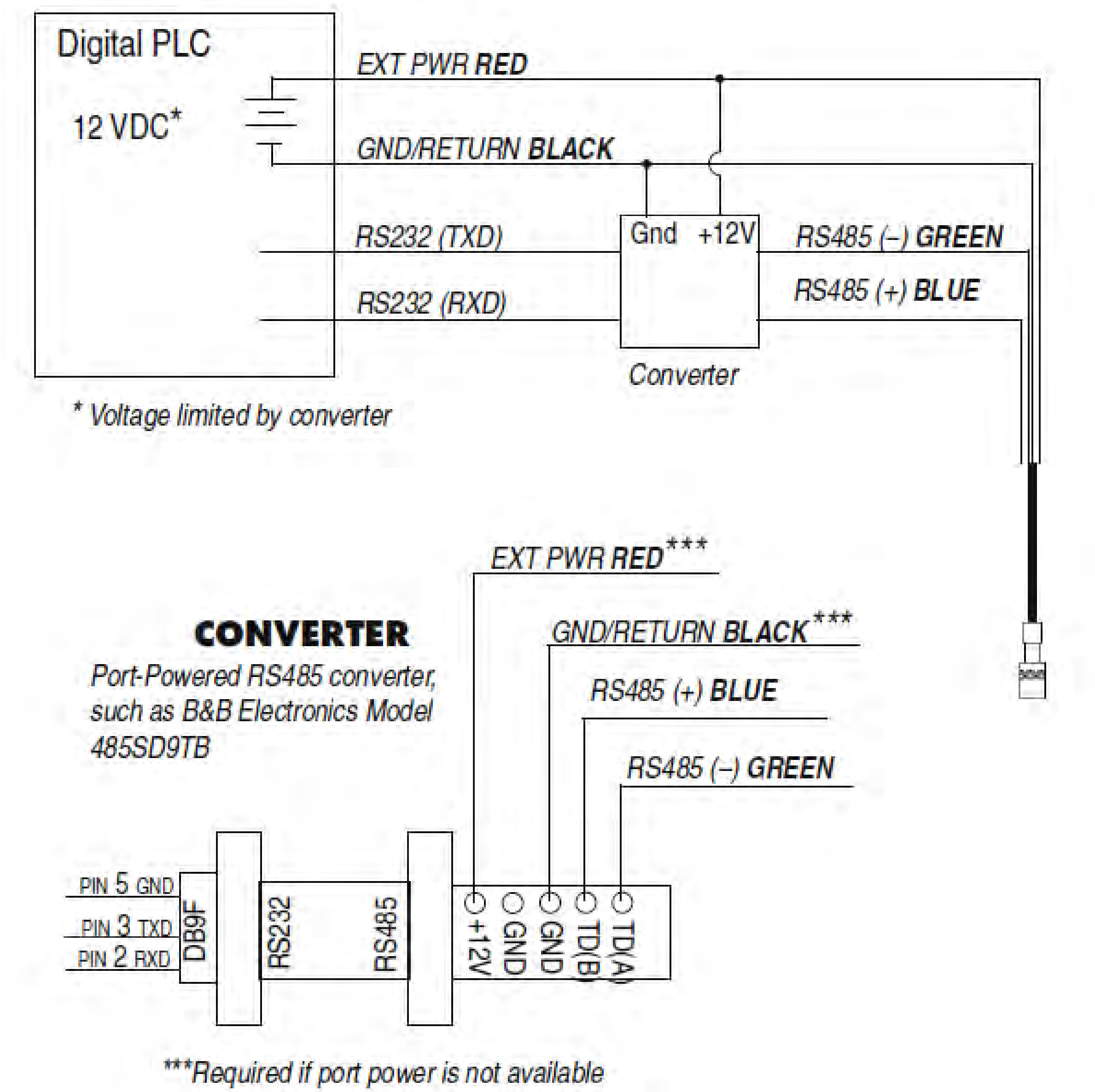


SDI-12 WHITE
Data Logger
9.6-16 VDC
EXT PWR RED
GND/RETURN BLACK
RS485 (–) GREEN
RS485 (+) BLUE
Max. cable length 200 ft

**Modbus Master**



**Modbus Master with RS232 (Converter Required)**



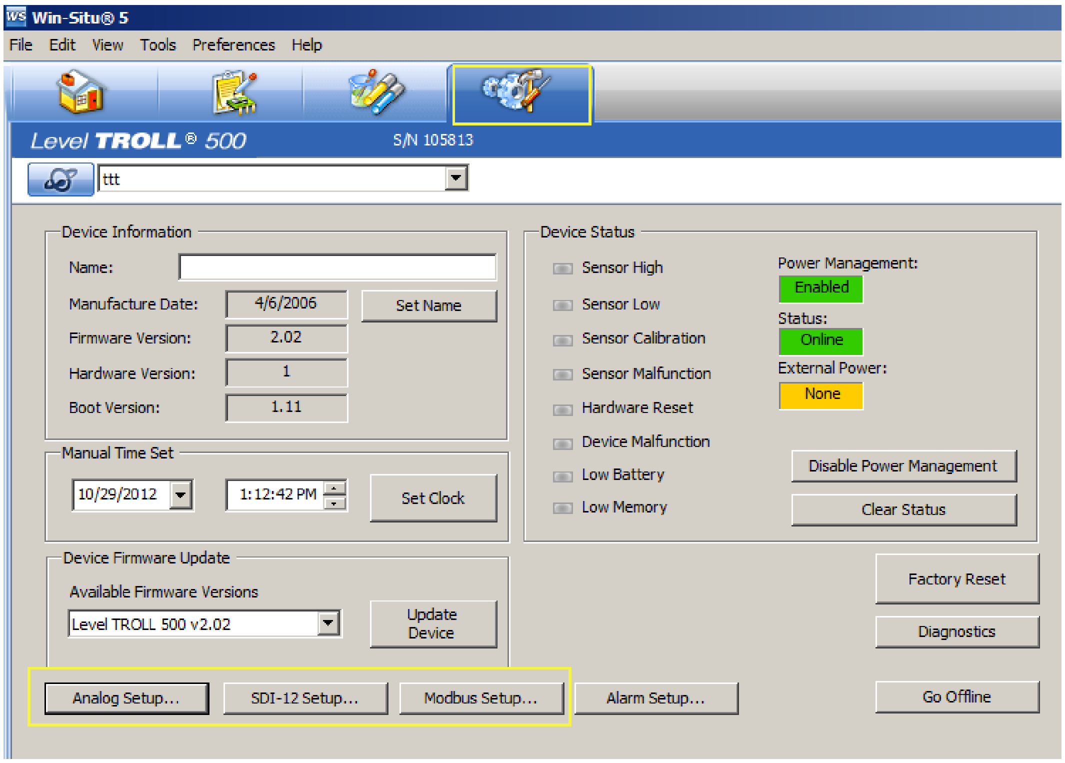
## Power Connections

The Red wire provides power for Modbus and SDI-12 modes. The Brown wire provides power for the 4-20 mA mode. If power is present on the Brown wire and not on the Red wire, the device enters the 4-20 mA mode automatically and stays in the 4-20 mode until power is removed from the Brown wire or is applied to the Red wire. The Red wire has priority. If power is applied to the Red and Brown wires at the same time, the device will operate in Modbus or SDI-12 modes but not in 4-20.

## Communication Protocols

The device automatically switches between Modbus and SDI-12 modes depending on which of the two interfaces has activity. Modbus and SDI-12 cannot be used at the same time. The communication protocol that is currently in use will block communication on the other.

Win-Situ 5 Software provides options for configuring analog/SDI-12 communications and Modbus communications on the **Tools** tab.




> ⚠ For additional information on Modbus and SDI-12 communications, including the SDI-12 commands and Modbus registers, see ***www.in-situ.com/Technical_notes*** and scroll to the Communications and Software Technical Notes section.

## Redundant Logging

The instrument is capable of internal logging while participating in a Modbus, SDI-12 or analog network. However, Win-Situ 5 Software cannot communicate with the instrument while it is transmitting Modbus, SDI-12, or 4-20 mA analog data, and the instrument cannot receive or respond to Modbus, SDI-12, or 4-20 mA analog commands while connected to a PC serial port.

If the PLC or data logger loses data, the data that was logged internally on the instrument can be retrieved using Win-Situ 5 Software.

If the PLC or data logger experiences power loss, the instrument will continue to collect data using its internal batteries and clock.

A port-powered RS485 converter like that shown for Modbus connections may be used for temporary connection of the Level TROLL to a serial port on a PC.

## Cleaning and Maintenance

### Overview

It is important for users to perform scheduled maintenance on their instruments to sustain the accuracy and longevity of the probes and cables. The frequency of this maintenance depends on the characteristics of the deployment site, including humidity levels and the degree of fouling.

Users should be aware of the conditions at their deployment sites and develop appropriate maintenance schedules to replace desiccant, clean the instruments, and send in the instruments for factory calibration. Users should check instruments often during the first portion of the deployment to determine the frequency of maintenance. General maintenance should be performed as often as possible. Factory maintenance and calibration should be performed every 12 to 18 months.

### Operating Considerations

The instrument has been designed to withstand harsh field conditions. However, as with any electronic instrument, it can be permanently damaged if used outside its operating specifications.

#### Temperature

Review the instrument specifications to determine the operating range. Do not deploy instruments in such a way that ice may form on or near the sensors or cable connections. Ice formation is a powerful expansive force that can over-pressurize the sensor or otherwise cause damage that is not covered by the warranty.

#### Pressure Range

The instrument can withstand pressures of up to two times (2X) the rated range of the pressure sensor without damage, although it may not read correctly at such pressure. If the pressure range is exceeded by 3X, the sensor will be destroyed.

#### Batteries

Internal batteries in the instrument are not user-replaceable. The approximate percentage remaining is displayed in Win-Situ software or the Vu-Situ mobile app when the instrument is connected.

If batteries are completely exhausted, external power and battery pack options are available. See page 24.

## Desiccant Pack Options

### Small Desiccant

The Small Desiccant is a disposable cap that ships with In-Situ products. The small desiccant is meant to protect the instrument and cable ***only during shipping and should not be used for deployments***.

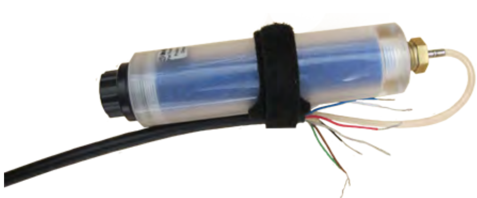
### Large and Extra Large Desiccant

The Large and Extra-Large Desiccant are used to protect equipment deployed in the field. The Large Desiccant is best suited for low-humidity environments or deployments where maintenance occurs regularly. The Extra-Large Desiccant is designed for high-humidity environments or deployments where maintenance occurs infrequently. Extra-Large Desiccants provide six times the drying capability of the Large Desiccant. When the desiccant expires, both can be refilled with fresh desiccant and re-used (see Desiccant Refill Kit below). The Large Desiccant is available with an ABS or a titanium twist-lock connector, while the Extra Large Desiccant uses a titanium connector only.

| Description | Part Number |
|---|---|
| Large Desiccant, Titanium | 0051810 |
| Large Desiccant, ABS | 0053550 |
| Extra Large Desiccant | 0090420 |

### Outboard Desiccant

The Outboard Desiccant is a replaceable desiccant pack designed to attach to the vent tube of a stripped-and-tinned cable.



| Description | Part Number |
|---|---|
| Outboard Desiccant | 0051380 |

#### Desiccant Refill Kit

The Desiccant Refill Kit supplies desiccant for the Large Desiccant, Extra Large Desiccant, and the Outboard Desiccant. It also contains replacement glass wool.

| Description | Part Number |
|---|---|
| Desiccant Refill Kit | 0029140 |

### Installing Desiccant with Twist-Lock Connectors

1. Remove the protective dust cap from the bottom of the desiccant pack, if applicable.
2. Remove expiring desiccant (if present) from the cable by grasping the textured section of the cable connector in one hand and the desiccant in the other. Twist in opposite directions to unlock the desiccant from the cable.
3. Attach the new desiccant pack to the twist-lock connector on the cable.

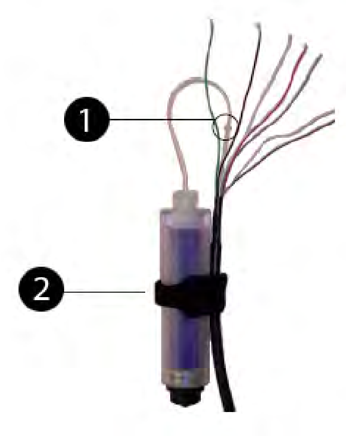
### Installing Outboard Desiccant

Vented cable must be installed with outboard desiccant to protect the cable and instrument electronics from condensation in high-humidity environments.

The desiccant can be removed from the vent tube, if necessary, to trim the conductor wires. However, you must reinstall the desiccant after trimming and connecting the wires.

1. Cut off the knot at the bottom of the vent tube extension.
2. Firmly attach the vent tube extension to the cable vent tube. Cover at least 6.4 mm (0.25 in.) of the cable vent tube for a secure attachment.
3. Use the attached hook-and-loop strap to secure the desiccant to the cable, below the stripped wires.

4. Remove the red dust cap from the black nylon cap to allow air to reach the cable's vent tube.




| | |
|---|---|
| 1 | Outboard desiccant is attached to the cable vent tube. |
| 2 | Desiccant is secured to the cable with a strap. |

### Using the Desiccant Refill Kit

1. Remove the black nylon vent cap from the top of the desiccant.
2. Pour out and discard the used desiccant. Check the glass wool in the bottom of the container and replace if necessary.

> ⚠ The glass wool prevents the desiccant beads from falling out the cable end of the desiccant pack. If the wool glass does this effectively, there is no need to replace it when refilling the desiccant.

3. Fill the container with fresh desiccant. Replace the vent cap. Reattach to cable if removed.

### Antifouling

#### TROLL Shield Nose Cone

The copper TROLL Shield Nose Cone is designed to reduce macro- and micro-fouling of the pressure sensor on Level TROLL and Aqua TROLL Instruments. Reduced fouling on the sensor improves measurement accuracy and extends the length of deployments.

For optimum performance, the TROLL Shield Nose Cone should be replaced every 12 months or sooner if site conditions are extremely harsh.

| Description | Part Number |
|---|---|
| TROLL Shield Nose Cone | 0081480 |

## O-ring Inspection and Replacement

Examine O-rings for wear, dryness, discoloration, stretching, cracks, nicks, and brittleness. Replace O-rings when any of these conditions are present. Replacing O-rings on an annual basis, regardless of their condition, is the best way to protect against moisture damage.

Perform the following steps to replace an O-ring.

1. Remove and discard the damaged O-ring.
2. Use a clean, dry, soft cloth to clean the O-ring groove to remove dirt or residue.
3. Lubricate the new O-ring using high-vacuum grease.
   a. Wash your hands thoroughly.
   b. Apply a small amount of grease to the pad of your index finger, and rub your index finger and thumb together to spread the grease evenly.
   c. Inspect the new O-ring and remove any debris stuck to it.
   d. Rub your fingers around the O-ring until there is a thin layer of grease on the entire O-ring.
4. Install the O-ring in the groove and remove any excess lubricant with a clean cloth.

   ***Do not allow water or lubricant to enter the connector.***

## Cleaning and Storage

### Cleaning the Instrument

Clean the instrument body with water and a soft brush or plastic scouring pad, or soak overnight in a mild acidic solution, such as household vinegar. ***NEVER*** submerge the connector portion of the instrument when it is not connected to a cable.

If the ports near the pressure sensor are clogged with silt or mud, try the following procedures.

- Agitate the instrument vigorously in a bucket of clean water.
- Apply a gentle rinse of water from a wash bottle.
- In severe cases, remove the nose cone and clean out the holes with a soft brush or pipe cleaner.

Do not attempt to remove material from the instrument by tapping the instrument against a surface. To avoid damage to the pressure sensor diaphragm, do not insert any object into the sensor opening or attempt to dig out dirt or other materials. **You void the instrument's warranty by inserting anything into the sensor opening.** If contamination cannot be removed using the recommendations above, please contact In-Situ for cleaning.

*A TROLL pressure sensor with the nose cone removed. Do not insert* ***ANY*** *object into the sensor opening. Doing so voids the warranty.*

### Twist-Lock Connectors

Keep the pins on all connectors free of dirt and moisture by using the soft protective dust caps when cable is not attached.

### Storage

Store the instrument in a clean, dry place. Place the protective red dust cap on the cable end or store with cable attached to protect the connector pins and O-ring. For vented cables, ensure the desiccant used is the appropriate size and change it when needed. Store the instrument where it will not roll off a bench onto a hard surface or sustain other mechanical shock. Protect the instrument from temperature extremes using the following guidelines:

- Level TROLL Instruments—store within the temperature range -40° C to +80° C (-40° F to +176° F)

## Factory Calibration and Service

### In-House Factory Calibration

Factory calibration of In-Situ instruments should be performed every 12 to 18 months, or at any point when the data appears to drift significantly. Factory calibration includes a thorough cleaning, all operational checks, necessary firmware upgrades, O-ring replacement, and full range calibrations of the pressure sensor, temperature sensor, and conductivity sensor (when applicable).

### Return Materials Authorization (RMA) Form

To obtain a factory calibration, fill out and return the online Return Materials Authorization (RMA) form located at ***www.in-situ.com/***.

### Obtaining Repair Service

If you suspect your system is malfunctioning and repair is needed, you can help assure efficient servicing by following these guidelines:

1. Call or email In-Situ Technical Support. Have the product model and serial number available.
2. Be prepared to describe the problem, including how the product was used and the conditions noted at the time of the malfunction.
3. If Technical Support determines that service is needed, they will ask your company to fill out the RMA form and pre-approve a specified monetary amount for repair charges. When the form and pre-approval is received, Technical Support will assign an RMA (Return Material Authorization) number.
4. Clean the product as described in the manual.
5. If the product contains a removable battery, remove and retain it unless you are returning the system for a refund or Technical Support states otherwise.
6. Carefully pack your product in its original shipping box, if possible.
7. Mark the RMA number clearly on the outside of the box.
8. Send the package, shipping prepaid, to:

In-Situ
ATTN: Repairs
221 East Lincoln Avenue
Fort Collins, CO 80524

The warranty does not cover damage during transit. In-Situ recommends insurance for all shipments. Warranty repairs will be shipped back prepaid.

### Outside the U.S.

Contact your international In-Situ distributor for repair and service information.

**Guidelines for Cleaning Returned Equipment**

Please help us protect the health and safety of our employees by cleaning and decontaminating equipment that has been subjected to potential biological or health hazards, and labeling such equipment. Unfortunately, we cannot service your equipment without such notification. Please complete and sign the form on page 77 (or a similar statement certifying that the equipment has been cleaned and decontaminated) and send it to us with each instrument.

- We recommend the glassware cleaning product, Alconox, available from In-Situ and from laboratory supply companies.
- Clean all cables and remove all foreign matter.
- Clean the cable connectors with a clean, dry cloth. Do not submerge the connectors.
- Clean the instrument including the nosecone, cable head, and protective caps.

| | |
|---|---|
| ⚠ | If an instrument is returned to our Service Center for repair or recalibration without a statement that it has been cleaned and decontaminated, or if it is the opinion of our Service Representatives that the equipment presents a potential health or biological hazard, we reserve the right to withhold service until proper certification is obtained. |

### *Decontamination and Cleaning Form*

**Decontamination & Cleaning Statement**

Company Name____________________________________ Phone ____________________

Address ________________________________________________________________

City ______________________________ State ______________ Zip ___________________

Instrument Type ______________________________ Serial Number ______________________

Contaminant(s) (if known) ________________________________________________________

__________________________________________________________________________________

Decontamination procedure(s) used __________________________________________________

__________________________________________________________________________________

Cleaning verified by ____________________________________ Title _______________________

Date ______________________________

In-Situ Inc.

## *Troubleshooting*

In addition to the following troubleshooting items, the In-Situ website includes instructional videos, technical notes, and more. See ***www.in-situ.com/***.

| Problem | Possible Cause | Possible Solution |
|---|---|---|
| Win-Situ 5 Software cannot connect to the instrument. | Wrong COM port is selected, communication settings are incompatible, cable connections are loose or dirty, or batteries are low. | Make sure cable connections are tight and connectors are clean and dry.<br><br>Make sure the cable is securely attached to the instrument.<br><br>Make sure the correct COM port is selected (select **Preferences** > **Comm Settings** to verify).<br><br>Make sure the communication settings in Win-Situ and in the instrument match. To reset the device communication settings to the serial defaults, click “Reset all Devices” in the Comm Settings dialog (**Preferences** > **Comm Settings**).<br><br>Make sure the internal battery has voltage remaining, or external power is supplied.<br><br>See ***www.in-situ.com/Technical_notes*** and scroll to the Communications and Software Technical Notes section for more information. |
| Real-time readings display the wrong units. | Default units are being used. | Click the **Sensors** tab, select the sensor, click the configure button and select the desired units for each parameter in the Sensor Setup window. |
| Cannot add a new log. | Only one active log can reside in the device at a time—an active log is a log that is Ready, Pending, Running, or Suspended as shown in the Status column of the Logging Tab.<br><br>The device has its maximum number of logs already stored—the Level TROLL 300, 500, and Baro TROLL have a capacity of 2 logs. | Stop or delete the log if possible. Alternatively, configure the new log after the active log is completed.<br><br>Download, and then delete a log you no longer need. This will make room for an additional log on the device. |
| New log exceeds available memory (software message). | The log as configured would exceed the device memory. | Edit the log and select a longer sampling interval.<br><br>If available, select the "wrap data" option. This causes more recent data to overwrite older data when memory is full.<br><br>For a log with a scheduled start, select None as the stop condition, or select a stop time that is closer to the start time. |

| Problem | Possible Cause | Possible Solution |
| --- | --- | --- |
| Cannot configure level or other parameters using the **Configure** button on the **Sensors** tab. The **Sensor Setup** screen is shown, but the **Configure**... button is dim. | The instrument is actively polling (continually updating real-time readings) in the **Home** tab. | Return to the **Home** tab and stop real-time readings by clicking the **Play** button. |
| | The instrument has an active log—a log that is Ready, Pending, Running, or Suspended as shown in the **Status** column of the **Logging** tab. Only one active log can reside in the device at a time. | Stop or delete the log if possible. Alternatively, configure parameters after the log is complete. |

## *Declarations of Conformity and Similarity*

### *Level TROLL 400 Instrument*

**EMC Verification**
**Declaration of Similarity**

**Equipment**

| | |
|---|---|
| Type of equipment: | Measurement instrumentation |
| Product name: | Level TROLL® 400 |
| Model: | Level TROLL® 400 |
| Manufacturer: | In-Situ, Inc.<br>221 East Lincoln Avenue<br>Fort Collins, CO 80524<br>USA |

| **Category** | **Standards** |
|---|---|
| Emission: | EN 61326 & FCC Part 15, Subpart B |
| Immunity: | EN61326 |

**Summary**

We confirm that the equipment referenced above, without reasonable doubt, will fulfill the requirements concerning electromagnetic compatibility according to the above mentioned standards harmonized with the EMC Directive 89/336/EEC. The Level TROLL 700 was tested and found to be in compliance in the month of January 2006.

Date of Issue: August 30, 2013

Ben Kimbell
Vice President of Research and Development

## Declaration of Conformity

Manufacturer: In-Situ, Inc.
221 East Lincoln Avenue
Fort Collins, CO 80524
USA

Declares that the following product:

| | |
|---|---|
| Product name: | Level TROLL |
| Model: | Level TROLL 500 |
| Product Description: | The Level TROLL measures and logs level and temperature in natural groundwater and surface water. |

is in compliance with the following Directives:

89/336/EEC for Electromagnetic Compatibility (EMC) Directive
73/23/EEC for Safety Directive

and meets or exceeds the following international requirements and compliance standards:

- **Immunity**
  EN 61326:1997, Electric Equipment for Measurement, Control and Laboratory Use
- **Emissions**
  Class A requirements of EN 61326:1997, Electric Equipment for Measurement, Control and Laboratory Use

Supplementary Information:
The device complies with the requirements of the EU Directives 89/336/EEC and 73/23/EEC, and the CE mark is affixed accordingly.

Todd Campbell
New Product Development Program Manager
In-Situ, Inc.
January 17, 2006

## Declaration of Conformity

Manufacturer: In-Situ, Inc.
221 East Lincoln Avenue
Fort Collins, CO 80524
USA

Declares that the following product:

Product name: Level TROLL
Model: Level TROLL 700
Product Description: The Level TROLL measures and logs level and temperature in natural groundwater and surface water.

is in compliance with the following Directives:

89/336/EEC for Electromagnetic Compatibility (EMC) Directive
73/23/EEC for Safety Directive

and meets or exceeds the following international requirements and compliance standards:

- **Immunity**
  EN 61326:1997, Electric Equipment for Measurement, Control and Laboratory Use
- **Emissions**
  Class A requirements of EN 61326:1997, Electric Equipment for Measurement, Control and Laboratory Use

Supplementary Information:
The device complies with the requirements of the EU Directives 89/336/EEC and 73/23/EEC, and the CE mark is affixed accordingly.

Todd Campbell
New Product Development Program Manager
In-Situ, Inc.
January 17, 2006

## TROLL Com Communication Device

### Declaration of Conformity

Manufacturer: In-Situ, Inc.
221 East Lincoln Avenue
Fort Collins, CO 80524
USA

Declares that the following product:

Product name: TROLL Com
Model: USB TROLL Com
Product Description: RS485 to USB converter

is in compliance with the following Directive

89/336/EEC for Electromagnetic Compatibility (EMC) Directive
73/23/EEC for Safety Directive

and meets or exceeds the following international requirements and compliance standards:

- **Immunity**
  EN 61326, Electrical Equipment for Measurement, Control and Laboratory Use, Industrial Location

- **Emissions**
  Class A requirements of EN 61326, Electrical Equipment for Measurement, Control and Laboratory Use

Supplementary Information:
The device complies with the requirements of the EU Directives 89/336/EEC and 73/23/EEC, and the CE mark is affixed accordingly.

Todd Campbell

Todd Campbell
New Product Development Program Manager
In-Situ, Inc.
June 17, 2006

## Declaration of Conformity

Manufacturer: In-Situ, Inc.
221 East Lincoln Avenue
Fort Collins, CO 80524
USA

Declares that the following product:

Product name: Level TROLL
Product name: Baro TROLL
Product Description: The Baro TROLL measures and logs barometric pressure and temperature.

is in compliance with the following Directives:

89/336/EEC for Electromagnetic Compatibility (EMC) Directive
73/23/EEC for Safety Directive

and meets or exceeds the following international requirements and compliance standards:

- **Immunity**
  EN 61326:1997, Electric Equipment for Measurement, Control and Laboratory Use
- **Emissions**
  Class A requirements of EN 61326:1997, Electric Equipment for Measurement, Control and Laboratory Use

Supplementary Information:
The device complies with the requirements of the EU Directives 89/336/EEC and 73/23/EEC, and the CE mark is affixed accordingly.

Todd Campbell
New Product Development Program Manager
In-Situ, Inc.
January 17, 2006

# Appendix B

# Slug Testing Guidance, Standard Operating Procedure, and Information

# Slug Test - Data Acquisition Sheet

## General Information

| | |
|---|---|
| Project Name: | Date of Test: |
| Well Number: | Test Performed By: |
| Well Location: | |

## Well Information

| | |
|---|---|
| Reported Well Depth from Land Surf, ft: | Date of Last Well Development: |
| Measured Depth from Top of Inside Casing (TIC), ft: | Initial Static Water Level TIC, ft.: |
| Stickup of TIC from land surface, ft: | Final Static Water Level TIC ft: |
| Well Depth, ft bgs (depth TIC – stickup): | Casing Inside Diameter, in. and Schedule: |
| Ht. of Water Column, ft: (well depth – DTW): | Borehole Dia., in. |

| | Type | Serial Number | Purpose and Placement | Reading in Air |
|---|---|---|---|---|
| Transducer #1 | | | | |
| Transducer #2 | | | | |

Data Logger Type and Serial Number:

Logging Program: Acquisition Rate:

Pressure or Pressure Head Units: Time Units:

Comments: (e.g. transducer diameter and cable diameter)

## Test Information

| | Test 01 | Test 02 | Test 03 | Test 04 | Test 05 |
|---|---|---|---|---|---|
| Initiation method | | | | | |
| Rising/falling head | | | | | |
| Pre-test DTW | | | | | |
| Post-test DTW | | | | | |
| Expected $H_0$ | | | | | |

| Additional comments[1] | |
|---|---|
| Test 01 | |
| Test 02 | |
| Test 03 | |
| Test 04 | |
| Test 05 | |

| | Test 06 | Test 07 | Test 08 | Test 09 | Test 10 |
|---|---|---|---|---|---|
| Initiation method | | | | | |
| Rising/falling head | | | | | |
| Pre-test DTW | | | | | |
| Post-test DTW | | | | | |
| Expected $H_0$ | | | | | |

| Additional comments | |
|---|---|
| Test 06 | |
| Test 07 | |
| Test 08 | |
| Test 09 | |
| Test 10 | |

File for Field Data:

[1] If pneumatic slug test is performed, record “air pressure before test initiation” under Additional Comments.

Slug length (ft): ______________________

Slug diameter (in): ____________________

Slug Volume ($ft^3$) = pi ((slug diameter/2)/12)$^2$ * slug length = ___________________

Prepared by the Kansas Geological Survey (distributed with permission)

Modified by CDM Smith

# FIELD GUIDE FOR SLUG TESTING AND DATA ANALYSIS™

midwest GEOSCIENCES group®
www.midwestgeo.com

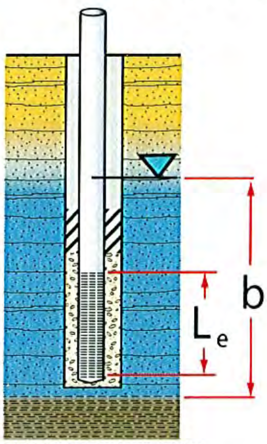
## STEP ONE: TEST WELL CONFIGURATION

K = Hydraulic Conductivity

b = Thickness of Tested Unit

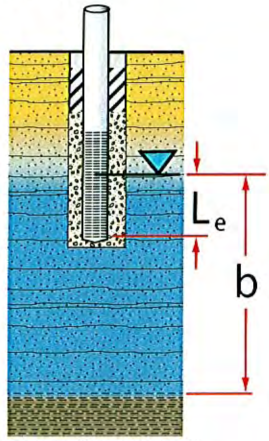
$L_e$ = Effective Screen Length *(portion of screen through which flow occurs, usually not the length of the filter pack)*

### UNCONFINED CONDITIONS



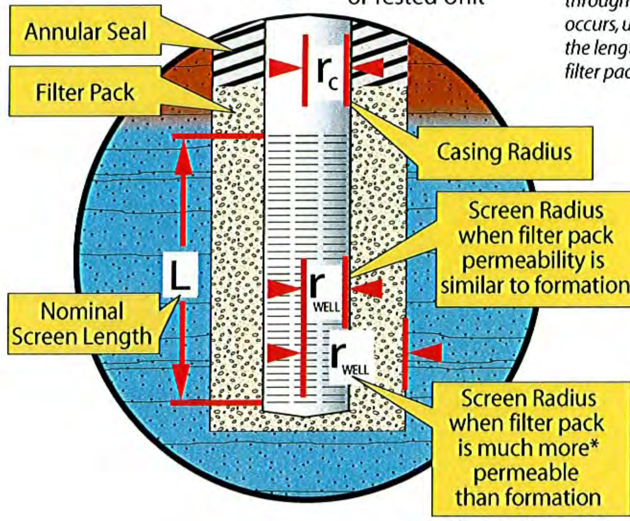

PARTIALLY PENETRATING
Screened Below the Water Table

$L_e = L$



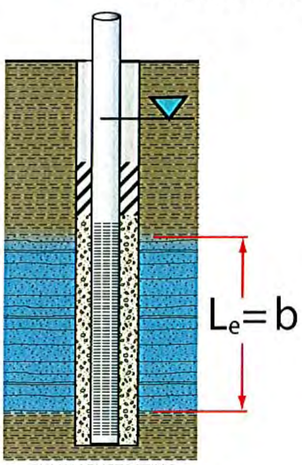

PARTIALLY PENETRATING
Screened Across the Water Table

$L_e < L$



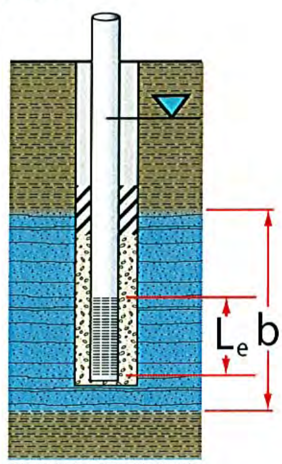

* factor of two or more

### CONFINED CONDITIONS




FULLY PENETRATING
Screened Across the Entire Unit

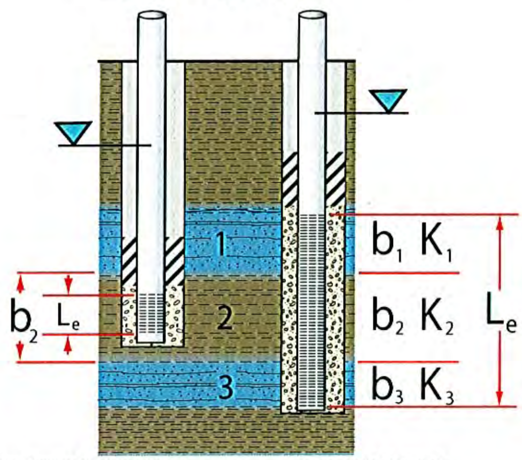
$L_e < L$




PARTIALLY PENETRATING
Screened Across a Portion of the Unit

$L_e = L$

### LAYERED SETTINGS




PARTIALLY PENETRATING
Screened Across a Portion of a Layer

$L_e < b_2$

$K \approx K_2$

FULLY PENETRATING
Screened Across Multiple Layers

$$K \approx \frac{[(b_1K_1)+(b_2K_2)+(b_3K_3)]}{L_e}$$

Slug tests are also an effective means of estimating K in aquitards. See Butler (1998) for specialized test procedures. Correct screen placement is essential for testing low-permeability units.

### WELL DEVELOPMENT IS CRITICAL

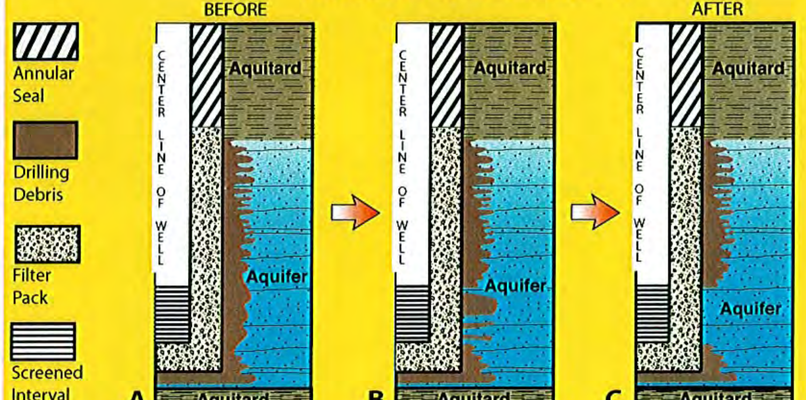
1. **MUST** develop well thoroughly before slug testing because a near-well zone of disturbance may be created during drilling. Characteristics of zone depend on formation properties and drilling method. Zone often consists of various types of "drilling debris".

Hydraulic conductivity estimates from tests in poorly or undeveloped wells may be much less than formation K due to impact of "drilling debris".

2. Perform slug tests and assess the sufficiency of well development during data processing and analysis (see Steps 4 and 5).

For monitoring wells, development should produce a situation between B and C. Assume $L_e$ = L for analysis.

### STAGES OF DEVELOPMENT



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# STEP TWO: SET UP AND TEST INITIATION

## FOR TESTS USING SOLID SLUGS OR BAILERS

### INITIAL ACTIVITIES

1. Measure depth to water.
2. Measure depth to bottom of well.
3. Measure slug volume (solid slug or bailer)

$$V_{SLUG} = \pi r^2_{SLUG} L_{SLUG}$$

> EXAMPLE: Solid slug, 2.5-cm diameter, 75-cm long
>
> $V_{SLUG} = (3.14)\,(1.25\text{cm})^2(75\text{cm}) = 368.2\ \text{cm}^3$

4. Calculate expected initial displacement

$$H_0^* = V_{SLUG} / \pi r^2_{CASING}$$

> EXAMPLE: Solid slug in 5-cm diameter well
>
> $H_0^* = (368.2\ \text{cm}^3) / (3.14)(2.5\text{cm})^2 = 18.8\ \text{cm}$

5. Calculate length of water column in well.
6. Check depth limit of transducer and determine appropriate transducer position.

> Height of water column above transducer should allow sufficient room for slug introduction and removal.

### EQUIPMENT

Must be appropriate for expected rate of head change. Always use a transducer and data logger for tests in moderate to high permeability formations (K > 0.001 cm/s). Manual measurement of water levels is a reasonable approach for tests in lower permeability formations.

### SET UP

1. Submerge transducer to pre-determined depth and allow 15 to 20 minutes for transducer to thermally equilibrate with water and transducer cable to stretch.

> Submerge transducer a sufficient distance to avoid interference during slug movement. If transducer is located within screened interval, place above well bottom to avoid plugging by settled fines.

2. Secure transducer cable to prevent movement during test.
3. Check data logger to ensure connectivity and communication.
4. Track water level through time to ensure near-static conditions have been achieved prior to test.
5. Prepare solid slug or bailer for test. Check bailer for leaks.

### FALLING HEAD TEST

Place bottom of slug just above top of water column. Measure drop distance on cord and fasten cord prior to test.

### RISING HEAD TEST

Place top of slug just below top of water column. Measure removal distance on cord and prepare to fasten cord after removal.

### TEST INITIATION

1. Double check data logger settings.
2. Verify water level has returned to static.
3. Start logging data 5 to 10 seconds prior to test initiation.
4. Create near-instantaneous water-level change relative to formation response.

> For tests in high-permeability formations, water level change produced by a solid slug or bailer may not be fast enough. Use pneumatic method for tests initiation (see Step Three).

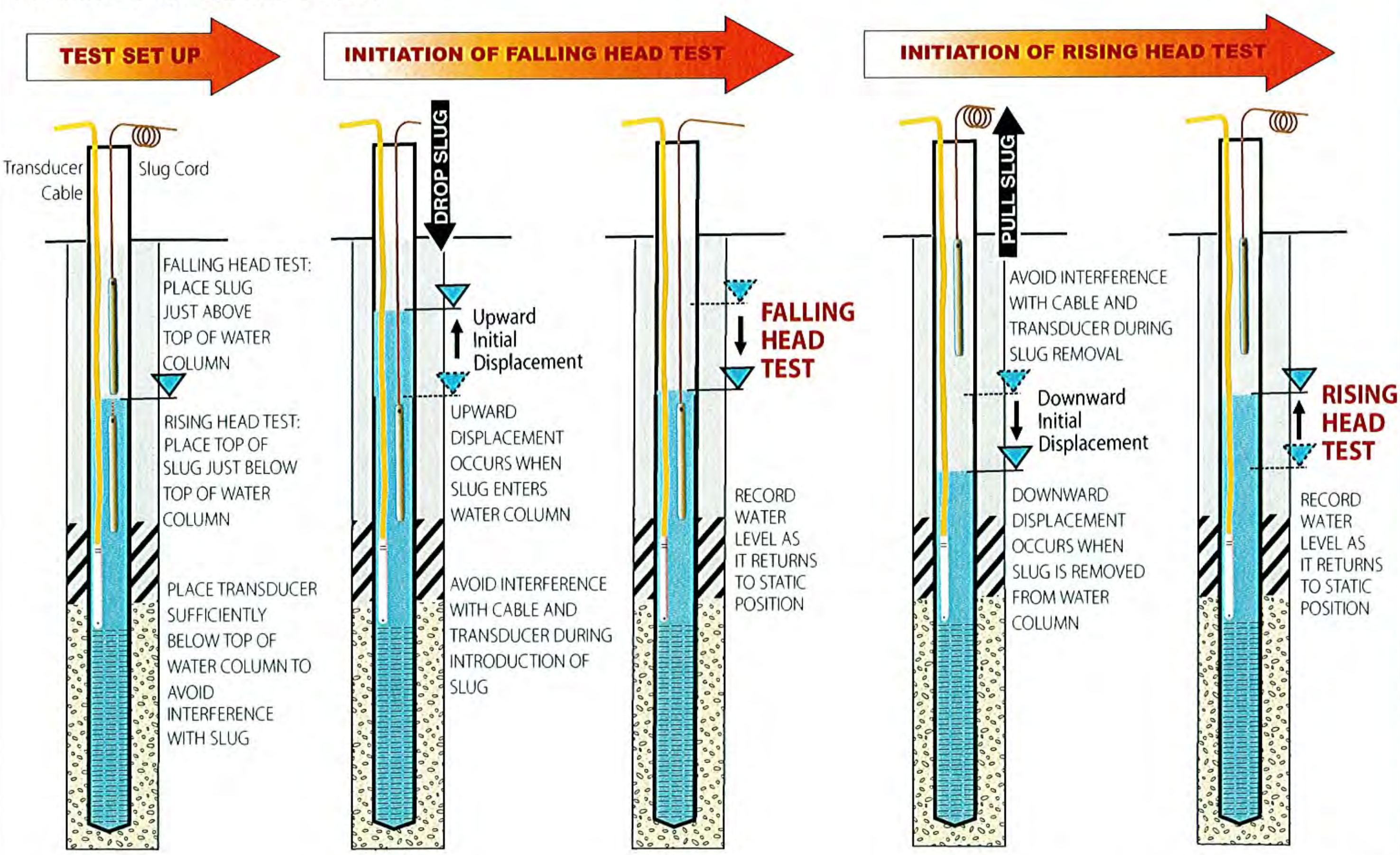
5. Avoid entanglement with transducer or its cable during test initiation.

> When moving slug to initiate test, try to minimize distance of movement by positioning slug a short distance above or below top of water column. This will help avoid getting the slug entangled in the tranducer cable or hitting the transducer.

### INITIAL DISPLACEMENT

In moderate or lower permeability formations (K < 0.02 cm/s), an initial displacement of 0.3 to 0.9 meters should produce a reasonable signal-to-noise ratio. In higher K formations, use smaller displacements (< 0.3 meters) to reduce non-Darcian flow losses. Slug size does not affect test radius - see Butler (1998).

### FALLING & RISING HEAD TEST



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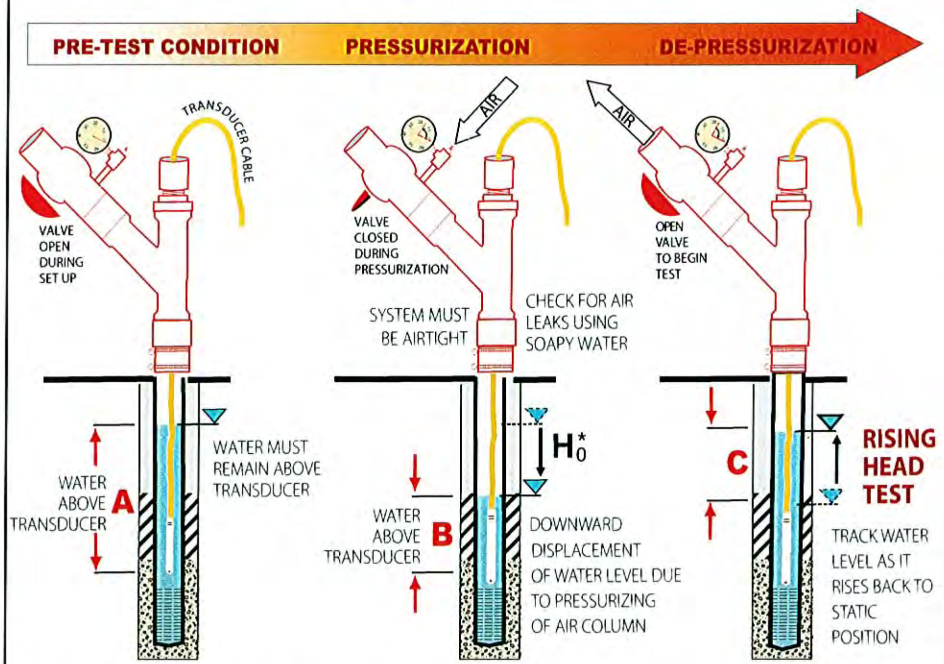
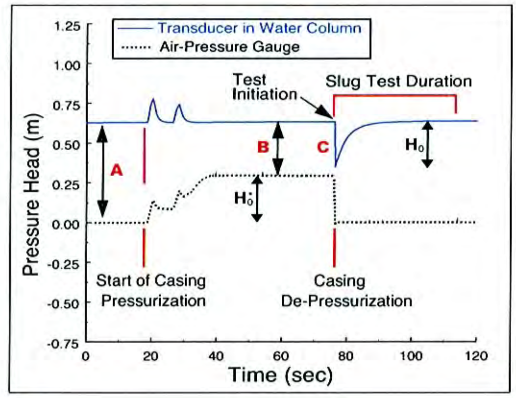
## FOR TESTS USING PNEUMATIC INITIATION SYSTEM




1. Use pneumatic method to initiate tests in highly permeable formations. The pneumatic method uses air pressure, either positive or negative, to displace water. Water level must remain above screen and transducer.
2. Rising head tests are performed by pressurizing air column, allowing pressures to stabilize, and then depressurizing air column.
3. Falling head tests are performed in a similar manner by applying a vacuum to air column.

# STEP THREE: TEST PERFORMANCE

### GENERAL PERFORMANCE GUIDELINES

1. Perform three or more tests at each well.
2. Use at least two initial displacements varying by a factor of two or more.
3. Conduct both rising and falling head tests if possible. First and last tests should use approximately same initial displacement.

> Repeat tests with different $H_0^*$ are used to assess the viability of assumptions underlying slug test analysis methods.

4. Run each test to near completion (i.e. heads within 5% of static).

> Running tests to near completion allows data to be analyzed with more sophisticated methods (Cooper et al. and KGS models). These methods can provide insights into impact of anisotropy, double-porosity behavior, and insufficient well development. See Butler (1998) for further details.

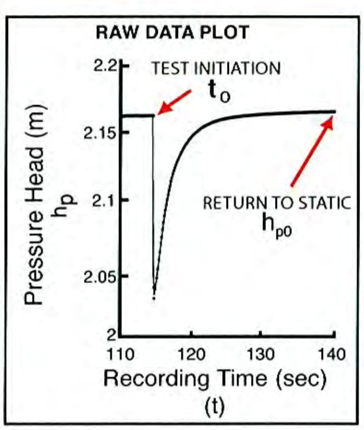
# STEP FOUR: DATA PROCESSING

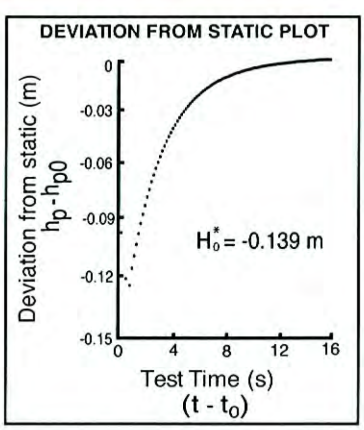
$H_0^*$ = Expected initial displacement estimated from geometrical considerations (solid slug) or air pressure readings (pneumatic initiation).

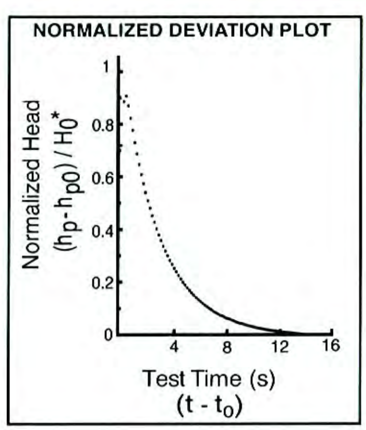
$H_0$ = Initial water-level displacement measured in well.

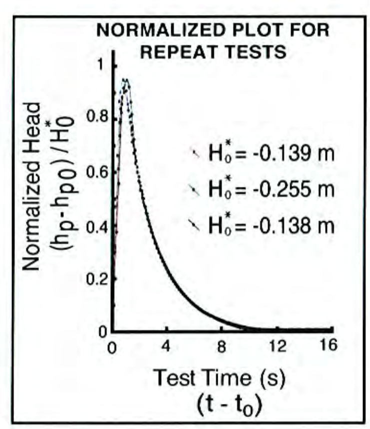
### GENERAL PROCESSING GUIDELINES

1. Estimate time test began ($t_0$) and the pressure head at static conditions ($h_{p0}$) from the raw data plot.
2. Subtract $h_{p0}$ and $t_0$ from the head ($h_p$) and time (t) records, respectively, to compute head deviation from static and time since test began (deviation from static plot).
3. Normalize data by dividing deviation data by the expected displacement ($H_0^*$) and plot normalized head vs. time.
4. Compare the expected displacement ($H_0^*$) with the initial water-level displacement measured in the well ($H_0$). Are they different? If so, possible explanations could include: (1) effective casing radius different from nominal casing radius, (2) test initiation too slow, (3) measurement rate too slow, and (4) transducer too deep in water column (high-K formation).
5. Compare normalized data plots from repeat tests at the same well. Coincidence of normalized plots suggests that assumptions underlying conventional analysis methods may be valid at that well. If normalized plots do not coincide, then more development may be necessary.



# STEP FIVE: DATA ANALYSIS

### SELECTION OF TEST FOR ANALYSIS

1. If normalized plots from a series of slug tests coincide, choose only one test for analysis. The selected test should have the lowest data noise level of that series.
2. If normalized plots do not coincide, seek explanation for lack of coincidence. Possible explanations include insufficiently developed well and non-laminar flow losses. See Butler (1998) and Butler et al. (2003) for further explanations of lack of coincidence of normalized plots.

### SELECTION OF TEST CATEGORY

Select appropriate category for well-formation configuration.

**CATEGORY I** - Wells in Confined Formations and Wells Screened Below the Water Table in Unconfined Formations.

**CATEGORY II** - Wells Screened Across the Water Table.

**CATEGORY III** - Wells in Category I and in Highly Permeable Formations.

### FRACTURED FORMATIONS

If formation is densely fractured and behaves as an equivalent porous media, standard methods are valid. If formation behaves as a double-porosity media, then validity decreases as well screen increases in length. If formation is sparsely fractured and flow is restricted to fractures, the validity of standard methods varies. If flow induced by test is radial, standard methods are valid. If flow is restricted to only a small portion of fracture plane, standard methods are not appropriate. See Butler (1998) and Shapiro and Hsieh (1998) for details.

## TEST CATEGORIES

### CATEGORY I ANALYSIS

A) Analyze data with Cooper et al. model for tests in fully penetrating wells.
B) Question: Can a good fit be obtained using a physically plausible storage estimate?
  - If so, the hydraulic conductivity estimate can be calculated from the transmissivity (T) estimate using $K = T / L_e$
  - If not, go to C.
C) Question: Is the well fully or partially penetrating?
  - If fully pentrating well, test may be affected by insufficient development or double-porosity flow. See Butler (1998).
  - If partially penetrating well, test may be affected by vertical flow above or below the screened interval. Go to D.
D) Analyze data with KGS model for tests in partially penetrating wells.
E) Question: Can a good fit be obtained using a physically plausible storage estimate?
  - If so, the hydraulic conductivity estimate should be reasonable.
  - If not, the test may be affected by insufficient development. See Butler (1998) for details.

### CATEGORY II ANALYSIS

A) Question: Do data display a double straight line on a log normalized head vs. linear time plot (see Category II Figure)?
  - If so, go to B.
  - If not, go to A of Category I Analysis.
B) Fit a straight line to the formation response portion of the plot (2nd straight line segment).
C) Estimate K with Bouwer and Rice model.
  - Use effective casing radius, not nominal casing radius, in analysis. See Butler (1998).

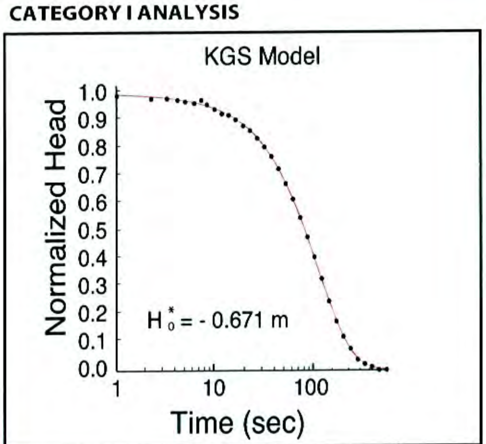
### BOUWER & RICE AND HVORSLEV MODELS

These approximate methods involve fitting a straight line to data plotted in a log normalized head vs. linear time format. Although K estimates are obtained rapidly, these methods, unlike the Cooper et al. and KGS models, cannot provide clues that the test has been significantly impacted by insufficient development. If flow is primarily horizontal, data will display a concave-upward curvature in this plotting format. Straight line should be fit to the 0.15 - 0.25 (Hvorslev) and 0.2 - 0.3 (Bouwer & Rice) normalized head range. These ranges should be with respect to $H_0^+$ when data plot as a double straight line (see Category II Analysis Plot).

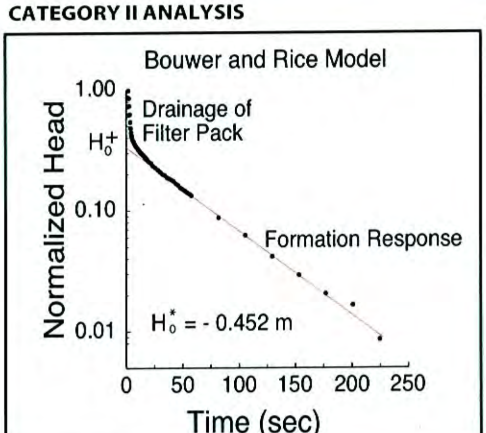
### CATEGORY III ANALYSIS

A) Question: Are data oscillatory in nature or display a concave-downward curvature on a log normalized head vs. linear time plot?
  - If so, go to B.
  - If not, go to A of Category I Analysis.
B) Question: Do normalized data plots coincide?
  - If so, go to C.
  - If not, go to D.
C) Question: Is well fully penetrating or nearly so?
  - If so, analyze data with Butler & Zhan model.
  - If not, analyze data with either Butler & Zhan model or high-K extensions of Hvorslev and Bouwer-Rice models.
D) Question: Do normalized data plots from tests initiated with similar $H_0^*$ coincide?
  - If so, go to E.
  - If not, further development may be needed.
E) Question: Can tests be repeated?
  - If so, repeat tests with smaller initial displacements and go to B.
  - If not, analyze data with non-linear slug test model of McElwee and Zenner. Note error in K estimate may increase as well screen approaches full penetration.

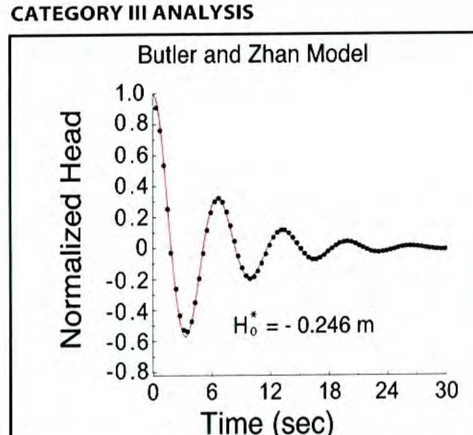
### CATEGORY I ANALYSIS




### CATEGORY II ANALYSIS




### CATEGORY III ANALYSIS




**REFERENCES** *Technical Content: J.J. Butler, Jr., G.M. Duffield, and D.L. Kelleher* *Graphic Design: D.L. Kelleher*

Butler, 1998, *The Design, Performance, and Analysis of Slug Tests*, Lewis Publishers, 252 pp.

Butler, Garnett and Healey, 2003, Analysis of slug tests in formations of high hydraulic conductivity, *Ground Water*, v. 41, no. 5, 620 - 630.

Shapiro and Hsieh, 1998, How good are estimates of transmissivity from slug tests in fractured rock? *Ground Water*, v. 36, no. 1, 37-48.

# Hydraulic Conductivity Testing

SOP 4-6
Revision: 6
Date: August 2020

**Approved:** Ernest Ashley **Technical Review:** John Dougherty

## 1.0 Objective
The objective of this technical standard operating procedure (SOP) is to define requirements for conducting and analyzing in situ hydraulic conductivity (slug) tests in small, developed wells.

## 2.0 Background
### 2.1 Definitions
***Note:*** Definitions are often promulgated or codified in state or local statutes, regulations, or ordinances and can vary between regulatory agencies. Definitions should be verified against the definitions provided by agencies regulating the work when applicable.

**Slug Testing** - A rapid and easy means of estimating the hydraulic conductivity of an aquifer. If the thickness of the aquifer is known, then the transmissivity can also be determined. Slug testing is accomplished by adding (or removing/displacing) a known volume to (or from) the monitoring well to create a rapid rise (or fall) in water level. Water levels are then measured as the water level in the well returns to static (pre-test) conditions. American Society for Testing and Materials method D4044 provides an overview of slug testing (ASTM 2015). Butler (2019) is a good reference for the design and analysis of slug tests over a full range of aquifer conditions.

**Slug Bar** - A weighted cylinder that is used in displacing a known volume water in a well. A bailer may be used to remove water in place of a slug bar under low-recharge aquifer conditions.

**Pneumatic System** - A system that uses an air pump, compressor, or compressed air cylinder to increase the air pressure in the well, which is sealed with an air-tight cap that has ports through which the compressed air is introduced and a water level indicator or pressure transducer can be inserted. This displacement method is commonly employed in high transmissivity aquifers where aquifer response is rapid and it is difficult to achieve the rapid initial displacement required using a slug bar or bailer. In all cases, the rate of water level recovery is then measured using a pressure transducer and data recorder or a water level meter and stopwatch (the former method is preferable in most environments). Data, as displacement-time pairs, are then graphed and used in equations to determine hydraulic conductivity.

### 2.2 Associated Procedures
- SOP 1-5, *Groundwater Sampling with Bailers*
- SOP 1-6, *Water Level Measurement*
- SOP 2-6, *Handling Investigative-Derived Waste*
- SOP 4-1, *Field Logbook Content and Control*
- SOP 4-3, *Well Development and Purging*
- SOP 4-4, *Design and Installation of Monitoring Wells in Aquifers*
- SOP 4-5, *Field Equipment Decontamination at Nonradioactive Sites*

### 2.3 Discussion
Advantages of slug testing over pump testing include the fact that little or no contaminated water is produced requiring containment and disposal as well as that several areas can be tested in a relatively short period of time. A disadvantage of slug testing is that the resulting estimate of hydraulic conductivity is limited to a small volume of the aquifer around the tested well and care must be taken in extrapolating the results from one well to other areas or intervals of the aquifer.

If possible, when designing the field program or considering in which interval to place a well screen, try to screen only one formation type. If a well is screened across more than one formation (such as fine sand and coarse sand or overburden and bedrock) the results must be analyzed and interpreted considering the hydrogeologic context.

## 3.0 Responsibilities

**Project Manager** - The project manager is responsible for ensuring that field personnel have been trained in conducting slug tests and for ensuring that slug tests are conducted in accordance with this procedure.

**Field Team Leader** - The field team leader is responsible for performing slug tests in accordance with this procedure and for verifying that the data collected are adequate and of high quality. The project field geologist shall perform a field calculation to check data quality.

***Note*:** Responsibilities may vary from site to site. Therefore, all field team member responsibilities shall be defined in the field plan or site-/project-specific quality assurance plan.

## 4.0 Required Equipment

The following equipment shall be used when performing a rising or falling-head slug test in a monitoring well. Site-specific conditions may warrant the use of additional equipment.

- Pressure transducer and data recorder, if data are to be automatically recorded (recommended) and manufacturers' instructions
- Laptop or hand-held computer for downloading and viewing data (field printer optional)
- Water level measuring device
- Stopwatch, if measurements collected manually (not recommended)
- Slug device of known volume
- Rope or wire
- Duct tape
- Field logbook
- Decontamination equipment and supplies
- Data on the construction of the well: depth to screen, screen length, well drilled diameter, riser diameter, height of sandpack above screen and length of riser above ground surface

Note that the well construction data shall be used so that the slug test data being collected are appropriate and of acceptable quality. Additional information (e.g., distance from screen to confining layer) may be necessary to analyze the data and determine the hydraulic conductivity. Data analysis is not covered under this procedure.

The slug bar shall be constructed of plastic, such as polyvinyl chloride (PVC), or metal such as aluminum or steel (depending upon the chemical environment in the well) and have no buoyancy. For example, a standard slug is constructed with a PVC pipe filled with sand and capped at both ends. The slug bar shall be of sufficient size to cause a recommended minimum of 1 to 3 feet of displacement in a well. A slightly lesser or greater head change is acceptable so long as a sufficient response curve is recorded that can be applied in subsequent analysis. For a 2-inch diameter monitoring well, the slug bar shall be no more than 1.5 inches in diameter and a minimum of 5 feet long. For a 4-inch diameter well, the slug bar shall be no more than 3 inches in diameter and a minimum of 5 feet long. The slug bar shall be securely fastened to a nylon rope or braided metal wire.

A standard sampling or well development bailer may be used in place of the slug bar, as long as the volume of water displaced by the bailer is sufficient to change the water level in the well a minimum of 1 to 3 feet. If the bailer is to be used for a falling-head test, it shall be filled with analyte-free water so that the bailer will not have any buoyancy.

## 5.0 Procedures

### 5.1 Preparation

The following steps must be followed when preparing for slug testing:

1. Lay plastic sheeting around the wellhead. Arrange needed equipment and decontamination materials on the sheet or on a table.

2. Put on personnel protective clothing, as specified in the site-specific health and safety plan.

3. Open the protective casing locking lid and vented riser caps following the procedures outlined in SOP 1-6. Note the physical condition of the well, including damage, deterioration and signs of tampering. Note any unusual odors, sounds, or difficulties in opening the well. Record organic vapor readings with a suitable organic vapor screening device.

4. Measure and record the static water level, the depth to the bottom of the well and inside diameter of the well casing. Record these data in the appropriate logbook.

5. If using a pressure transducer and data logger (transducers with built-in data loggers are commonly used for slug tests), lower the pressure transducer into the well to a sufficient depth so that the transducer will be below the maximum depth reached by the bottom of the slug bar or other displacement device. If necessary, calibrate the transducer as specified by the manufacturer. Allow the transducer to temperature equilibrate in the well for approximately 15 minutes (or as recommended by the manufacturer) after insertion and before any calibration or test procedure to ensure that it will accurately record water level changes. Make sure that the transducer is not placed below its maximum operating depth, or it will not be able to detect any change in pressure. For example, pressure increases 1 pound per square inch (psi) per 2.3 feet of head; therefore, a 10 psi transducer will function to a depth of 23 feet below the water level in the well.

6. Secure the pressure transducer cable using a Kellems grip or similar device. The transducer cable shall lay flat along side the well riser, so that disturbance by the slug bar will be avoided.

   ***Note*:** Do not kink the transducer cable, otherwise the pressure equalization vent tube in the cable will be damaged and the transducer will not function properly.

7. Allow the water level in the well to recover to static after emplacement of the pressure transducer, before starting the test. Measure and record this water level.

8. Program the data logger to record logarithmically, with a maximum time interval of no more than 1 minute between readings. If the formation is expected to have low hydraulic conductivity, the maximum interval between readings can be set to a longer time interval, such as 10 minutes.

9. Confirm and/or set the transducer and logger parameters as recommended by the manufacturer. This task may also be performed before placing the instrument in the well.

10. Determine the distance from the top of the well riser to the water surface in the well and add 1 foot to this length. The resulting length is the amount of wire or rope needed so that the slug bar or bailer will be submerged a minimum of 1 foot when it is placed in the well. A loop shall be placed in the rope or wire at this length and a strong metal rod or wooden stick placed and secured through the loop. When inserted into the well, the slug bar shall be a distance (more than 1 foot) above the transducer to avoid disturbing the measuring device.

11. If depth readings are to be recorded manually (this procedure is not recommended but may be used in formations suspected of having low hydraulic conductivity, less than 1 foot per day), readings shall be taken every 10 seconds for the first minute of the test, every 30 seconds for the next 4 minutes and every minute until 10 minutes. Thereafter, readings shall be taken every 5 minutes for the duration of the test. If the well has not recovered within 1 hour, readings shall be taken every 0.5 hours until 6 hours and 1 hour every hour thereafter. This process will require two personnel during the first 10 minutes of the test: one to act as time keeper/data recorder and one to measure depth to water in the well.

## 5.2 Standard Displacement Slug Tests

### 5.2.1 Falling-Head Slug Test Procedure

This test can only be conducted in wells whose screens are fully submerged, otherwise, displaced water will be introduced into the unsaturated zone and recovery rates will be due to flow in both the unsaturated and saturated zones. All slug test analytical procedures assume flow in the saturated zone only. The following steps must be followed when performing falling-head slug tests:

1. Place the slug or bailer in the well until the bottom of the displacement device is no more than 6 inches to 1 foot above the water level in the well. The person holding the device shall be holding the rope or wire by the rod or stick described in Section 5.1, ninth bullet.
2. Switch on the data recorder or set the water level meter probe near the level at which water is expected to rise.
3. To start the test, the person holding the slug bar will signal the person operating the data logger or water level indicator, then rapidly lower the displacement device into the well until the stick or rod is resting horizontally on top of the well riser. The slug bar shall not be dropped, to minimize sloshing in the well. The data logger is turned on immediately prior to the slug bottom entering the water.
4. Continue recording depth-time data until the well has recovered to at least 90 percent of the static water level. When using data recorders, it is advisable to check and record the reading every few minutes to ensure that data are being properly recorded. If 90 percent recovery has not occurred within 12 hours, the test may be stopped. Field conditions and time constraints may warrant stopping the test in less than 12 hours. The final decisions under these circumstances will be the responsibility of the field team leader.
5. Record the time of test completion and file name in the logbook.
6. Review the response curve. If a sufficient response curve was not recorded (e.g., logging was not started soon enough to identify maximum water level displacement), then the test shall be repeated. If an acceptable response curve is not being recorded due to field conditions (e.g., no water level response due to high hydraulic conductivity) the project manager shall be notified and a determination on the well test shall be made.
7. Decontaminate all equipment according to SOP 4-5. Clean up the site, and close and lock the well before leaving. Contaminated plastic sheeting and disposable protective clothing shall be taken to designated disposal containers.
8. Download the data logger to a computer or to hardcopy to ensure that the data is not inadvertently lost. If the data were recorded manually, calculate the relative change in head by subtracting the recorded depths to water during recovery from the initial static depth to water reading and record the absolute value of that change, for each depth-time data pair.

***Note:*** Both rising- and falling-head slug tests may be carried out in the same operation by first measuring the rate of water level fall immediately after slug insertion, then measuring the rate of water level rise after slug withdrawal. Be sure that the well has recovered to the static water level before conducting the rising-head test. If using a data logger, the recovery tests needs to be set up and run as a separate test.

### 5.2.2 Rising-Head Slug Test Procedure

The steps for a rising-head test are essentially the same as those for a falling-head test. In a well screened across the water table, a rising-head test is the only test that is valid. The following steps must be followed when performing rising- head slug tests:

1. Lower the slug bar or bailer of known volume into the well until it is fully submerged. Allow the well to re-equilibrate to static water level. In formations of suspected low hydraulic conductivity, re-equilibration may take several hours or overnight. In such cases, it is suggested that the displacement device be placed in the well at the end of a field day and the test conducted the following day.
2. Turn on the data recorder, if used, or verify that static water level has been re-established with a water level meter.
3. To start the test, the person holding the slug bar will signal the person operating the data logger or water level indicator, then rapidly and smoothly raise the displacement device from the well until the bottom of the slug bar is above the water level in the well. The data logger is turned on or manual measurements commence at the moment the slug bar is raised and before it (or any

portion of it) is removed from the water. If a data logger is being used, the slug bar wire or rope shall be secured to the well casing or riser for the duration of the test and only removed from the well after the test has been completed, to avoid disturbing or dislocating the pressure transducer.

4. Continue recording depth-time data until the well has recovered to at least 90 percent of the static water level. When using data recorders, it is advisable to check and record the reading every few minutes to ensure that data are being properly recorded. If 90 percent recovery has not occurred within 12 hours, the test may be stopped. Field conditions and time constraints may warrant stopping the test in less than 12 hours. The final decisions under these circumstances will be the responsibility of the field team leader.

5. Record the time of test completion and file name in the logbook.

6. Review the response curve. If a sufficient response curve was not recorded (e.g., logging was not started soon enough to identify maximum water level displacement), then the test shall be repeated. If an acceptable response curve is not being recorded due to field conditions (e.g., no water level response due to high hydraulic conductivity), the project manager shall be notified and a determination on the well test shall be made.

7. Decontaminate all equipment according to SOP 4-5. Clean up the site, and close and lock the well before leaving. Contaminated plastic sheeting and disposable protective clothing shall be taken to designated disposal containers.

8. Download the data logger to a computer or to hardcopy to ensure that the data is not inadvertently lost. If the data were recorded manually, calculate the relative change in head by subtracting the recorded depths to water during recovery from the initial static depth to water reading and record the absolute value of that change, for each depth-time data pair.

## 5.3 Pneumatic Rising-Head Tests

This test can be performed in aquifers of high hydraulic conductivity that are expected to respond very rapidly to slug displacement. It can only be performed in wells where the screen is substantially below the water table, otherwise, increased air pressure in the well casing will be able to bleed off to the unsaturated zone through the well screen and the test will not be successful.

### 5.3.1 Required Equipment

In addition to the required equipment outlined in Section 4.0, the following equipment shall be used when conducting a pneumatic rising-head slug test:

- Minimum 30-psi rated transducer and data logger
- Electric water level indicator with on/off switch
- Pressure-tight "tree" assembly, as described below
- Short length (6 inches) of flexible rubber hose whose inside diameter is the same as the outside diameter of the well riser
- Two 2- or 4-inch diameter hose clamps
- Compressor, air pump, or compressed air tank with hose and appropriate adapters

The pressure-tight tree assembly is a device placed on the top of the well that will accomplish the following:

- Form a pressure-tight seal between the well and the atmosphere
- Allow the injection of compressed air into the well via an air hose connected to the pump, compressor, or air supply
- Provide a pressure-tight passage for a pressure transducer cable and a water level meter
- Allow for rapid well depressurization

The tree is illustrated in Figure 1. If the top of the riser is threaded, the device may be screwed onto the riser if the threads are compatible (Teflon™ tape shall be used to ensure a good seal). If the threaded end of the riser has been cut off, a slip coupling will need to be placed over the base of the tree and the top of the riser. A small length of flexible rubber hose the same inside diameter as the outside diameter of the coupling will need to be slipped over the coupling and secured in place with tightly closed hose clamps to form a pressure-tight seal between the riser and the well.

The simplest method for providing access through the tree for the pressure transducer cable indicator is to use a modified standard large diameter black rubber cork. A hole that is the same diameter as the cable shall be drilled through the cork's axis and a vertical slit shall be cut radially from the hole to an edge of the cork. The pressure transducer cable shall be threaded through the hole and the water level indicator tape shall be placed flat in the slit. The cork shall be firmly placed in the top of the tree to form a pressure-tight seal. To ensure that the cork does not pop out while the well is under pressure, it can be secured in place with duct tape or a friction fit plastic cap placed over the cork and onto the tree.

The tree will have a standard ball valve with an inside valve orifice diameter no less than the diameter of the well riser as shown in Figure 1. In addition, a pressure-tight coupling (swage-loc, quick-connect, or Schrader valve) will be attached to the side of the tree to act as a compressed air inlet.

### 5.3.2 Preparation

Preparation procedures for the pneumatic test are similar to those for the standard slug bar displacement test, with the exception that an electronic data logger is a necessity for this procedure.

### 5.3.3 Pneumatic Slug Test Procedure

1. Install the test tree to the top of the well, using a method appropriate to the type of riser present (threaded or unthreaded). Make sure that the seal to the riser top is pressure-tight.

2. Lower the pressure transducer into the well through the top of the tree to a minimum of 10 feet below the water table. The pressure transducer shall be rated no less than 30 psi. Allow the transducer to equilibrate at least 15 minutes before initiating any calibration or test procedure.

3. Turn on and insert a water level indicator into the well to approximately 5 feet depth below the water table. Turn off the indicator.

4. Secure the water level indicator and pressure transducer to the test tree using the rubber cork described in Section 5.3.1. Insert the transducer cable into the hole in the rubber cork via the slit and place the water level indicator tape flat in the slit. Place the cork firmly in the top of the tree so that no gaps are left in the cork. Place small strips of duct tape over the assembly to ensure that the seal is airtight and that the cork cannot loosen when the well is pressurized.

   ***Note***: During this procedure, do not kink the transducer cable or the pressure equalization vent tube in the cable will be damaged and the transducer will not function.

5. Connect the pressure transducer to the data logger and calibrate the system according to manufacturer's instructions. Set the data logger to record logarithmically with a maximum recording interval of no more than 1 minute. Set the logger to record relative change in head only.

6. Connect the air hose to the compressed air supply, pump, or compressor and to the tree. Make sure the ball valve is securely closed.

7. Turn on the water level indicator and start feeding compressed air to the well. When the water level in the well has been depressed sufficiently, the water level indicator submergence tone will stop sounding. The pressure required shall be no more than 2 or 3 pounds over atmospheric pressure.

8. Simultaneously open the ball valve and activate the data logger. Open the ball valve quickly so that the pressure is released at once.

9. In highly permeable aquifers, the water level shall recover to pre-test water levels within a few seconds. Full recovery shall be accomplished in no more than 1 minute. In any event, do not stop the test until a minimum of 90 percent recovery can be confirmed with the data logger.

10. Review the response curve. If a sufficient response curve was not recorded (e.g., logging was not started soon enough to identify maximum water level displacement), then the test shall be repeated. If an acceptable response curve is not being recorded due to field conditions (e.g., no water level response due to high hydraulic conductivity) the project manager shall be notified and a determination on the well test shall be made.

11. Record the time of test completion and file name in the logbook.

12. Decontaminate all equipment according to SOP 4-5. Clean up the site, and close and lock the well before leaving. Contaminated plastic sheeting and disposable protective clothing shall be taken to designated disposal containers.
13. Download the data logger to a computer or to hardcopy to ensure that the data is not inadvertently lost.

### 5.4 Considerations For Subsequent Groundwater Sampling
Groundwater samples are often collected for chemical analyses after slug testing of monitoring wells. Therefore, it is very important to avoid introducing anything into the well that might impacts subsequent analyses. It is especially important to consider field equipment material at sites that will be sampled for per- and polyfluoroalkyl substances (PFAS). Development of awareness in PFAS guidance and incorporation into specific SOPs is necessary because cross-contamination is a prominent concern for data quality, particularly with PFAS action levels in the low parts per trillion (ppt) range. Procedural or equipment modifications to field activities may be required when sampling for PFAS analysis will occur.

**Avoid**
- **Polytetrafluoroethylene (PTFE/Teflon®), low density polyethylene (LDPE)**, sticky notes, waterproof field book, aluminum foil
- Consult materials checklists for equipment concerns

A check list containing common materials and sampling equipment that may contain PFAS compounds is attached and also can be found here:

https://www.yammer.com/cdmsmith.com/#/files/214861635584

## 6.0 Data Reduction and Analysis Procedures
### 6.1 General
The following slug test data reduction procedure and report is recommended.

- All raw data shall be printed out and listed as an appendix to the analysis report.

- All data shall be plotted using the graphing method of the accepted analytical solution. These plots shall be included as an appendix to the analysis report.

- All well geometry data shall be tabulated and included in the analysis report. Most of these data must be known before the start of testing, except for items related to the water level in the well at the time of testing. The purpose of this tabulation is to ensure consistent calculation of all variables required in the data analysis, make input into a data analysis computer program an easier task, and to make technical review of the analyses and input values easier. This table shall include the following items for each tested well or piezometer (the list of items may vary depending on the analytical method employed):

- Well ground surface elevation
- Well reference elevation (i.e., top of riser)
- Depth to static water level at start of test
- Elevation of static water level at start of test
- Depth to top of screen or open interval from ground surface or top of casing
- Depth to bottom of screen or open interval from ground surface or top of casing
- Elevation of top of screen or open interval
- Elevation of bottom of screen or open interval
- Depth to base of aquifer (if available)
- Elevation of base of aquifer (if available)
- Aquifer saturated thickness
- Depth to top of screen or open interval relative to the top of the aquifer
- Depth to bottom of screen or open interval relative to the top of the aquifer
- Length of saturated well screen
- Length of saturated riser
- Diameter of well riser and screen (or open interval)
- Diameter of borehole
- Grain-size of filter pack

- The report shall include a detailed description of the data collection procedures and test methods.

- The report shall include a detailed listing of all analysis results.

- When reviewing the data for analysis, note that if the water level recovered to the static level (or close to it) before the test was stopped, only the data before 100 percent recovery shall be included in the data plot. Plotting 100 minutes of data when the recovery occurred rapidly (e.g., 30 seconds or 2 minutes) will make analysis of the actual response very difficult and often lead to a substantial underestimate of the formation hydraulic conductivity. Raw data plots shall also be examined for evidence of sloshing of the water level in the well caused by insertion or removal of the slug bar. In most cases, these early data points can also be removed from the data set and time values reset to the new starting point represented by the remaining data. This evaluation is shown on Figure 2. The data may also be removed using common software packages developed for analyzing slug tests.

### 6.2 Review and Analysis of Data

Slug test response generally falls into three categories illustrated on Figure 3. Overdamped or normal response occurs where the well recovers to static level without exceeding that level. Critically damped response occurs where the well recovers to static level and the water level flows above (rising-head test) or below (falling-head test) then recovers to static in a sinusoidal manner within one cycle, as shown in Figure 3. The third category is underdamped harmonic oscillatory response, where the water level in the well oscillates around the static water level as a sine wave of decreasing amplitude.

Slug test data are recommended to be analyzed with computer software; however, data may also be analyzed manually. The groundwater modeling tool kit contains Aquifer$^{WIN32}$ (ESI International), which is a program that may be used for analyzing slug test data. Other programs are also available (e.g. AQTESOLV®). Software packages are useful since they can be used to manage a significant amount of data in short time periods and contain many different confined and unconfined slug test solutions. The trained user can use these benefits to generate detailed response curve graphs, precise hydraulic conductivity values, and insights into the hydrogeologic framework near the well. Regardless of the analytical method employed or whether the data is analyzed manually or by computer, the analyst shall review the original technical paper or textbook summary of the method to understand the mechanics and assumptions underlying the method before attempting any analysis.

Slug test data analyses and hydraulic conductivity calculations shall be performed by an experienced professional. Data analysis and parameter calculations are beyond the scope of this SOP and, therefore, are not discussed here.

## 7.0 Restrictions and Limitations

In wells in which the static water level and water levels induced during testing are above the top of the screened or open hole interval, both rising-head and falling-head tests shall be conducted to provide a redundancy check of results. However, in most cases, rising-head tests provide more consistent data, less subject to sloshing of the water level due to displacement by the slug bar than is often observed in falling-head tests. Falling-head slug tests are invalid in wells where the static water level is at or below the top of the screened or open-hole interval.

Regardless of which testing method is used, it is recommended that the hydraulic conductivity testing be performed three times in each well, if time constraints such as recovery time or the project schedule will allow multiple tests. Varying the displacement (different slugs or pneumatic displacement) by a foot or so, will also provide additional useful data. The purpose of multiple testing is to demonstrate the precision of the test results. Ideally, the test results will be similar, which results in an increased level of confidence in the data. In addition, if one of the data sets is bad, there is additional data available for analysis.

## 8.0 References

American Society for Testing and Materials. 2015 *Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers.* D4044 – 15

Butler, James. 2019. The Design, Performance, and Analysis of Slug Tests (2nd Edition). Lewis Publishers.

ESI International, see their website, http://esinternational.com, for current information on Aquifer$^{win32}$

**Figure 1**
**Pneumatic Slug Test "Tree" Schematic**

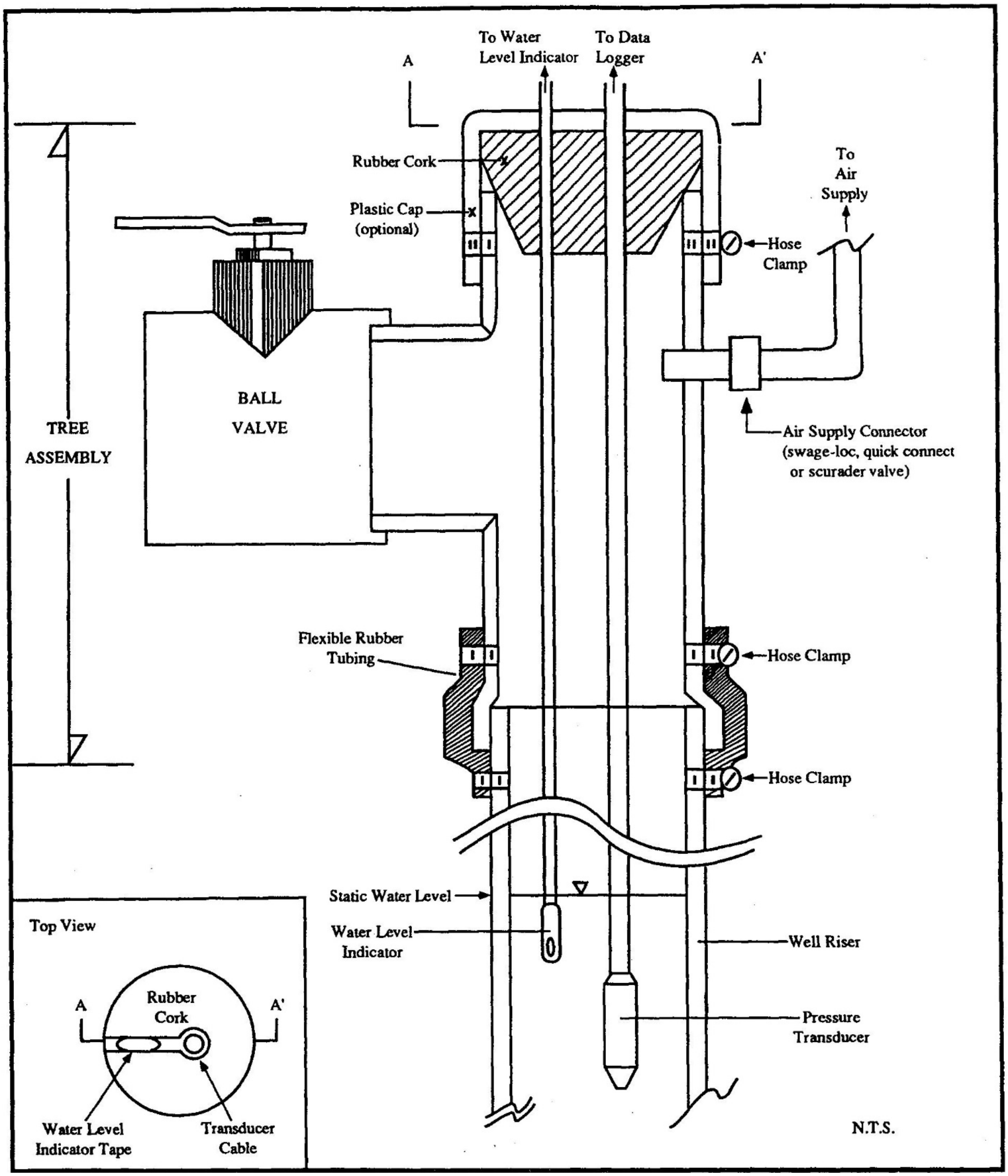


**Figure 2**
**Deletion of Nonessential Data**

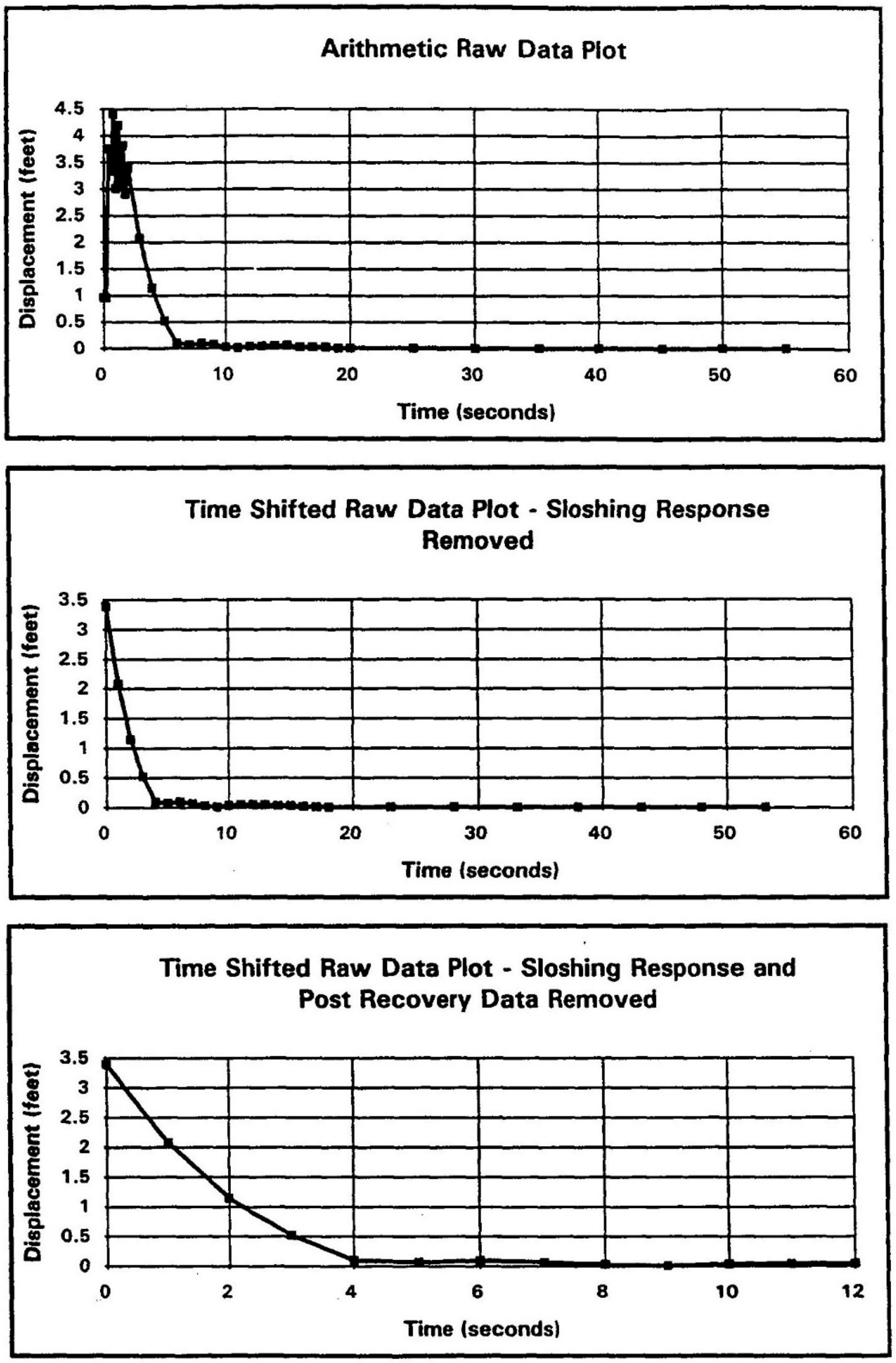
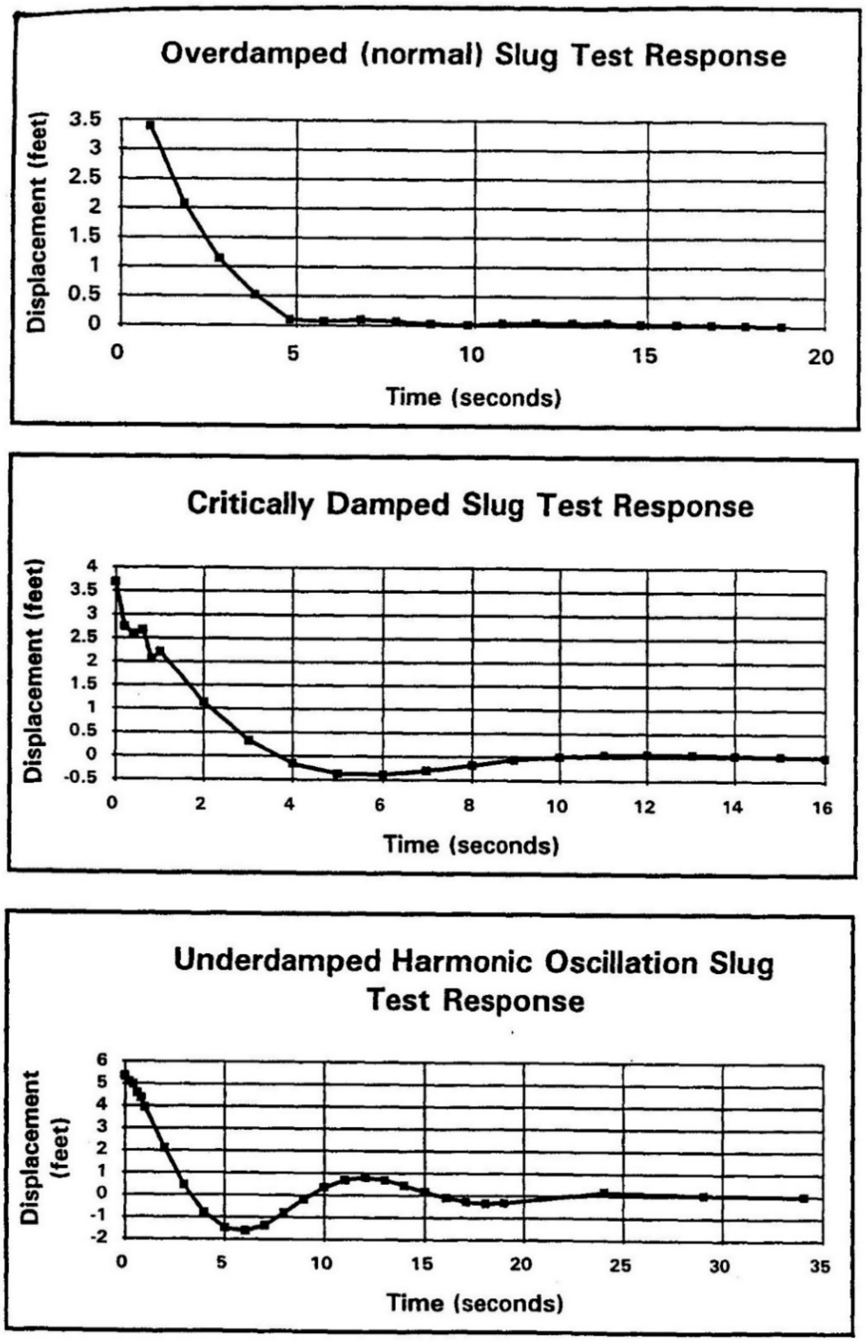


**Figure 3**
**Typical Slug Test Responses**



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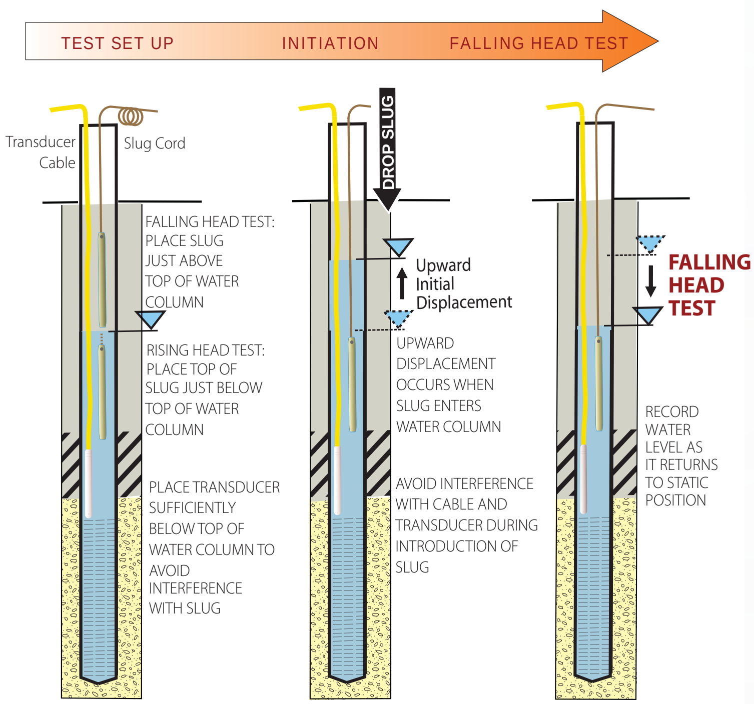
## Anatomy of a Fall Head Slug Test

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# Appendix C

# American Petroleum Institute's Light Nonaqueous Phase Liquid Baildown Test User Guide

# API LNAPL Transmissivity Workbook: A Tool for Baildown Test Analysis

## User Guide

API PUBLICATION 4762
APRIL 2016

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AMERICAN PETROLEUM INSTITUTE

# API LNAPL Transmissivity Workbook: A Tool for Baildown Test Analysis

## User Guide

**Regulatory and Scientific Affairs**

API PUBLICATION 4762
APRIL 2016

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# PREFACE

LNAPL transmissivity provides a useful measure of potential hydrocarbon liquid mobility within the subsurface environment. The magnitude of LNAPL transmissivity is being accepted as a metric for hydrocarbon recovery system performance and determination of technology-specific endpoints. Baildown tests are a simple method for estimating LNAPL transmissivity. This manuscript describes a spreadsheet tool that can be used to analyze results from baildown tests.

# TABLE OF CONTENTS



## APPENDIXES

# LIST OF FIGURES

# LIST OF SYMBOLS

| | |
|---|---|
| $b_n$ | LNAPL thickness in well |
| $b_{nR}$ | initial LNAPL thickness in well (same as at radius of influence) |
| $b_{nW}$ | limiting effective LNAPL thickness in well (see Appendix F) |
| $DZ_{12}$ | depth to top of perching layer |
| $F(\ )$ | Cooper, Bredehoeft and Papadopulos slug test function |
| $G(\ )$ | Jacob-Lohman free-flowing discharge function |
| $h_n$ | LNAPL head |
| $J$ | Kirkman J-ratio (see Appendix B) |
| $L_e$ | initial LNAPL column height (contacting screen) in well |
| $N$ | number of increments |
| $Q_n$ | LNAPL discharge |
| $Q_{ni}$ | LNAPL discharge at time $t_i$ |
| $R$ | radius of influence |
| $r_c$ | radius of casing |
| $r_e$ | effective well radius |
| $r_{e(i)}$ | effective well radius at time $t_i$ (varies with LNAPL column location in well) |
| $r_w$ | well borehole radius |
| $S$ | coefficient of storage |
| $s_n$ | LNAPL drawdown |
| $S_n$ | LNAPL storage parameter |
| $s_{ni}$ | LNAPL drawdown at time $t_i$ |
| $S_y$ | LNAPL specific yield |
| $T$ | transmissivity |
| $t_i$ | time epoch |
| $T_n$ | LNAPL transmissivity |
| $V_n$ | LNAPL volume |
| $W(\ )$ | Theis well function |
| $z_{an}$ | elevation of air-LNAPL interface in well |
| $z_{nw}$ | elevation of LNAPL-water interface in well |
| $\Delta s_n$ | LNAPL drawdown correction |
| $\Delta t_a$ | time adjustment factor |
| $\rho_r$ | LNAPL-to-water density ratio |

# ACRONYMS

| | |
|---|---|
| BOS | Bottom of Screen |
| B&R | (generalized) Bouwer and Rice method |
| CSM | Conceptual Site Model |
| C&J | Cooper and Jacob method |
| CB&P | Cooper, Bredehoeft and Papadopulos method |
| CV | Coefficient of Variation |
| DTP | Depth to Product |
| DTW | Depth to Water |
| ITRC | Interstate Technology Regulatory Council |
| LNAPL | Light Non-Aqueous Phase Liquid |
| SOP | Standard Operating Procedure |
| SSD | Sum-Square-Difference |
| TOS | Top of Screen |

# API LNAPL Transmissivity Workbook:
# A Tool for Baildown Test Analysis—User Guide

## 1. Introduction

LNAPL transmissivity is a measure of lateral mobility of free-product hydrocarbon liquid within the groundwater environment. The magnitude of LNAPL transmissivity has been suggested as a possible endpoint criterion for LNAPL mass removal using LNAPL hydraulic recovery systems (ASTM E 2531-06 [Tbl X5.1], 2006; ITRC, 2009). Such hydraulic recovery systems include skimmer wells, single-pump wells, dual-pump wells, and trenches. Coupled with the LNAPL CSM, the magnitude of LNAPL transmissivity will assist in the selection of recovery system. As such, methods and their consistent application for estimating LNAPL transmissivity are significant. Perhaps the simplest methods for estimating LNAPL transmissivity are borehole slug test methods, or baildown tests, in which a volume of LNAPL is rapidly removed from a well and the rate of fluid-level recovery (water and LNAPL) is measured and analyzed. Several analytical methods are available to analyze the data from baildown tests to estimate LNAPL transmissivity and described herein. A more general discussion of LNAPL transmissivity measurement is provided by ASTM (2011).

Following a brief description of suggested well configuration, pre-test and test measurements and methods, application of the spreadsheet tool is discussed. Subsequent sections provide a more detailed discussion of significant parameters and basis for the various analysis procedures. A number of example applications are presented. Further details on the different methods are provided in the appendices. Noteworthy is the introduction of the J-ratio (*J*) described in Appendix A, which appears to render discussions over preference between Lundy and Zimmerman (1996) versus Huntley (2000) methods moot.

## 2. Well Configuration Data

The following well configuration data should be gathered for baildown test analysis:

1. Elevation of ground surface. This generally serves as the datum with elevations specified as depth below ground surface, bgs. Elevations presented with the geologic log are generally expressed as depth bgs. If data are not conveniently available (or necessary), enter 0 on the spreadsheet.
2. Elevation of top of casing (depths to fluid levels are usually measured from top of casing). If data are not conveniently available (or necessary), enter 0 on the spreadsheet.
3. Well casing radius, $r_c$ (ft).
4. Well borehole radius, $r_w$ (ft).
5. Depth of top of screen (ft bgs). The top of screen can be interpreted to be the top of screen or filter pack, depending on the well construction and gauged fluid levels, and it is

up to professional judgment to correctly select between these. If data are not conveniently available (or necessary), enter 0 on the spreadsheet.

6. Depth of bottom of screen (ft bgs). If data are not conveniently available (or necessary), enter 0 on the spreadsheet.

## 3. Pre-Test Data

Certain data should be gathered before performance of the baildown test, in order to establish and verify initial conditions. The depth to product (DTP) and depth to water (DTW) should be measured over a period equal to the expected test duration; if the test duration is unknown then use of historic hydrograph data and gauging 8 hours before the test would provide a basic level of understanding for equilibrium conditions. The DTP and DTW should then be measured immediately before start of the test to confirm that fluid levels are stable and in equilibrium. The best practice to confirm equilibrium fluid levels is to gauge the well until it fully recovers as discussed in ASTM E2856-11, Section 6.1.4.16 (2011). Additionally, when conditions allow, it is useful to remove LNAPL from the well during a period before the test (e.g. within one month) to confirm equilibrium contact between formation and well hydrocarbon liquid. This is necessary especially if standing LNAPL is observed or LNAPL has not been recovered from a well for a while. Baildown tests are analyzed by slug test methods modified for two fluids, and it is important that formation and well fluids are in equilibrium. If tidal fluctuations are present the DTP and DTW must be measured regularly for at least a week leading up to the test. In any case it is imperative that the LNAPL/water interface should be positioned across the well screen for confined LNAPL conditions, or the air/LNAPL interface for perched LNAPL conditions, if not both the interfaces.

## 4. Baildown Test Procedures and Data

In performance of a baildown test a volume of hydrocarbon liquid is rapidly removed from the well and the DTP and DTW are measured as a function of time during the fluid recovery period. Fluid recovery rates generally vary logarithmically, so measurements should be taken more frequently during the initial period following hydrocarbon removal, and the measurement frequency decreases during the later period of the test. The ASTM standard E2856-11 provides a thorough procedure for conducting baildown tests, however, a brief description of significant features are provided below:

- Initial hydrocarbon liquid removal should be rapid. Commercial peristaltic pumps (such as Spill Buddy ™) are preferred since the pump intake can be located to remove only hydrocarbon liquid during the baildown stage. If a bailer is used then additional precautions are necessary to minimize fluid disturbance during LNAPL removal. If removal of larger LNAPL volumes is required, then vacuum trucks can be used, recognizing that significant volumes of water may be removed in addition to LNAPL.

- Following the baildown stage of hydrocarbon liquid removal, the DTP and DTW are measured as a function of time. Measurements can be taken using interface probes (optical and electrical resistivity), and data are recorded as depth (feet) below top of casing.
- In general, the interface depth measurements are taken more frequently during the initial recovery period, and the frequency decreases as recovery proceeds. If recovery rates are too rapid for (near) simultaneous measurement of DTP and DTW, then a pressure transducer can be placed below the LNAPL-water interface and connected to a data-logger. In this case only the DTP need be measured, and such measurements combined with the data-logger record and LNAPL density can be used to calculate the DTW at desired time intervals.
- When possible, recovery monitoring should continue until essentially complete LNAPL recovery is achieved. In low LNAPL transmissivity locations, time requirements might be excessive and early termination will be necessary. Nearly full recovery is especially important for confined and perched LNAPL conditions, to help verify the site conceptual model for the test.
- A record of 20 to 30 measurements (each for DTP and DTW) is generally adequate for data analysis. When possible, these data should be evenly spread in terms of recovery volume. [For example, if the initial LNAPL thickness in a well is 4 ft and the LNAPL thickness after baildown is 0.5 ft, then measurements might be taken when the LNAPL thickness roughly has the following sequence of values: 0.50, 0.52, 0.54, … 3.90, .. ft.]

## 5. Post-Test Data

LNAPL transmissivity value from a baildown test is estimated based on measurement of LNAPL drawdown and recharge to the well as a function of time, along with a conceptual site model that can include geologic log and well configuration data to identify possible unconfined, confined, or perched LNAPL conditions. Estimation of formation discharge (well recharge) is based on changes in DTP and DTW values. Changes in fluid levels in the well compared with screen elevations determine the effective storage associated with the well. This storage can include only the casing volume or the casing volume plus some fraction of the pore space of the filter pack that has been drained of LNAPL during the baildown stage of the test. This latter case becomes more complicated, depending on the fluid levels versus the well screen interval, since only part of the LNAPL column in the well may be in contact with the screened interval of the well. These issues are discussed in more detail in Appendix B with regard to estimation of the effective well radius, $r_e$.

The post-test data that must be calculated include estimation of LNAPL drawdown ($s_n$) and well discharge ($Q_n$) as a function of time, and this in turn depends on the effective well radius value along with DTP and DTW measurements.

The LNAPL drawdown is measured based on the DTP, along with any correction that is applied to account for initial non-equilibrium between formation and wellbore LNAPL. Specifically, the drawdown corresponding to time $t_i$ is calculated using

$$(5.1) \quad s_{ni} = DTP_i - DTP_0 - \Delta s_n$$

In Eq. (5.1) $DTP_0$ is the initial (pre-test) depth to product and $\Delta s_n$ is a possible LNAPL drawdown correction as discussed below.

The LNAPL discharge from the formation to the well is calculated based on the effective well radius ($r_{e(i)}$) and changes in DTP and DTW over time. Once the effective well radius has been determined, the well discharge from time $t_i$ to time $t_{i+1}$ is calculated using the following equation:

$$(5.2) \quad Q_{ni} = \pi \, r_{e(i)}{}^2 \left( DTP_i - DTP_{i+1} + DTW_{i+1} - DTW_i \right) \Big/ \left( t_{i+1} - t_i \right)$$

This equation accounts for the increase in LNAPL storage volume over the time interval, and specifically identifies that the effective well radius might not be constant (such as a change from well casing storage to casing/screen plus filter pack storage).

# 6. Overview and General Discussion: Analysis of LNAPL Transmissivity Baildown Test Data

This section briefly summarizes methods for analysis of LNAPL transmissivity baildown test data. Additionally, use of time cutoff and time adjustment to eliminate early-time data influenced by filter pack drainage or other factors is discussed, and a default method for estimation of LNAPL storage coefficient is described. Finally, a flowchart that outlines the LNAPL transmissivity estimation process using this workbook is presented.

## 6.1. Methods for Estimating LNAPL Transmissivity

Among the variety of methods suggested in the literature for analysis of slug test data, three different methods are presented here for analysis of unconfined LNAPL transmissivity baildown tests. These three methods are designated through their original presentation in the literature as follows:

- B&R - Bouwer and Rice (1976)
- C&J - Cooper and Jacob (1946)
- CB&P - Cooper, Bredehoeft and Papadopulos (1967)

LNAPL baildown tests are inherently transient, meaning that fluid levels and flow rates change with time. Experience with transient aquifer tests suggests that at least two parameters are necessary to describe system performance. With a conventional pumping test one estimates the aquifer transmissivity and storage coefficient. For LNAPL baildown test analysis, both parameters are also necessary, though only the LNAPL transmissivity is of direct interest.

The Bouwer and Rice (B&R) method is conceptually the simplest. The method uses a linear model (Thiem equation) to relate LNAPL discharge to LNAPL drawdown, and is based on continuity of LNAPL volume within the well. LNAPL drawdown versus time data are used to determine the LNAPL transmissivity, based on an estimate of the well radius of influence provided through the empirical analysis presented by Bouwer and Rice (1976). Interesting questions remain in the literature between the applications of the B&R method for LNAPL baildown testing as presented by Lundy and Zimmerman (1996) and Huntley (2000). These approaches differ in terms of assumed fluid levels in the well during recovery. The Huntley method assumes that the water table elevation remains constant during the recovery period. The Lundy method, which proposes removal of a small slug of LNAPL from the well, assumes that the depth to water remains constant during the recovery period. This difference in assumptions results in the Huntley method including an additional factor $1/(1 - \rho_r)$ in the calculation of LNAPL transmissivity, where $\rho_r$ is the LNAPL-water density ratio. For many LNAPL transmissivity baildown tests, neither assumption is observed. For the general case, Andrew Kirkman (personal communication) suggests introduction of the J-ratio parameter that is directly based on measured data to address this issue. The Kirkman J-ratio is described in Appendix A and the J-ratio method is used herein for both the B&R, and the CB&J methods. The magnitude of the J-ratio is determined by the user using Fig. 4 on the “Figures” worksheet. The B&R method is developed in Appendix C.

The Cooper and Jacob (C&J) method provides an estimate of the LNAPL transmissivity based on the LNAPL discharge to the well and LNAPL drawdown, as a function of time. The method also requires estimation of an LNAPL storage coefficient. Guidance on suggested magnitudes of the LNAPL storage coefficient is provided for the user. The C&J method is developed in Appendix D.

The Cooper, Bredehoeft and Papadopulos (CB&J) method provides an estimate of the LNAPL transmissivity based on measurements of LNAPL drawdown versus time. The method also requires an estimate of the LNAPL storage coefficient. The CB&P method does not directly use the LNAPL discharge to the well, and it does require an estimate of the effective initial LNAPL drawdown. The CB&P method is developed in Appendix E.

LNAPL can also be found under confined or perched conditions. Methods based on the Bouwer and Rice method of analysis are developed for confined and perched LNAPL in Appendices F and G, respectively.

Discussion

There is no *a priori* preferred method for analysis of LNAPL baildown test data. The B&R method is good for long well purging events, whereas relatively instantaneous events are used with the C&J and CB&P methods because they incorporate transient storage effects. The B&R method is independent of absolute time; rather, just the slope of the log-normalized drawdown versus change in linear time is important. However, if a straight line is not observed with B&R and it concaves upward (as a result of storage effects), then C&J or CB&P are more able to account for the effects attributed to storage. Absolute time is critical for both C&J and CB&P, and thus it is necessary to adjust the effective time origin when early-time data is eliminated because of filter pack drainage. With the B&R method, the well radius of influence is estimated using well configuration data based on analog simulation analysis described by Bouwer and Rice (1976) for flow of groundwater to a well in an unconfined aquifer. This relationship is assumed to hold for LNAPL. The C&J method is based on an approximate solution describing flow of groundwater to a well under conditions of constant discharge and variable drawdown, and constant drawdown and variable discharge. The relationship is also assumed to apply to flow of LNAPL to a well when both the LNAPL discharge and LNAPL drawdown vary with time. The CB&P method is based on an analytical solution for a slug test in a confined aquifer, and is assumed to apply for LNAPL under unconfined conditions. With the CB&P method, both the effective initial drawdown and LNAPL storage coefficient must be estimated along with the LNAPL transmissivity. Because the CB&P method does not directly consider data regarding LNAPL discharge to the well, it is possibly the most uncertain method of analysis. Nevertheless, when properly applied, the user can often estimate LNAPL transmissivity value with coefficient of variation (ratio of the standard deviation to mean value) of 20 % or less when considering analyses using all three methods.

## 6.2. Time Cutoff and Time Adjustment

Early-time data from baildown testing may be significantly impacted by filter-pack drainage or other effects that do not reflect LNAPL flow from the formation to the well during recovery. Such data may be eliminated by specifying a cutoff time. Data from times earlier than the cutoff time are not considered in estimation of LNAPL transmissivity. The cut-off time may be used with the B&R, C&J, and CB&P methods. The B&R method does not depend on the time origin, so no further adjustments are necessary. However, both the C&J and CB&P methods include an LNAPL storage coefficient as a parameter, which represents a capacitance factor, and time origin is significant to the theoretical model. For the C&J method a time adjustment of the apparent time origin may be applied. One may think of the Time Adjustment as accounting for the delay in LNAPL flow from the formation to the well associated with the duration of significant filter-pack drainage. Limited experience suggests that the Time Adjustment and $Time_{cut}$ may be related through the following: Time Adjustment = (0.6 or 2/3) * $Time_{cut}$. The effects of $Time_{cut}$ and Time Adjustment are shown in Figure 6.1. In this figure, it is desired to eliminate data earlier than 25 minutes because of effects from filter-pack drainage ($Time_{cut}$ = 25 minutes); for a discussion of how this 25-minute $Time_{cut}$ was selected, see discussion leading to Fig. 7.4 below. A Time Adjustment = 15 minutes is applied for analysis of LNAPL transmissivity using the C&J method, meaning that the apparent time origin for data later than 15 minutes is shifted as shown. For the CB&P method, one simply uses the estimated drawdown at the $Time_{cut}$ as the initial drawdown value.

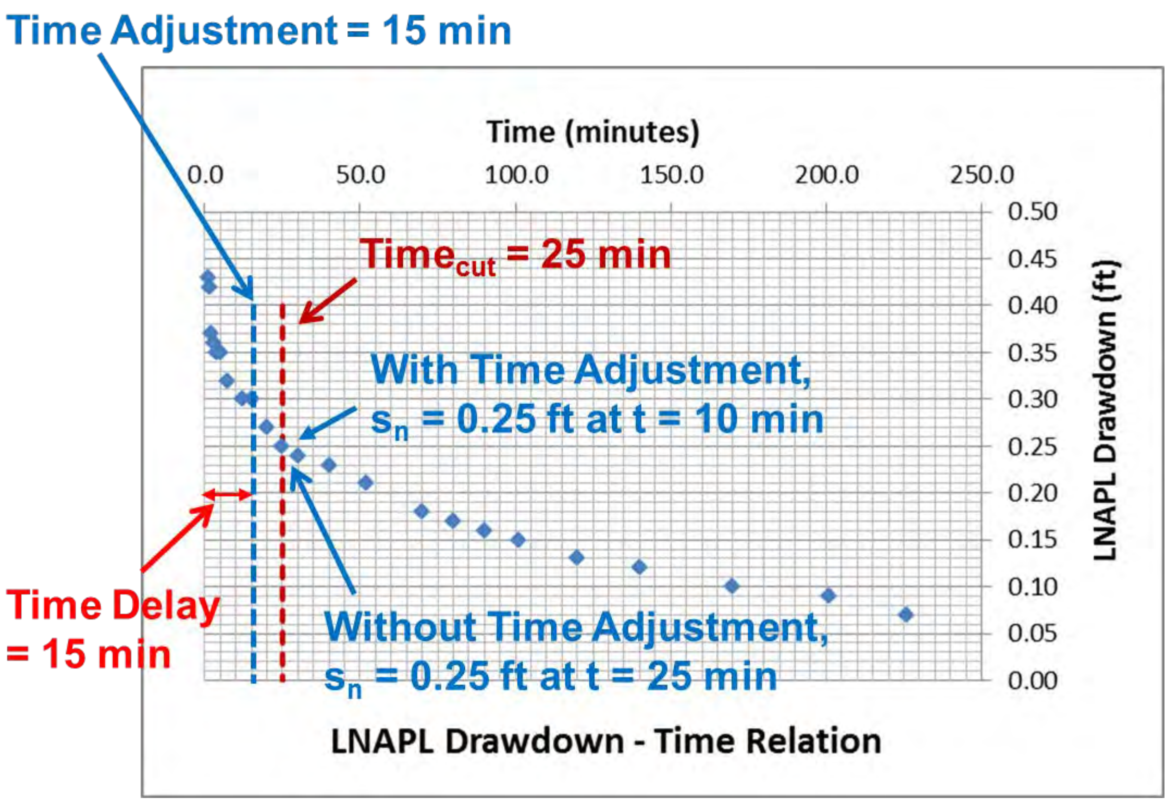



**Figure 6.1.** **Application of Time$_{cut}$ and Time Adjustment to eliminate early-time data influenced by filter-pack drainage or other effects**

## 6.3. Analysis of LNAPL Storage Coefficient

The storage parameter $S_n$ is used in the C&J and CB&P methods. The maximum value should equal a reasonable drainable porosity value for the formation. An upper bound estimate would be 0.15 for coarse sands, 0.06 for fine sands, 0.004 to 0.025 for silts. Clays would be on the low end of silts or lower unless LNAPL exists in secondary porosity. These values assume that the recoverable fraction of LNAPL is up to 50% saturation for coarse sands and 5% for silts and clays. These values will be lower (i.e., a factor of 10 to 50) for wells with minimal LNAPL recovery. Results are relatively insensitive to this parameter if realistic values are used. The table below provides general guidance on appropriate values.

**Table 6.1: Recommended Relationship between LNAPL Transmissivity and LNAPL Storage Coefficient (from ASTM, 2011)**

| LNAPL Transmissivity ($ft^2$/d) | LNAPLStorage (vol/vol) |
|---|---|
| 50 | 0.175 |
| 20 | 0.122 |
| 10 | 0.070 |
| 5 | 0.053 |
| 1 | 0.035 |
| 0.1 | 0.008 |

A “Default” option is available for estimating the LNAPL storage coefficient for the C&J and CB&P methods. An approximate model is fit to the data in Table 6.1, as shown in Figure 6.2.

(6.3.1) $$S_n = 0.025\sqrt{T_n}$$

In Eq. (6.3.1) the units of $T_n$ are $ft^2$/d. The default option is selected by entering the letter d in the $S_n$ entry cell. With the default option selected, the LNAPL storage coefficient is estimated implicitly as part of determining the LNAPL transmissivity.

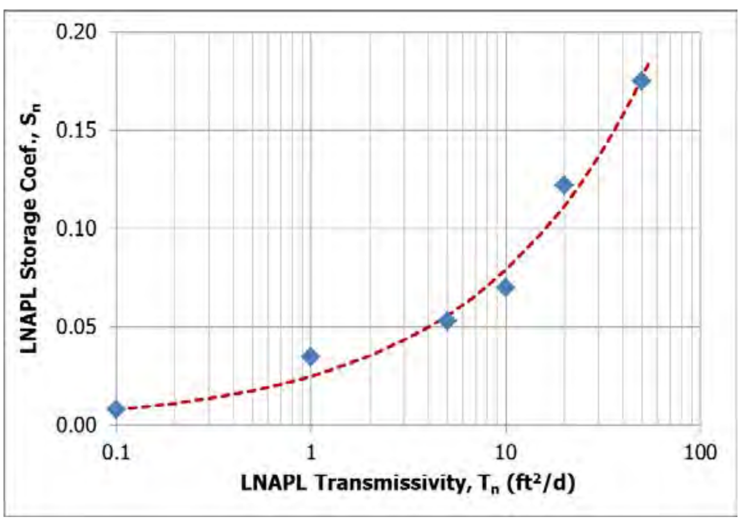



**Figure 6.2. LNAPL storage coefficient vs. LNAPL transmissivity**

## 6.4. General overview of LNAPL transmissivity estimation process

The process for estimating LNAPL transmissivity from LNAPL baildown test data using the API LNAPL Transmissivity Workbook is outlined in the flowchart shown in Figure 6.3. Further details are provided in ASTM (2011).

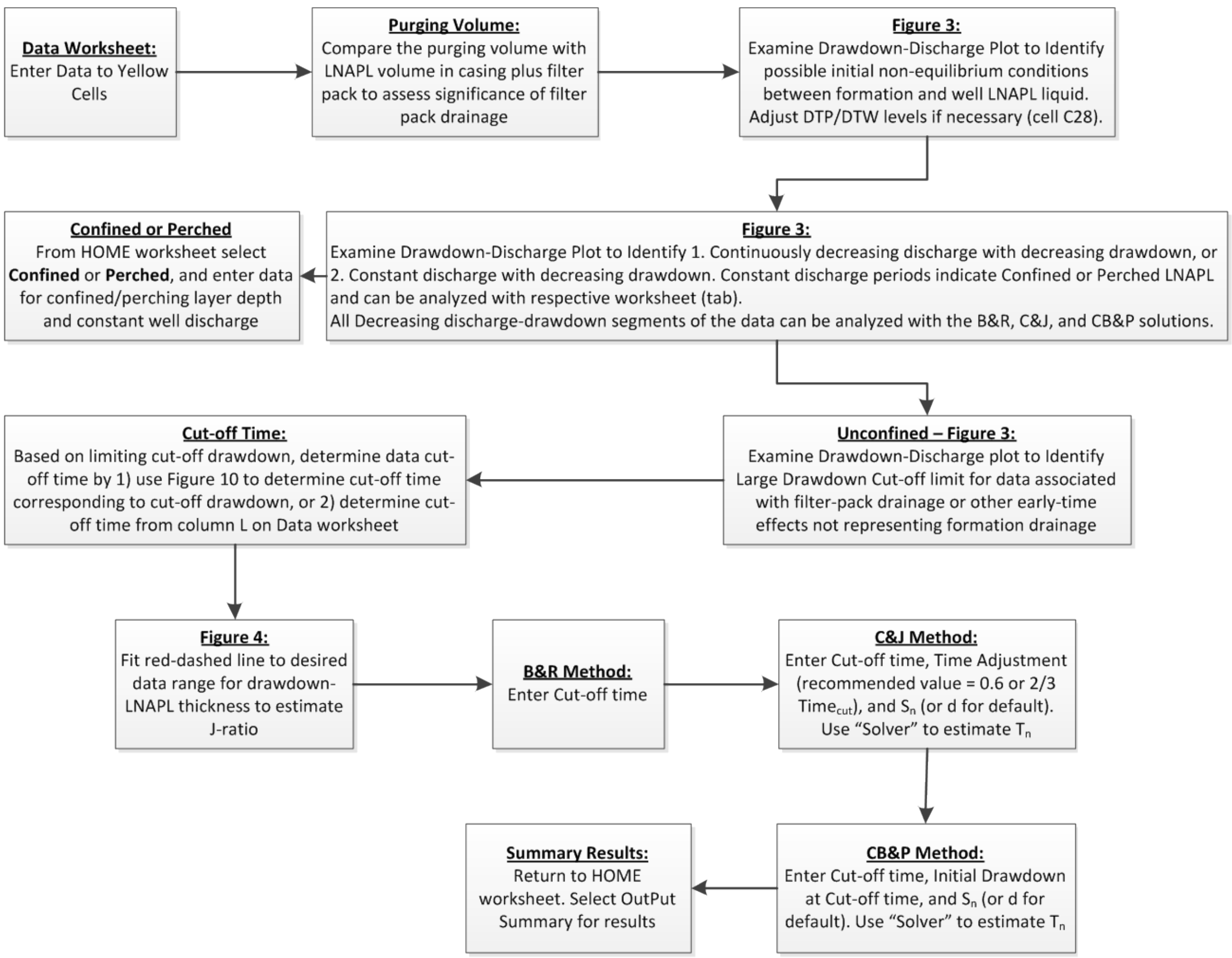



**Figure 6.3. Flowchart outlining steps in LNAPL baildown test analysis**

# 7. LNAPL Transmissivity Workbook

The *API LNAPL Transmissivity Workbook* tool is a Microsoft Excel ™ spreadsheet that may be used to estimate LNAPL transmissivity values from baildown test data under unconfined, confined and perched conditions. For unconfined conditions, three methods are used to calculate LNAPL transmissivity, and the results are averaged. The Kirkman J-ratio is required for two of these methods, and the magnitude of the J-ratio is determined by the User with Fig. 4 on the "Figures" worksheet. For both confined and perched LNAPL conditions, only a single estimate of LNAPL transmissivity is made based on the constant LNAPL discharge rate during part of the recovery period of the test.

The application tool has ten different worksheets that are designated as follows:

- HOME - Control and output worksheet
- Data - Entry of well configuration and fluid level data
- Figures - Basic figures showing data
- B&R - Bouwer and Rice method worksheet
- C&J - Cooper and Jacob method worksheet
- CB&P - Cooper, Bredehoeft and Papadopulos method worksheet
- B&R Type Curve - Set of type curves provided as aid to field work
- Confined - Confined LNAPL worksheet
- Perched - Perched LNAPL worksheet
- Flowchart - Flowchart outlining steps in LNAPL baildown test analysis

As discussed below, not all worksheets are visible at any time, though the first three worksheets and the last worksheet are always available.

## 7.1 "HOME" Worksheet

An example "HOME" worksheet is shown in Figure 7.1. This is the primary worksheet that outlines the steps in data analysis as follows:

1. Reset Output Summary
2. Enter Data & View Figures
3. Choose Well Conditions
4. LNAPL Transmissivity Summary

Step 1 hides the method-specific worksheets. The "Data", "Figures", and "Flowchart" worksheets remain visible and accessible. No existing data are cleared when the RESET button is selected. Step 2 requires entry of data on the "Data" worksheet and review of data on the "Figures" worksheet. Step 2 provides preliminary information to guide in selecting LNAPL condition (unconfined, confined, or perched) for analysis. If unconfined conditions are observed, then the J-ratio MUST be determined using Fig. 4 on the "Figures" worksheet. Based on Step 2 assessment, Step 3 is selection of LNAPL condition which makes visible either the worksheets appropriate for unconfined conditions, or individually, the worksheets for confined or perched conditions. Step 4, selection of the OUTPUT SUMMARY button copies results from the method-specific worksheets to summary output.

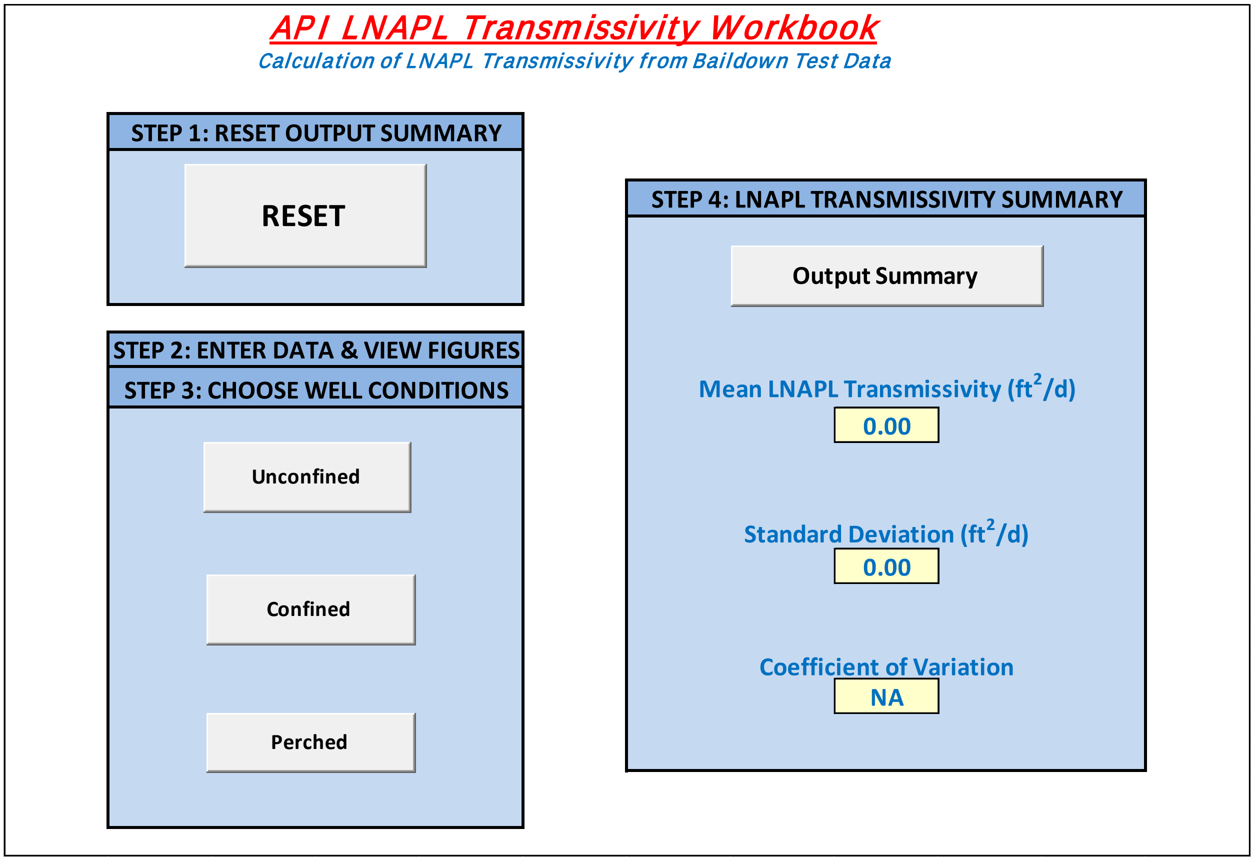



**Figure 7.1. "HOME" worksheet**

## 7.2 "Data" Worksheet

An example "Data" worksheet page is shown in Figure 7.2. The cells for data entry are shown in light yellow color and user must input the data in the units indicated. Other cells are locked to help protect against inadvertent modification to the worksheet. This worksheet includes the well configuration data listed in Section 3, along with records of depth to product (DTP) and depth to water (DTW) as a function of time, as measured from the top of casing. The initial values of DTP and DTW are also entered. The LNAPL Specific Yield, $S_y$, on this worksheet refers to the filter pack. A default value 0.175 is recommended, though the value can be modified by the user. The default value is based on an assumed filter-pack porosity of 0.35, and an assumed specific yield of 50 % of the void space. The LNAPL Density Ratio, $\rho_r$, is estimated from field data on product type. The LNAPL Baildown Volume is entered for comparison purposes only; it is not used elsewhere in the workbook. The "Drawdown Adjustment" value is read from the data entry for Fig. 3 on the "Figures" worksheet. Calculations performed on this worksheet include adjustment of fluid levels to give depth bgs, estimation of the water table depth based on DTP and DTW along with LNAPL-water density ratio, LNAPL drawdown using Eq. (5.1) and LNAPL discharge using Eq. (5.2), and the effective well radius as outlined in Appendix B. If both the ground surface elevation and top of casing elevation are entered as zero, then no adjustment is made to DTP and DTW fluid levels. For unconfined conditions with the LNAPL column within the screened interval of the well, these data are not necessary.

| | | | | |
|---|---|---|---|---|
| Well Designation: | YYY | Beckett and Lyverse (2002) | | |
| Date: | date | | | |
| Ground Surface Elev (ft msl) | 0.0 | Enter These Data | | Drawdown |
| Top of Casing Elev (ft msl) | 0.0 | | | Adjustment |
| Well Casing Radius, $r_c$ (ft): | 0.170 | $r_{e1}$ | | (ft) |
| Well Radius, $r_w$ (ft): | 0.500 | | | 0.08 |
| LNAPL Specific Yield, $S_y$: | 0.175 | | | |
| LNAPL Density Ratio, $\rho_r$: | 0.780 | | | |
| Top of Screen (ft bgs): | 0.0 | | | |
| Bottom of Screen (ft bgs): | 0.0 | | | |
| LNAPL Baildown Vol. (gal.): | | | | |
| Effective Radius, $r_{e3}$ (ft): | 0.260 | Calculated Parameters | | |
| Effective Radius, $r_{e2}$ (ft): | 0.245 | | | |
| Initial Casing LNAPL Vol. (gal.): | 2.10 | | | |
| Initial Filter LNAPL Vol. (gal.): | 2.81 | | | |

| | Enter Data Here | | | | | Water Table Depth | LNAPL Drawdown | Average | LNAPL Discharge | $s_n$ | $b_n$ | $r_e$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time (min) | DTP (ft btoc) | DTW (ft btoc) | DTP (ft bgs) | DTW (ft bgs) | (ft) | $s_n$ (ft) | Time (min) | $Q_n$ ($ft^3$/d) | (ft) | (ft) | (ft) |
| Initial Fluid Levels: | 0 | 22.29 | 25.38 | 22.29 | 25.38 | 22.97 | | | | | 3.09 | |
| Enter Test Data: | 1.0 | 22.80 | 23.30 | 22.80 | 23.30 | 22.91 | 0.43 | | | | 0.50 | |
| | 1.5 | 22.79 | 23.38 | 22.79 | 23.38 | 22.92 | 0.42 | 1.3 | 55.041 | 0.43 | 0.59 | 0.260 |
| | 2.0 | 22.74 | 23.41 | 22.74 | 23.41 | 22.89 | 0.37 | 1.8 | 48.925 | 0.40 | 0.67 | 0.260 |
| | 3.0 | 22.73 | 23.50 | 22.73 | 23.50 | 22.90 | 0.36 | 2.5 | 30.578 | 0.37 | 0.77 | 0.260 |
| | 4.0 | 22.72 | 23.54 | 22.72 | 23.54 | 22.90 | 0.35 | 3.5 | 15.289 | 0.36 | 0.82 | 0.260 |
| | 5.0 | 22.72 | 23.59 | 22.72 | 23.59 | 22.91 | 0.35 | 4.5 | 15.289 | 0.35 | 0.87 | 0.260 |
| | 7.5 | 22.69 | 23.66 | 22.69 | 23.66 | 22.90 | 0.32 | 6.3 | 12.231 | 0.34 | 0.97 | 0.260 |
| | 12.0 | 22.67 | 23.89 | 22.67 | 23.89 | 22.94 | 0.30 | 9.8 | 16.988 | 0.31 | 1.22 | 0.260 |
| | 15.0 | 22.67 | 23.90 | 22.67 | 23.90 | 22.94 | 0.30 | 13.5 | 1.019 | 0.30 | 1.23 | 0.260 |
| | 20.0 | 22.64 | 23.98 | 22.64 | 23.98 | 22.93 | 0.27 | 17.5 | 6.727 | 0.29 | 1.34 | 0.260 |
| | 25.0 | 22.62 | 24.04 | 22.62 | 24.04 | 22.93 | 0.25 | 22.5 | 4.893 | 0.26 | 1.42 | 0.260 |
| | 30.0 | 22.61 | 24.07 | 22.61 | 24.07 | 22.93 | 0.24 | 27.5 | 2.446 | 0.25 | 1.46 | 0.260 |
| | 40.0 | 22.6 | 24.15 | 22.60 | 24.15 | 22.94 | 0.23 | 35.0 | 2.752 | 0.24 | 1.55 | 0.260 |
| | 52.0 | 22.58 | 24.22 | 22.58 | 24.22 | 22.94 | 0.21 | 46.0 | 2.293 | 0.22 | 1.64 | 0.260 |
| | 70.0 | 22.55 | 24.31 | 22.55 | 24.31 | 22.94 | 0.18 | 61.0 | 2.039 | 0.20 | 1.76 | 0.260 |
| | 80.0 | 22.54 | 24.36 | 22.54 | 24.36 | 22.94 | 0.17 | 75.0 | 1.835 | 0.18 | 1.82 | 0.260 |
| | 90.0 | 22.53 | 24.39 | 22.53 | 24.39 | 22.94 | 0.16 | 85.0 | 1.223 | 0.17 | 1.86 | 0.260 |
| | 101.0 | 22.52 | 24.44 | 22.52 | 24.44 | 22.94 | 0.15 | 95.5 | 1.668 | 0.16 | 1.92 | 0.260 |
| | 120.0 | 22.5 | 24.50 | 22.50 | 24.50 | 22.94 | 0.13 | 110.5 | 1.288 | 0.14 | 2.00 | 0.260 |
| | 140.0 | 22.49 | 24.57 | 22.49 | 24.57 | 22.95 | 0.12 | 130.0 | 1.223 | 0.13 | 2.08 | 0.260 |
| | 170.0 | 22.47 | 24.65 | 22.47 | 24.65 | 22.95 | 0.10 | 155.0 | 1.019 | 0.11 | 2.18 | 0.260 |
| | 201.0 | 22.46 | 24.74 | 22.46 | 24.74 | 22.96 | 0.09 | 185.5 | 0.986 | 0.10 | 2.28 | 0.260 |
| | 226.0 | 22.44 | 24.79 | 22.44 | 24.79 | 22.96 | 0.07 | 213.5 | 0.856 | 0.08 | 2.35 | 0.260 |

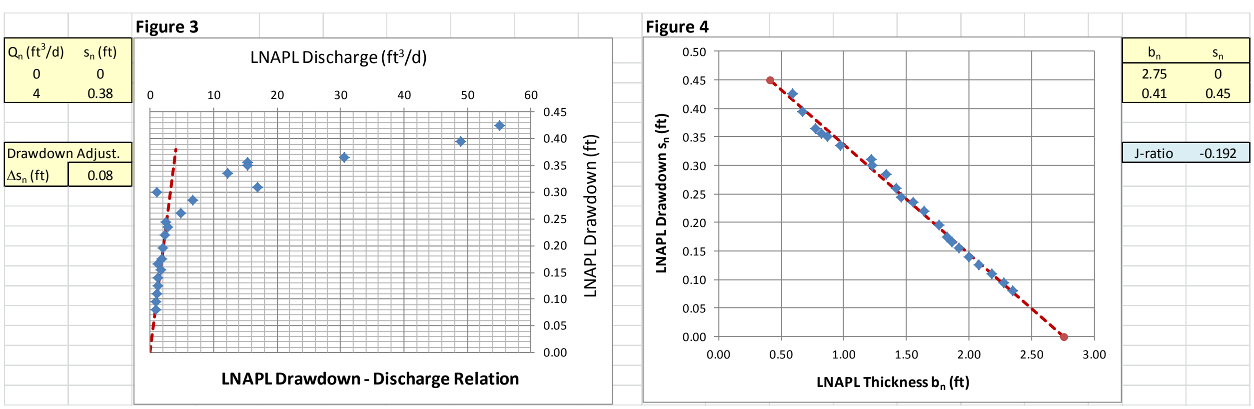
**Figure 7.2. "Data" entry worksheet**

## 7.3 "Figures" Worksheet

This worksheet contains ten miscellaneous figures showing the input and the output data. As discussed below, the most important diagnostic tools include the plot of LNAPL drawdown versus discharge, and the plot of LNAPL drawdown versus LNAPL thickness (J-Ratio). The figures (objects) are not protected to allow edits (i.e., axis scales, etc.). The figures are numbered one through ten and are described as follows:

- Fig 1: Depth to Fluid Interface vs. Time (arithmetic time scale). This figure also shows the initial DTP and DTW. Depending on the screen interval data entered on the "Data" worksheet, the screened interval of the LNAPL column is also shown. The entire screen length is not shown. Instead, only the screened interval extending one foot above and/or below the initial LNAPL well thickness is shown. Fig. 1 is useful for evaluating how the potentiometric surface varied over the test duration. Looking for trends of water-table fluctuation will help identify any significant deviations from the assumed constant background conditions.

- Fig 2: Depth to Fluid Interface vs. Time (logarithmic time scale). This figure also shows the initial DTP and DTW. Depending on the screen interval data entered on the “Data” worksheet, the screened interval of the LNAPL column is also shown. The entire screen length is not shown. Instead, only the screened interval extending one foot above and/or below the initial LNAPL well thickness is shown. Similar to Fig. 1, however the early portion of the test can be better viewed for longer term tests.
- Fig 3: LNAPL Drawdown vs. LNAPL Discharge. This is an important diagnostic tool used to determine Drawdown Adjustment that is copied to the “Data” worksheet and other worksheets to account for initial non-equilibrium between formation and well fluids. The LNAPL Drawdown-LNAPL Discharge data should extrapolate to the origin (zero value) for small values. To aid analysis, a linear model is added with data entry in the yellow-fill box adjacent to the figure, as shown in Figure 7.3(a). LNAPL drawdown-discharge should exhibit a direct relationship. Deviations from this indicate the baildown test may be significantly affected by outside factors (e.g., nearby changes in pumping) or confined or perched conditions (where constant discharge is observed).
- Fig 4: LNAPL Drawdown vs. LNAPL Thickness. This is an <u>essential</u> diagnostic tool that is used to estimate the J-ratio magnitude, as described in Appendix A, and used with the “B&R” worksheet and “CB&P” worksheet. A linear model is provided with data entry in the yellow-fill box adjacent to the figure, and with estimated J-ratio value shown in the blue-fill box adjacent, as shown in Figure 7.3(b).




(a) (b)

**Figure 7.3. Fig. 3 and Fig. 4 from the “Figures” worksheet showing data entry boxes for estimation of drawdown adjustment and J-ratio**

- Fig. 5: Depth to Product (DTP) vs. LNAPL Discharge. This figure may be helpful as a diagnostic tool to identify soil stratigraphic influences.
- Fig 6: Depth to Water (DTW) vs. LNAPL Discharge. This figure may be helpful as a diagnostic tool to identify soil stratigraphic influences.
- Fig 7: LNAPL Thickness vs. Time. This figure may be useful for evaluating if the fluid levels reach equilibrium at the end of the test.
- Fig 8: LNAPL Discharge vs. Time. This figure represents an alternative method for evaluating if the baildown test has completed and the well reaches equilibrium conditions.
- Fig 9: LNAPL Well Inflow Volume vs. Time. Fig. 9 is analogous to Fig. 7 except provided in terms of the total well volume. In addition for being useful to evaluate test completion, this figure is useful for design of future baildown tests in terms of volume to remove from the well and filter pack.
- Fig 10: LNAPL Drawdown vs. Time. Linear model tool is also added with data entry in the yellow-fill box adjacent to the figure. In combination with Fig. 3, this figure is useful in identifying cut-off time for early-time data.

## 7.4 "B&R" Worksheet

The "B&R", or Bouwer and Rice worksheet calculates the LNAPL transmissivity and standard deviation based on the Bouwer and Rice (Bouwer and Rice, 1976; Bouwer, 1989) method using the method of linear least squares. As shown in Eq. (C.3), according to this method, the logarithm of the drawdown varies as a linear function of time. A straight line is automatically fit to the log-drawdown vs. time data and the slope of this line is used to determine the LNAPL transmissivity. The variance of the slope of the line is used to estimate the LNAPL transmissivity standard deviation. The ratio of the radius of influence to the effective radius is calculated using the polynomial approximation presented by Butler (2000). The user may eliminate early time data from the analysis by entering a non-zero value for the cutoff time (yellow cell). An example worksheet is shown in Figure 7.5. The only active cell on this worksheet is the cut-off time, and the LNAPL transmissivity value is automatically calculated. The lower figure on the worksheet shows the fit of the model data to the B&R Type Curve (see discussion below).

For the example shown in Figure 7.5 the cut-off time is set at 25 minutes. This cut-off time is based on eliminating early-time data associated with large filter pack drainage to the well. The drawdown-discharge curve for this example (Fig. 3 on the "Figures" worksheet) is shown in Figure 8.1 (c) and Figure 8.1 (d) (expanded scale after drawdown correction). In particular, Figure 8.1 (d) shows that the linear relationship between drawdown and discharge is reached once the LNAPL drawdown is about 0.25 ft. The LNAPL drawdown vs. time curve (Fig. 10 from the "Figures" worksheet) is shown in Figure 7.4, which gives the corresponding cut-off time 25 minutes for an LNAPL drawdown of 0.25 ft.

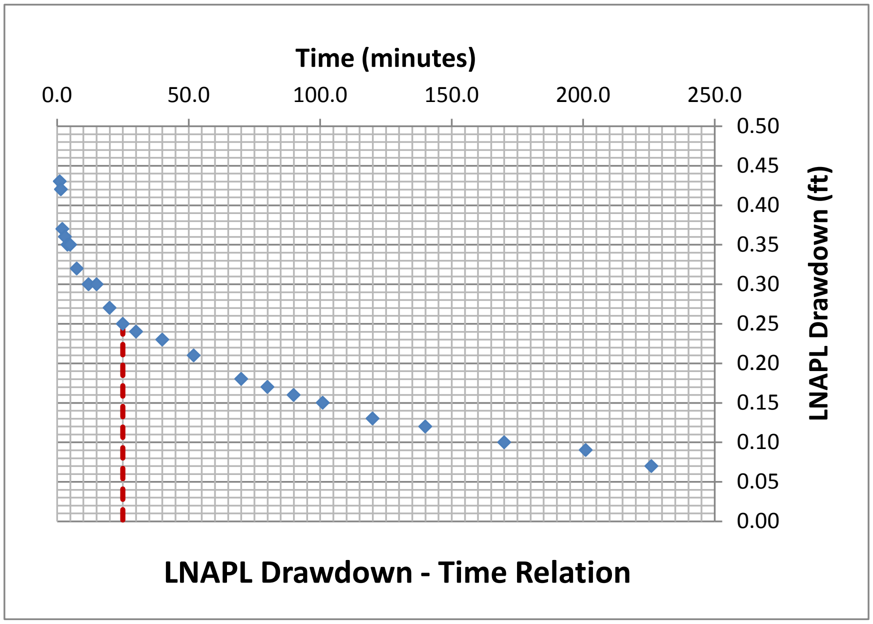



**Figure 7.4. LNAPL Drawdown vs. Time Curve (Fig. 10 from "Figures" Worksheet)**

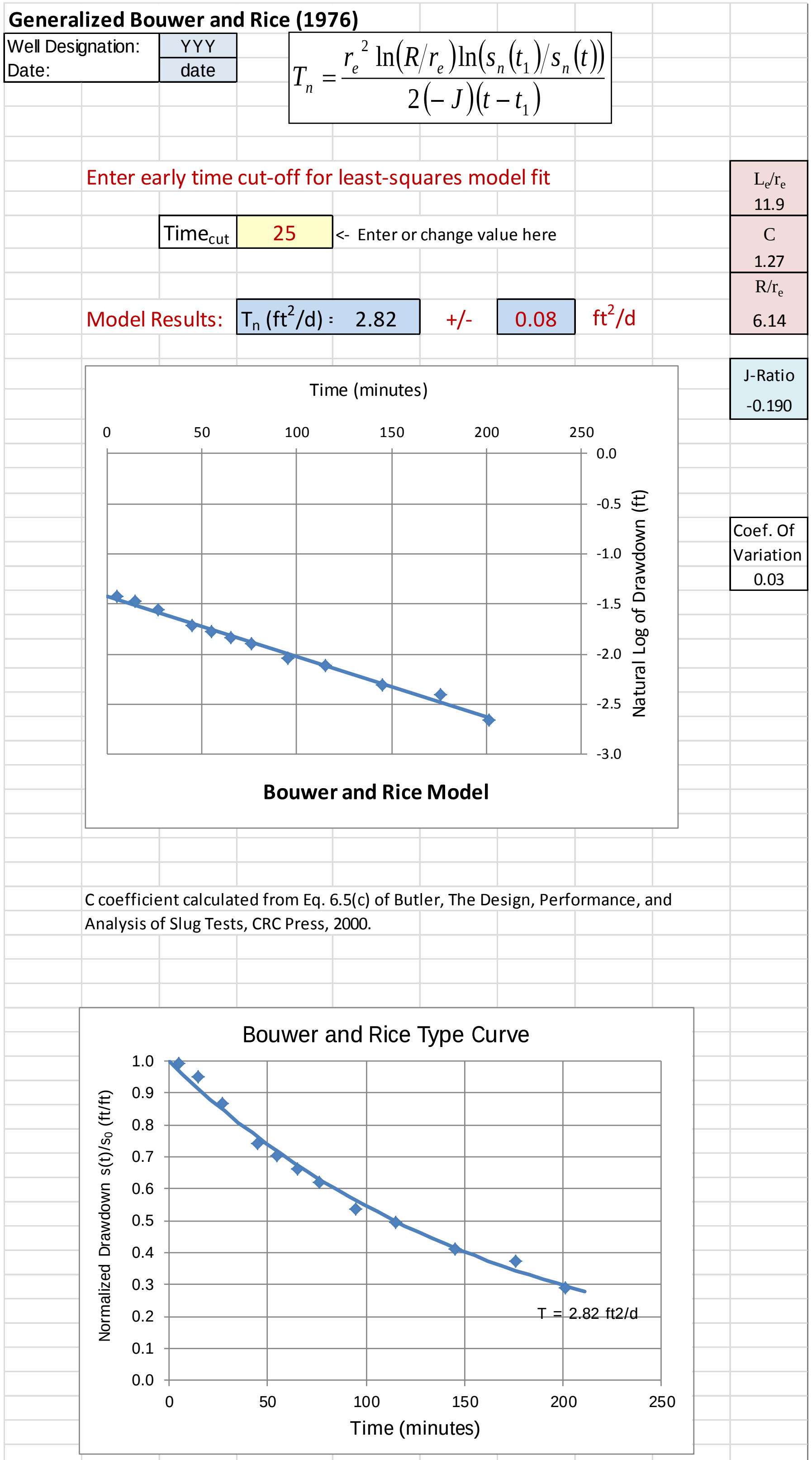



**Figure 7.5. “B&R” worksheet**

## 7.5 "C&J" Worksheet

The Cooper and Jacob (C&J) worksheet is used to calculate the LNAPL transmissivity value based on the Cooper and Jacob (1946) equation. [As described in Appendix D, the Theis equation is actually used in calculations, though the more commonly used Cooper and Jacob designation has been retained here.] The method used is modified from that presented as method three of Huntley (2000). The method is outline in Appendix D. Unlike the B&R method, both the C&J method and the CB&P method use a storage parameter ($S_n$) in addition to LNAPL transmissivity ($T_n$) to fit the model and data. Use of the storage parameter implies that the time origin is critical to data analysis for both methods. Yet, it is recognized that early-time data can be impacted by filter-pack drainage and not reflect natural LNAPL flow from the formation to the well. Thus the user may specify a cut-off time to eliminate early-time data from the analysis. To provide consistency with the model basis, the user may also adjust the time origin to a fraction of the cut-off time. There is little guidance towards an appropriate fraction, though the range 50 % to 80 % appears reasonable. Recommended values are 0.6 or 2/3, whichever is more convenient. Both the cut-off time and time adjustment values are specified by the user (light yellow cells). For further discussion, see Section 6.2. In some cases, repeating the test with alternative field methods that reduce the removal time or reduce the filter pack recharge may help reduce the need for the time adjustment.

The estimate of LNAPL transmissivity is found by minimizing the root-mean-square error between model prediction and data by varying the storage coefficient and LNAPL transmissivity. An example worksheet is shown in Figure 7.6. The Adjusted Time is set to 6 minutes, which is 60 % of the cut-off time. The Excel "Solver" function is used to find the root-mean-square error, which is the square root of the sum square difference (SSD) provided by Eq. (D.6). Instead of using "Solver" to find both $S_n$ and $T_n$, it is recommended that the user select a trial value of $S_n$ and use "Solver" to find $T_n$. Alternatively, the letter d may be entered as the Trial $S_n$ value to select the default option described in Section 6.3.

**Cooper and Jacob (1946)**

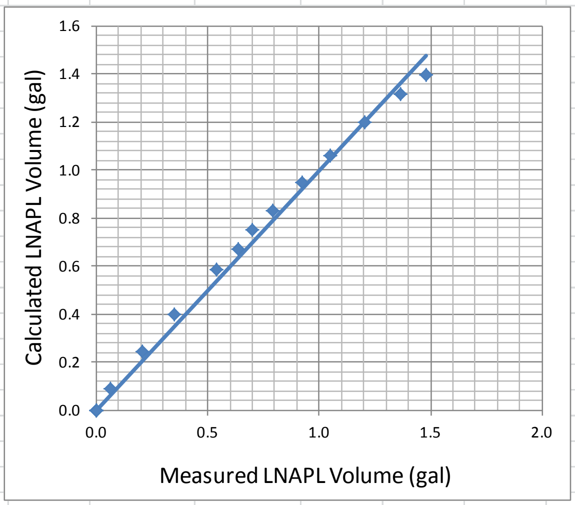
| | |
|---|---|
| Well Designation: | YYY |
| Date: | date |

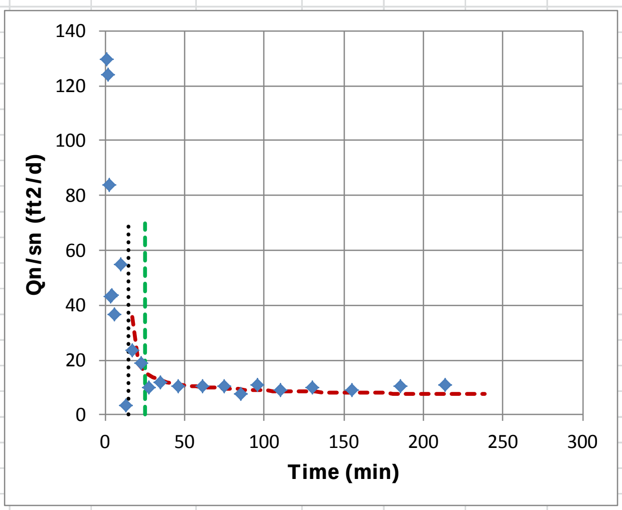
$$V_n(t_i) = \sum_j^i \frac{4\pi T_n s_j}{\ln\left(\frac{2.25 T_n t_j}{r_e^2 S_n}\right)} \Delta t_j$$

Enter early time cut-off for least-squares model fit

| | | |
|---|---|---|
| $Time_{cut}$ (min): | 25 | <- Enter or change values here |
| Time Adjustment (min): | 15 | |
| Trial $S_n$: | d | <-- Enter d for default or enter $S_n$ value |
| Root-Mean-Square Error: | 0.147 | <-- Minimize this using "Solver" |
| | 0.047 | <-- Working $S_n$ |
| Trial $T_n$ ($ft^2$/d): | 3.543 | <-- By changing $T_n$ through "Solver" |
| | | Add constraint $T_n$ > 0.00001 |

**Model Result:** $T_n$ ($ft^2$/d) = **3.54**




Height
70

**Figure 7.6. “C&J” worksheet**

## 7.6 “CB&P” Worksheet

The Cooper, Bredehoeft and Papadopulos (CB&P) worksheet is used to calculate the LNAPL transmissivity value based on the Cooper, Bredehoeft and Papadopulos (1967) slug test model. Application of this model for an LNAPL baildown test is described in Appendix E, and an example worksheet is shown in Figure 7.7. For application of this method, there are three unknown parameters: initial LNAPL drawdown $s_n(0)$, LNAPL transmissivity $T_n$, and LNAPL storage coefficient $S_n$. Trial estimates of these quantities are entered on the worksheet, and the Excel “Solver” function is used to minimize the root-mean-square error given by the square-root of Eq. (E.7). An estimate of the initial drawdown is provided by the extrapolated drawdown at the cut-off time. Alternatively, the initial drawdown is selected so that the drawdown ratio $s_n/s_{n0}$ extrapolates to 1 at time = 0 (which includes the cut-off time adjustment). The algorithm used to evaluate the model equations is derived from Charbeneau (2000).

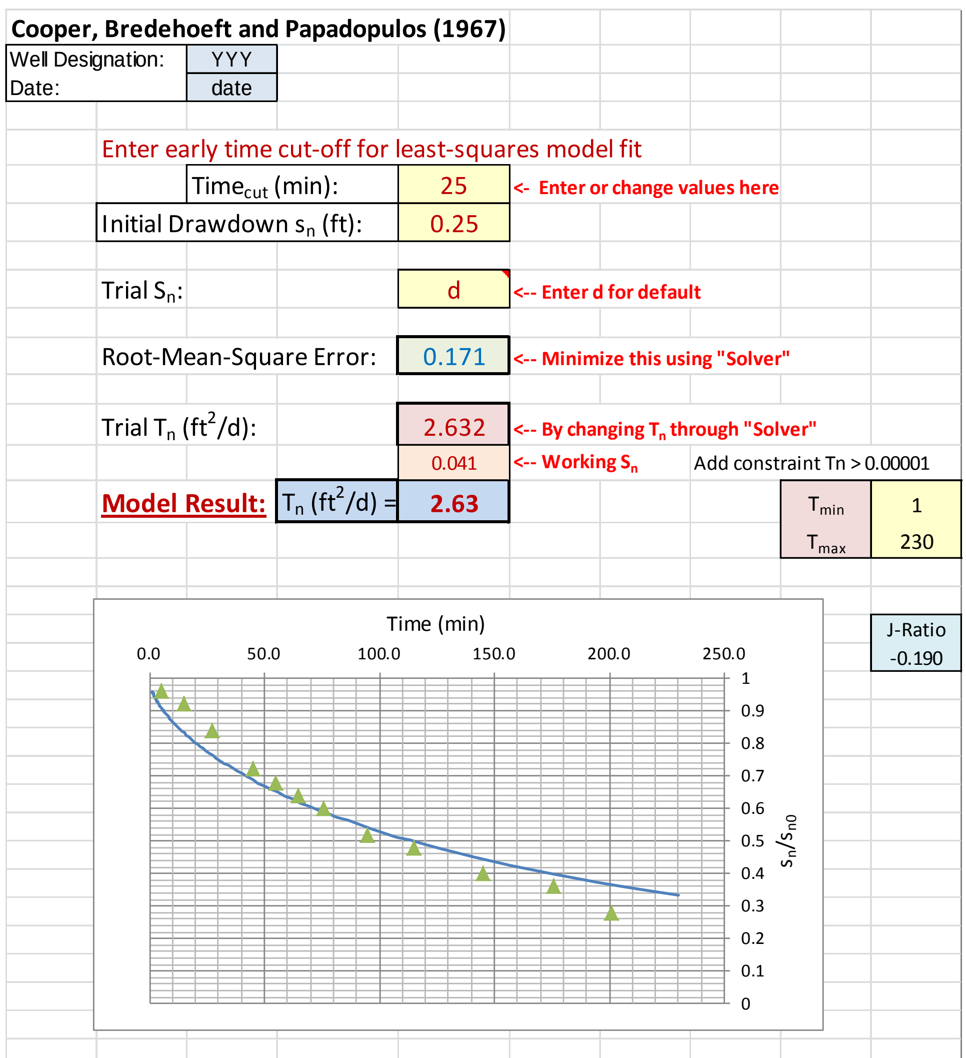



**Figure 7.7. “CB&P” worksheet**

## 7.7 “B&R Type Curve” Worksheet

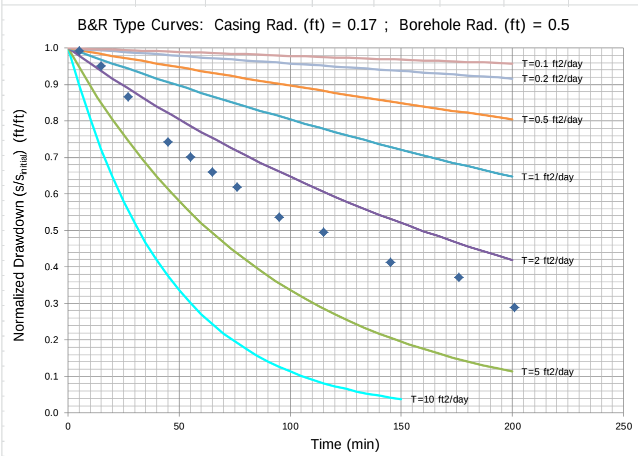
This worksheet presents a type curve based on the Bouwer and Rice method along with a supporting data sheet. The type curve was developed to support rapid field evaluation of LNAPL baildown tests when the user is primarily interested in ‘order-of-magnitude’ estimates of LNAPL transmissivity and possible early termination of a field test of a particular well. The type curve is a normalized plot of the Bouwer and Rice solution present at the top of the B&R worksheet, where the type curve shows normalized drawdown as a function of time for selected values of LNAPL transmissivity. The use of the type curve requires that the well-specific construction and specific yield data be entered into the “Data” worksheet in order to generate the correct type curves. A J-ratio of ($\rho_r$ – 1) is recommended unless well-specific behavior is available. The user may change the range of LNAPL transmissivity curves shown on the curve and associated maximum times (which may correspond to the test time) (light yellow cells). The lower part of the worksheet provides a data sheet that may be copied for field use. The type curve application was suggested by Andrew Kirkman. Figure 7.8 shows an example worksheet.

**Bouwer and Rice Short Term LNAPL Mobility Test Type Curves**

B&R Type Curves: Casing Rad. (ft) = 0.17 ; Borehole Rad. (ft) = 0.5

Enter these values

| Type Curve ID | Type Curve Name | Notes | Max Time (min) | Transmissivity ($ft^2$/day) | | J-Ratio | |
|---|---|---|---|---|---|---|---|
| 1 | T=10 ft2/day | | 150 | 10 | | | |
| 2 | T=5 ft2/day | | 200 | 5 | | -0.192 | <-- If uncertain use |
| 3 | T=2 ft2/day | | 200 | 2 | | | -0.22 |
| 4 | T=1 ft2/day | | 200 | 1 | | | |
| 5 | T=0.5 ft2/day | | 200 | 0.5 | | | |
| 6 | T=0.2 ft2/day | | 200 | 0.2 | | | |
| 7 | T=0.1 ft2/day | | 200 | 0.1 | | | |




**Field Data**

| Record Data in Fields Below | | | | | | Calculate and Plot Fields Below | | |
|---|---|---|---|---|---|---|---|---|
| Well ID | | Well Dia. (ft) | Total Depth (ft) | | | | | |
| Notes | Date | Time | Elapsed Time (min) | Depth To Product (TOC) | Depth to Water (TOC) | Product Thickness (ft) | Drawdown (s) DTP-DTP(initial) (ft) | Normalized Drawdown ($s/s_{initial}$) |
| Initial Measurement | | | | | | | | |
| Stopped Bailing/Start Gauging | | | 0 | | | | | |
| Well Starts recovering | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

**Figure 7.8. “B&R Type Curve” worksheet**

## 7.8 "Confined" Worksheet

The "Confined" worksheet is used to estimate LNAPL transmissivity under confined LNAPL conditions. This worksheet is visible and available when the CONFINED button is selected under Step 3 Conditions on the "Selection and Results" worksheet. The basic equations are presented in Appendix F, and an example worksheet is shown in Figure 7.9. The depth to base of confining bed is entered to determine the effective limiting thickness of LNAPL in the well $b_{nW}$ (see Eq. F.2). The constant discharge from the steady discharge portion of the test is then entered and used to calculate the LNAPL transmissivity. The radius of influence term for the skimmer well equation is determined from the Bouwer and Rice (B&R) worksheet.

**Confined LNAPL Model:**

$$T_n = \frac{Q_n \ln(R/r_w)}{2\pi(1-\rho_r)(b_{nR}-b_{nW})}$$

| Well Designation: | HMW-44C |
|---|---|
| Date: | 12-Aug-09 |

| | |
|---|---|
| Depth to base of confining bed (ft bgs) [from boring log | 29.35 |
| Constant LNAPL discharge to well (ft$^3$/d): | 8 |
| Depth to top of screen (ft bgs): | 27.2 |
| Corrected water table elevation (ft bgs): | 28.0 |
| Limiting effective LNAPL thickness in well, $b_{nW}$ (ft): | 1.7 |
| Limiting effective LNAPL drawdown, $s_{nW}$ (ft): | 0.09 |
| Initial LNAPL thickness, $b_{nR}$ (ft): | 2.1 |
| Radius of influence ratio (from Bouwer and Rice), $R/r_w$: | 6.5 |
| **LNAPL Transmissivity, $T_n$ (ft$^2$/d):** | **25.67** |

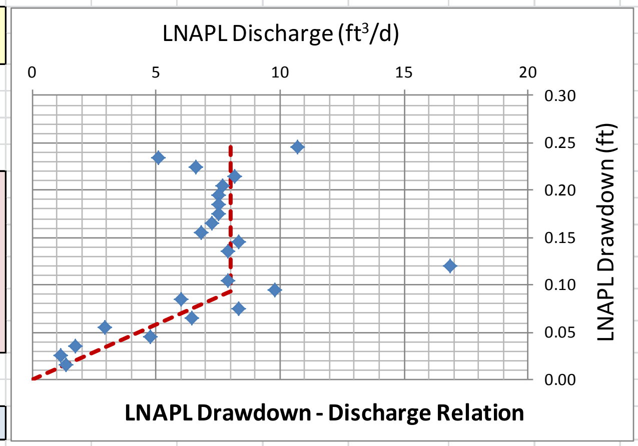



**Figure 7.9. "Confined" worksheet**

## 7.9 "Perched" Worksheet

The "Perched" worksheet is used to estimate LNAPL transmissivity under perched LNAPL conditions. The basic equations are presented in Appendix G. The depth (bgs) to the top of the perching layer, $DZ_{12}$, is entered to determine the effective limiting drawdown of LNAPL in the well based on the initial depth to product $DTP_0$. The constant discharge from the steady discharge portion of the test is then entered and used to calculate the LNAPL transmissivity. The radius of influence term for the skimmer well equation is determined from the Bouwer and Rice (B&R) worksheet. The worksheet mirrors the "Confined" worksheet and is not repeated here.

# 8. Examples and Important Diagnostic Tools

An important diagnostic tool is a plot of the well drawdown versus well discharge. The general shape of this relationship can be used to identify conditions with significant borehole recharge from the filter pack, screen for perched or confined LNAPL conditions, and help identify whether formation LNAPL was initially in equilibrium with well-bore LNAPL (and whether drawdown adjustment might be necessary). Some example curves are discussed below.

Figure 8.1 shows a number of drawdown-discharge curves. Figure 8.1(a) shows an example for unconfined LNAPL where significant borehole recharge from the filter pack is not an issue. While the initial calculated data (point with large $Q_n$, large $s_n$) is not consistent with other data on this figure, it is based on measurements taken at 0.5 and 1 minute into the test and could be associated with measurement uncertainty. Figure 8.1(b) gives an example where borehole recharge from the filter pack is significant. The initial data show large discharge which is primarily associated with filter pack drainage. Once the drawdown falls below 0.35 feet, consistent linear drawdown-discharge behavior is observed.

Figures 8.1(c) and (d) show the same data set. First, Figure 8.1(c) shows that significant borehole recharge does occur. Also, significantly, the linear part of the curve does not approach zero drawdown at zero discharge. Instead, it appears that the extrapolated limit has zero discharge with $s_n = 0.08$ ft. Such behavior suggests that the formation and wellbore LNAPL fluids were not initially in equilibrium, and that a drawdown correction of $\Delta s_n = 0.08$ ft should be applied to the data before LNAPL transmissivity analysis. Figure 8.1(d) shows an expanded view of this data <u>after</u> the correction has been applied. Such a correction does affect the resulting LNAPL transmissivity value that is calculated. With the correction $\Delta s_n = 0.08$ ft, the average LNAPL transmissivity $T_n = 2.99$ ft$^2$/d with CV = 0.16. For the same data and analysis without the 0.08 ft correction, the drawdowns are larger and the estimated LNAPL transmissivity is smaller with an average value $T_n = 1.89$ ft$^2$/d and coefficient of variation = 0.19.

Figure 8.1(e) shows behavior that suggests confined (or perched) LNAPL conditions. In this case it represents confined conditions with the water table initially located at an elevation above the confined LNAPL and with resulting exaggerated LNAPL thickness in the well. Immediately following LNAPL removal from the well, there is no LNAPL within the wellbore to “push” back against LNAPL inflow from the formation, and LNAPL discharge from the formation occurs at a constant rate while the LNAPL drawdown is declining. Once the LNAPL column within the wellbore increases in thickness to contact the mobile formation LNAPL, the inflow rate is retarded and decreases at a linear rate along with the LNAPL drawdown. One may analyze LNAPL transmissivity from the constant inflow rate along with limiting LNAPL drawdown value (about 0.1 ft in this example), or one can use standard (unconfined) equations on the data from the linear drawdown-discharge part of the curve. Figure 8.1(f) shows large initial LNAPL inflow, which in this case is likely associated with aggressive purging in addition to filter pack drainage (this corresponds to Figure B.1(c)).

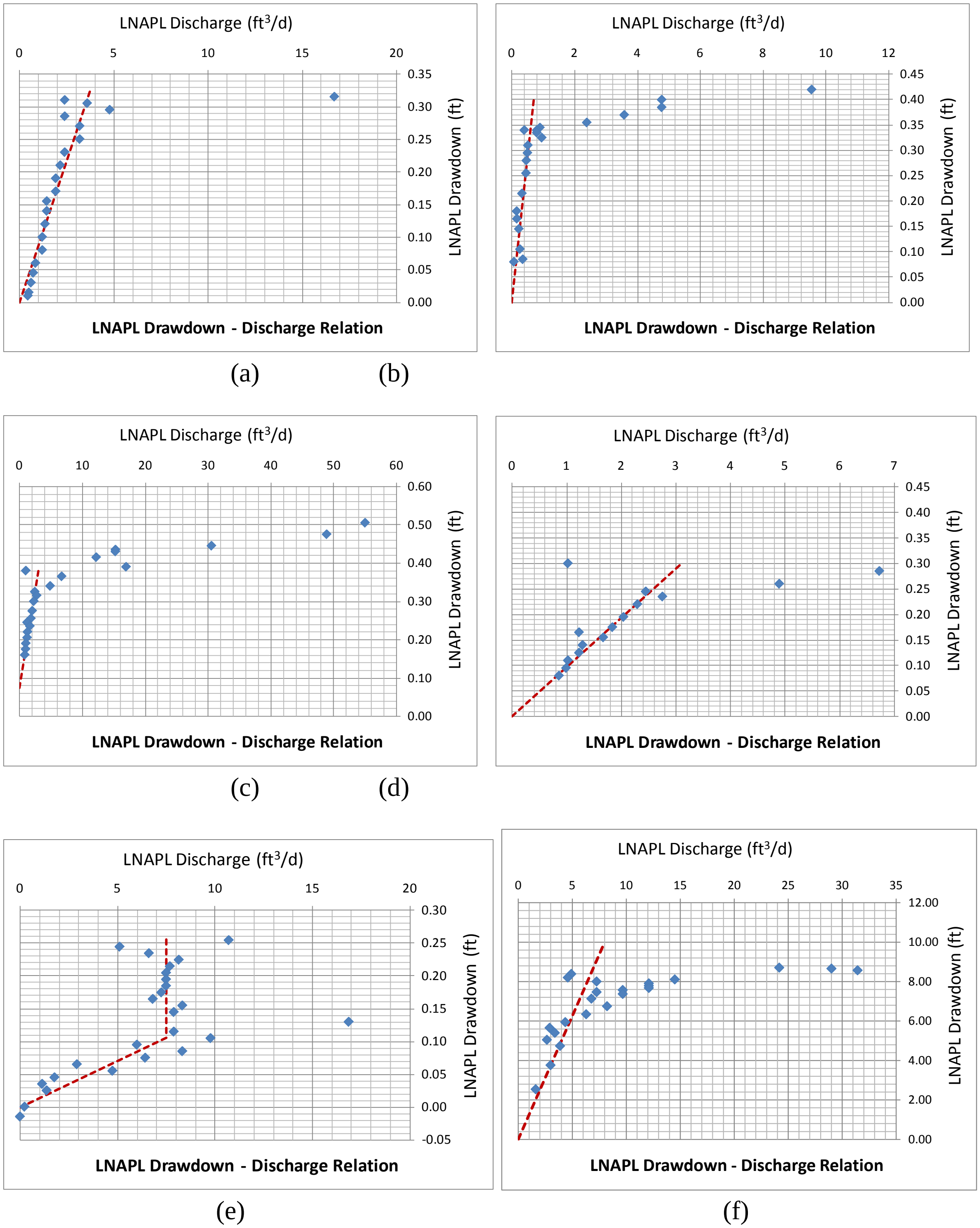



**Figure 8.1. Example LNAPL drawdown-discharge curves**

A couple of examples are considered in a little more detail. The first example, Figure 8.2, shows results from a baildown test with initial LNAPL thickness approximately 1.5 ft. During fluid removal from the wellbore both LNAPL and water were removed, and there is significant fluid recovery during approximately the first 6 minutes of the test, after which the calculated water table elevation remains stable. While there is significant scatter in the early-time data (larger drawdown values), the latter-time data shows a nearly linear relationship between discharge and drawdown. It also appears that the drawdown intercept with the $Q_n$ = 0 axis has a residual value of about $s_n$ = 0.02 ft (0.24 inch). While this magnitude correction appears small, it does represent nearly 20 % of the drawdown being analyzed during the test analysis. A drawdown correction of magnitude 0.018 ft is applied (larger corrections would result in negative drawdown and require further individual data adjustment or use of an alternative model for analysis). A cut-off of 10 minutes is assumed, and the data gives $J$ = -0.179. The calculated LNAPL transmissivity is $T_n$ = 10.45 $ft^2$/d, and the coefficient of variation (ratio of standard deviation to mean transmissivity value based on the three methods of data analysis that are discussed below) is $CV$ = 0.13. [If drawdown correction is not applied the model provides a LNAPL transmissivity estimate $T_n$ = 5.34 $ft^2$/d with CV = 0.28.]

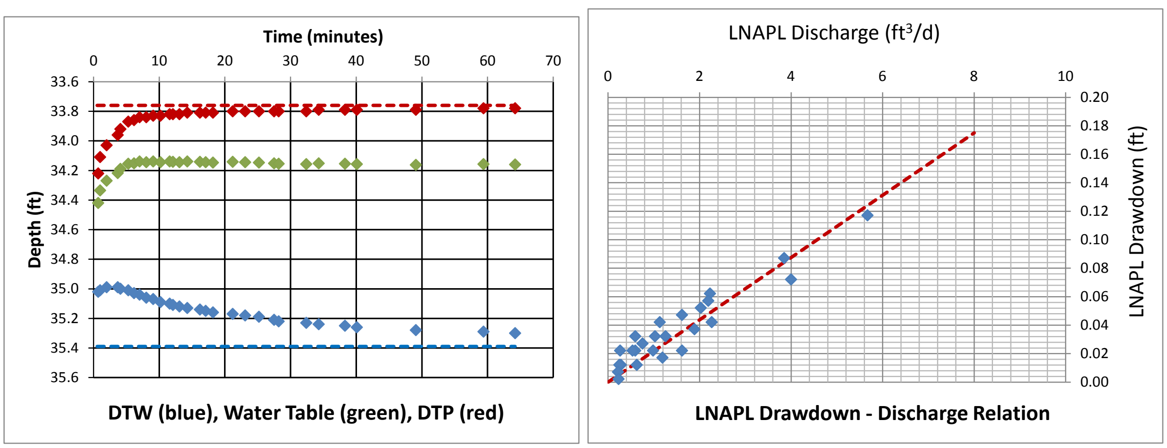
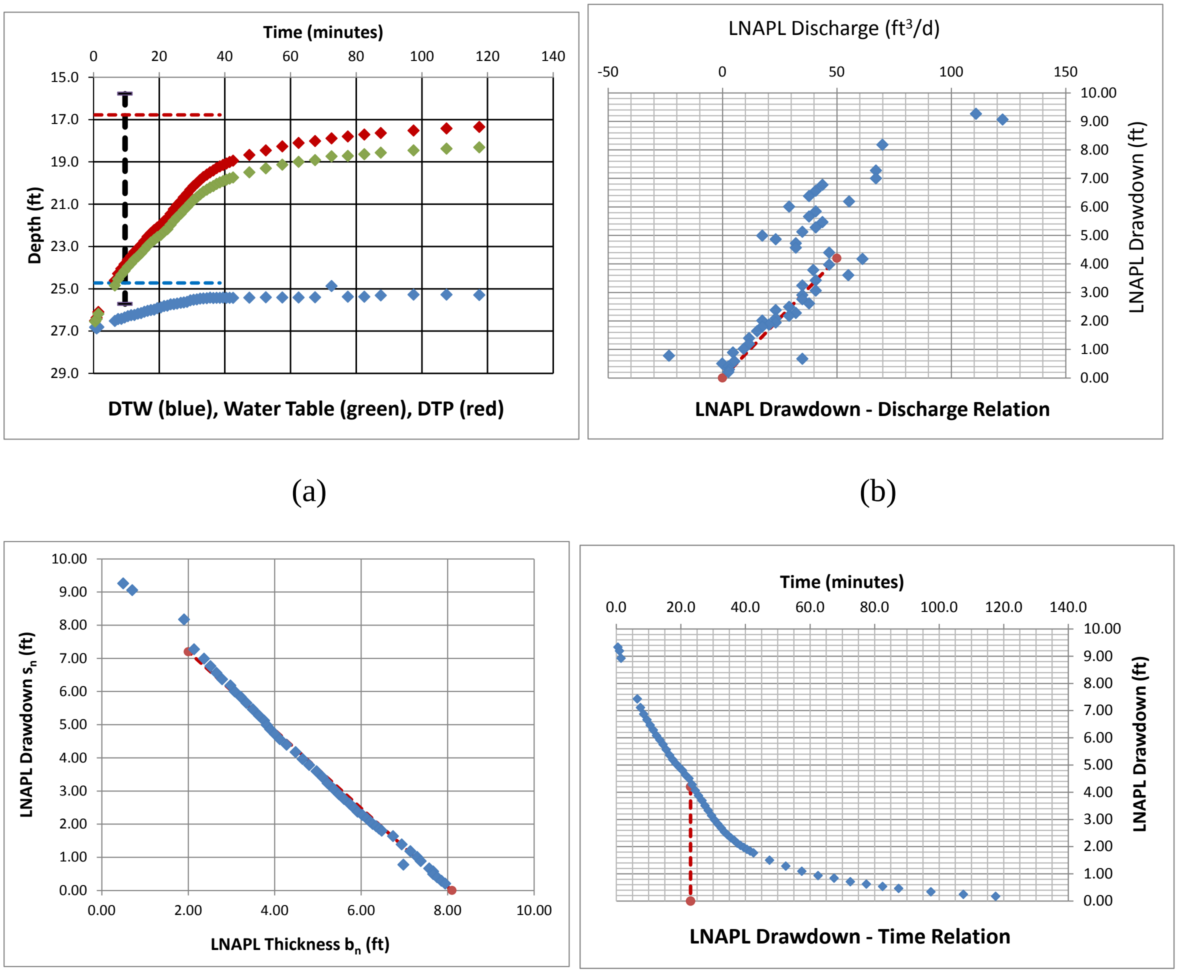



**Figure 8.2. Example E1: $T_n$ = 10.4 $ft^2$/d; $CV$ = 0.13**

The second example shown in Figure 8.3 represents a test where purging resulted in significant removal of both LNAPL and groundwater. The bottom of screen is located at a depth 27 ft, and this is the initial elevation for fluid interfaces in the well. Figure 8.3(b) shows the LNAPL drawdown-discharge graph. The expected linear relationship between LNAPL drawdown and discharge is not observed until the drawdown reaches approximately 4.2 ft. Figure 8.3(c) shows that the J-ratio is $J$ = -1.18. This is consistent with a rising water table and LNAPL-water interface elevation throughout the test. Figure 8.3(d) is the graph of LNAPL drawdown versus time (Fig. 10 on the “Figures” worksheet). The LNAPL drawdown is 4.2 ft at a time of 24 minutes. A cut-off time of 25 minutes is assumed, with an Adjustment Time $\Delta t_a$ = 15 minutes for the C&J and CB&P methods. Results from the three analysis methods give $T_n$ = 3.08 $ft^2$/d with $CV$ = 0.07.




(a) (b)

(c) (d)

**Figure 8.3. Example E2: $T_n$ = 3.08 ft$^2$/d; $CV$ = 0.07**

A third example shown in Figure 8.4 corresponds to the confined LNAPL test shown in Figure 7.9. The LNAPL transmissivity value calculated in Figure 7.9 is based on a single data corresponding to the drawdown and discharge at the end of the “constant discharge” segment. The following example shows that consistent results can be achieved if only the late-time data is used. The drawdown-discharge curve of Figure 8.4(b) shows that the linear relationship is observed starting at a drawdown of about 0.1 ft. Figure 8.4(c) shows that $J$ = -0.257, which is close to the values that would be used with the Huntley method of analysis (for this well, $\rho_r$ = 0.764). Figure 8.4(d) shows that a drawdown of 0.1 ft is observed at a time 12 minutes, which serves as the cut-off for the three methods of analysis. A time adjustment $\Delta t_a$ = 8 minutes is used for the C&J method. Results from the three methods give $T_n$ = 23.56 ft$^2$/d with $CV$ = 0.14. This LNAPL transmissivity estimate compares favorably with the estimate $T_n$ = 25.67 ft$^2$/d from Figure 7.9.

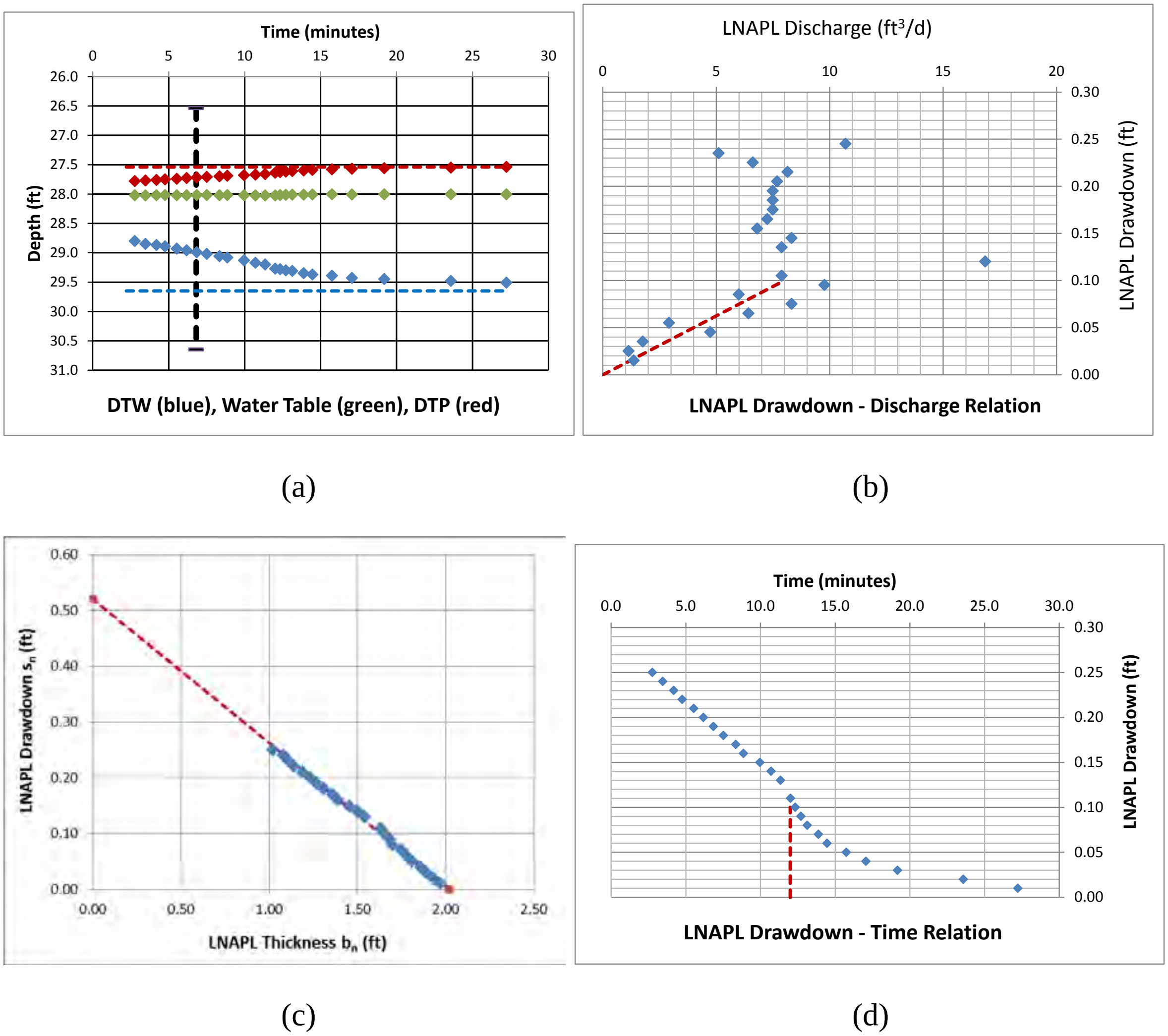



**Figure 8.4.** **Example E3: $T_n$ = 23.56 ft$^2$/d; CV = 0.14**

## 8. Bibliography

ASTM (2006). *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface*, ASTM E2531-06.

ASTM (2011). *The Standard Guide for Estimation of LNAPL Transmissivity* ASTM E2856-11.

Beckett, G.D. and Lyverse, M.A. (2002). "A Protocol for Performing Field Tasks and Follow-up Analytical Evaluation for LNAPL Transmissivity Using Well Baildown Procedures." AQUI-VER, Inc. and Chevron Texaco Energy Research and Technology Co.

Bouwer, Herman (1989). "The Bouwer and Rice Slug Test - An Update". *Ground Water*, 27(3), 304-309.

Bouwer, Herman, and Rice, R.C. (1976). "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells". *Water Resources Research*, 12(3), 423-428.

Butler Jr., James J. (2000). *The Design, Performance, and Analysis of Slug Tests*. Lewis Publishers, New York.

Charbeneau, Randall J., (2000). Groundwater Hydraulics and Pollutant Transport. Prentice Hall, New Jersey.

Cooper Jr., Hilton H., Bredehoeft, John G., and Papadopulos, Istavros R. (1967). "Response of a Finite-Diameter Well to an Instantaneous Charge of Water". *Water Resources Research*, 3(1), 263-269.

Cooper, H.H., and Jacob, C.E. (1946). "A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History". *American Geophysical Union Transactions*, 27, 526-534.

Huntley, David. (2000). "Analytic Determination of Transmissivity from Baildown Tests", *Ground Water*, 38(1), 46-52.

ITRC (2009). "Evaluating LNAPL Remedial Technologies for Achieving Project Goals".

Lundy, Don A. and Laura M. Zimmerman (1996). "Assessing the Recoverability of LNAPL Plumes for Recovery System Conceptual Design." Proceedings of the $10^{th}$ Annual National Outdoor Action Conference and Exposition, National Ground Water Association, Las Vegas, NV. May 13-15.

# Appendix A: Kirkman J-Ratio

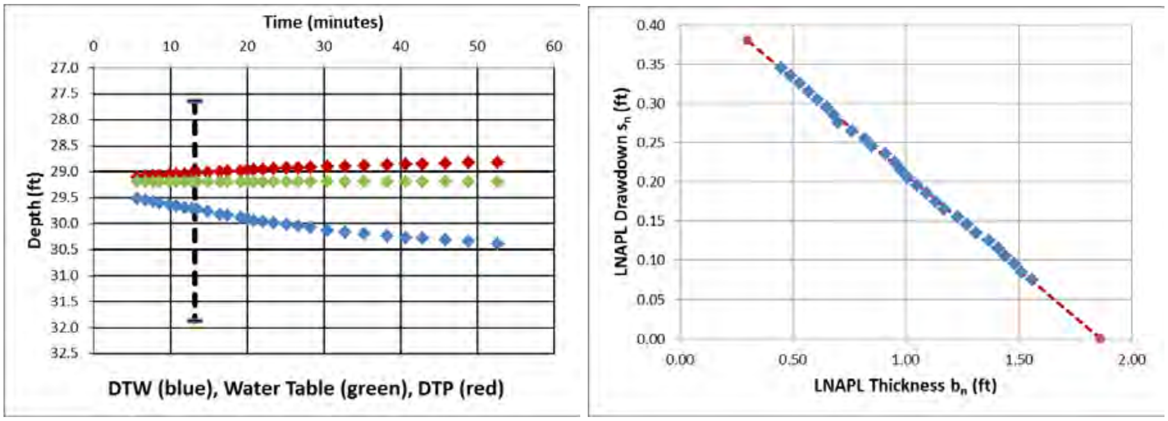
The LNAPL discharge from the formation to the well is also related to changes in LNAPL drawdown. This relationship is critical to the generalized Bouwer and Rice method and Cooper, Bredehoeft and Papadopulos method discussed herein. With the effective well radius (see Appendix B), the relationship is written

$$\text{(A.1)} \quad Q_n = \pi r_e^2 \frac{db_n}{dt} = \frac{\pi r_e^2}{J} \frac{ds_n}{dt}$$

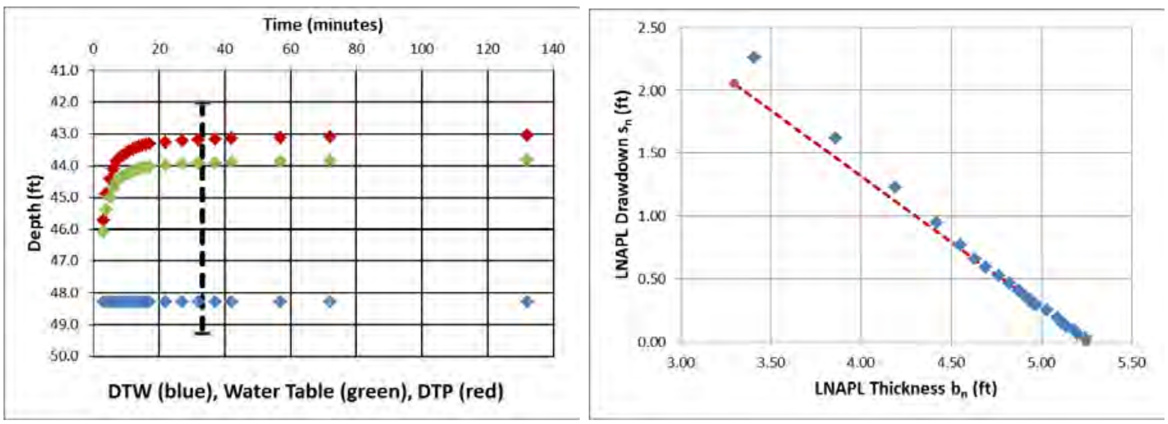
Equation (A.1) states that the LNAPL discharge is equal to the rate of LNAPL accumulation within the well. Andrew Kirkman (personal communication) has suggested that this rate can be generally related to the change in LNAPL drawdown through introduction of a J-ratio parameter. The J-ratio is the slope of the linear relationship between LNAPL drawdown and LNAPL well thickness:

$$\text{(A.2)} \quad J = \frac{\Delta s_n}{\Delta b_n}$$

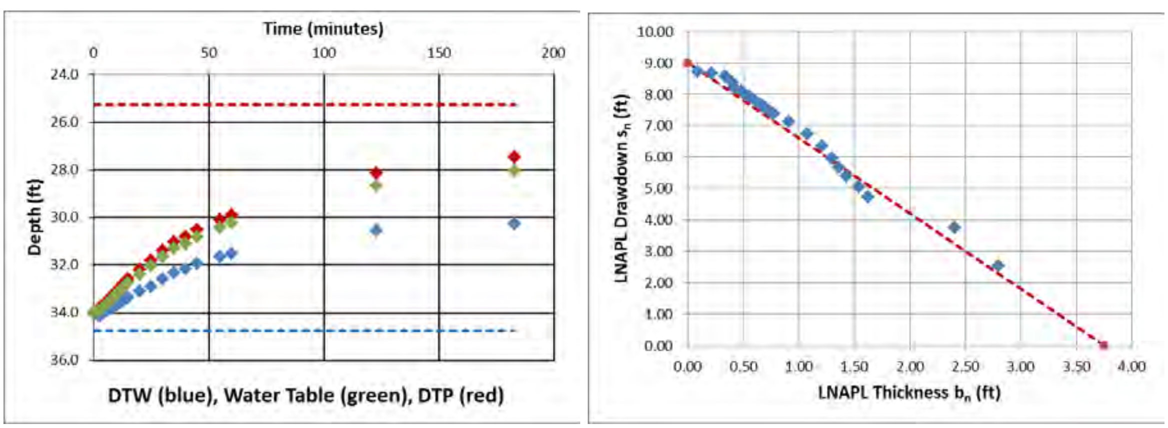
The magnitude of the J-ratio varies with the nature of LNAPL recharge to the well. If, during a baildown test, LNAPL is removed from the well using a peristaltic pump with no removal of water and the water recovers quickly (i.e., water transmissivity is much greater than LNAPL transmissivity through the well screen), then the water table elevation should remain constant and $J = -(1 - \rho_r)$. If both LNAPL and water are removed during a baildown test, and if the LNAPL transmissivity greatly exceeds the water transmissivity for recharge to the well, then the elevation of the LNAPL-water interface can remain constant and $J = -1$. Values outside of this range are also observed. Three examples are shown in Figure A.1. In case (a) the water table elevation remains constant, and the value $J = -0.244$ is close to $J = -(1 - \rho_r)$ [for this well, $\rho_r = 0.764$]. For case (b), the LNAPL-water interface elevation remains constant and $J = -1.051$. For case (c) the interface elevations increase throughout the recovery period and $J = -2.400$.




(a)




(b)




(c)

**Figure A.1. Variation of J-ratio with nature of recharge to the well. (a) J = -0.244; (b) J = -1.051; (c) J = -2.400**

# Appendix B: Effective Well Radius

During a baildown test the fluid levels in a well are monitored, and it is necessary to relate the LNAPL volume flux, $dV_n$, into the well to the increase in LNAPL thickness, $db_n$, or equivalently to the increase in LNAPL head, $dh_n$, or decrease in LNAPL drawdown, $-ds_n$. By definition of the J-ratio (see Eq. A.2), $ds_n = J\, db_n$. Clearly,

(B.1) $$dh_n = dz_{an} = -\, ds_n = -\, J\, db_n$$

(B.2) $$db_n = dz_{an} - dz_{nw} \rightarrow dz_{nw} = dz_{an} - db_n = -\,(J + 1)\, db_n$$

In general during a baildown test, after removal of LNAPL from the well, the air-LNAPL interface elevation increases ($dz_{an} > 0$). However, depending on test conditions, the elevation of the LNAPL-water interface can increase, decrease, or remain constant. This is accounted for through the magnitude of the J-ratio. If the J-ratio magnitude is less than -1, then the elevation of the LNAPL-water interface increases ($dz_{nw} > 0$). Otherwise, if the magnitude of the J-ratio is greater than -1, then the elevation of the LNAPL-water interface decreases ($dz_{nw} < 0$). Finally, if $J = -1$, then the elevation of the LNAPL-water interface remains constant ($dz_{nw} = 0$).

The increase in LNAPL volume within the well (well casing plus filter pack) depends on the location of the LNAPL column within the well. Three cases are shown in Figure B.1. In the first case both $z_{an}$ and $z_{nw}$ are located within the casing. In the second case $z_{an}$ is located within the casing while $z_{nw}$ is located within the screen section of the well with filter pack. Finally, in the third case both $z_{an}$ and $z_{nw}$ are located within the screened section with filter pack. The elevation of top of screen (TOS) and bottom of screen (BOS) are also shown.

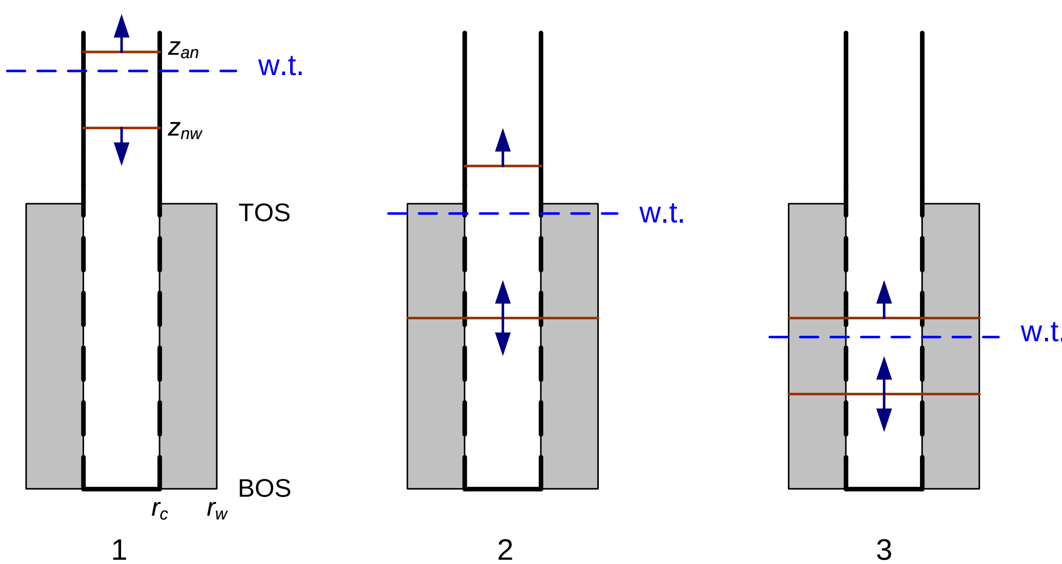



**Figure B.1. Three cases showing configuration of LNAPL column in a well**

To simplify analysis, it is useful to handle the three cases shown in Figure B.1 with a consistent notation by introducing the effective well radius, $r_e$. Then for all three cases one has

(B.3) $$dV_n = \pi\, r_e^{\,2}\, db_n$$

For Case 1 one clearly has

(B.4) $$r_{e1} = r_c$$

Similarly, for Case 3 one has

(B.5) $$r_{e3} = \sqrt{r_c^{\,2} + S_y\left(r_w^{\,2} - r_c^{\,2}\right)}$$

Case 2 is a little more subtle. One has

$$dV_n = \pi\, r_{e1}^{\,2}\left(dz_{an}\right) + \pi\, r_{e3}^{\,2}\left(-\,dz_{nw}\right)$$

Using Eqs. (B.1) and (B.2) this may be written

$$dV_n = \pi\, r_{e1}^{\,2}\left(-J\; db_n\right) + \pi\, r_{e3}^{\,2}\left(\left(J+1\right)\, db_n\right)$$

Comparing this result with Eq. (B.3) gives

(B.6) $$r_e = \sqrt{-J\, r_{e1}^{\,2} + \left(J+1\right) r_{e3}^{\,2}}$$

# Appendix C: Generalized Bouwer and Rice Method

The Bouwer and Rice (1976) method for slug test analysis is based on combining a simple representation for flow to the well from the Thiem equation (steady state radial flow to a well) and continuity of fluids within the well. The flow equation takes the form

(C.1) $$Q_n = \frac{2\pi T_n s_n}{\ln(R/r_w)}$$

Importantly, in Eq. (C.1) it is assumed that the effective radius of influence $R$ is constant, so that there is a linear relation between the discharge $Q_n$ into the well and the LNAPL drawdown $s_n$. The continuity equation for fluids in the well is problematic only in terms of determining an appropriate effective well radius $r_e$, as discussed above. With the effective well radius determined and with use of the Kirkman J-ratio, the continuity equation takes the form

(C.2) $$Q_n = \pi r_e^{\,2} \frac{db_n}{dt} = \frac{\pi r_e^{\,2}}{J} \frac{ds_n}{dt}$$

Combining Eqs. (C.1) and (C.2) and integrating gives the generalized Bouwer and Rice formula for determining the LNAPL transmissivity

(C.3) $$\frac{ds_n}{s_n} = \frac{2\,J\,T_n}{r_e^{\,2}\ln(R/r_w)}dt \quad \rightarrow \quad T_n = \frac{r_e^{\,2}\ln(R/r_w)\ln(s_n(0)/s_n(t))}{2(-J)t}$$

# Appendix D: Cooper and Jacob/Jacob and Lohman Method

Jacob and Lohman (1952) investigated the non-steady flow to a free-flowing well with constant drawdown in an extensive confined aquifer. The model assumes that the well drawdown $s_w$ is constant (= difference between the static head measured during shut-in of the well and the outflow opening of the well). The discharge to the well is given by the following expression

(D.1) $$Q = 2\pi T s_w G(u_w)$$

The function G( ) is the Jacob-Lohman free-flowing discharge function and

(D.2) $$u_w = \frac{r_e^{\,2} S}{4Tt}$$

For all but extremely small values of t, Jacob and Lohman state that the function G( ) can be approximated by G ( ) = 2/W( ), where W( ) is the Theis well function. If, in addition, $u_w < 0.01$, the Theis well function may be approximated as follows:

(D.3) $$W(u_w) \cong \ln\left(\frac{0.561}{u_w}\right)$$

Thus Eq. (D.1) becomes

(D.4) $$Q = \frac{4\pi T s_w}{\ln\left(2.25Tt/r_e^{\,2} S\right)}$$

Equation (D.4) is the Cooper and Jacob (1946) approximation for the Theis well function for transient flow to a well in a confined aquifer with constant discharge and variable drawdown. Thus we find that Eq. (D.4) approximately applies both for constant drawdown and variable discharge, and for constant discharge and variable drawdown. During a baildown test both the LNAPL drawdown and discharge vary with time. With the C&J method, it is assumed that this relationship holds throughout the recovery period following baildown.

In application for baildown test analysis, Eq. (D.4) can be integrated between times $t_i$ and $t_{i+1}$ to give the volume inflow to the well as follows:

(D.5) $$V(t_i, t_{i+1}) = \int_{t_i}^{t_{i+1}} Q_n \, dt = \int_{t_i}^{t_{i+1}} \frac{4\pi T_n s_n}{\ln\left(2.25 T_n t / r_e^{\,2} S_n\right)} \, dt$$

The volume inflow to the well is separately measured (see Eq. 5.2). The calculated inflow volume from the right of Eq. (D.5) depends on the drawdown, which is also separately measured (see Eq. 5.1) and the parameters $T_n$ and $S_n$. By comparing the measured and calculated cumulative inflow volumes for each time increment, the parameters $T_n$ (and $S_n$) can be estimated using the method of least squares. The sum-square-difference (SSD) is calculated using

$$SSD = \sum_{J=1}^{N}\left[\sum_{i=1}^{J} Q_{ni}\Delta t_i - \sum_{i=1}^{J}\frac{4\pi T_n s_i}{\ln\left(2.25T_n\left(t_{i+1/2}-\Delta t_a\right)/r_e^2 S_n\right)}\Delta t_i\right]^2 \quad \text{(D.6)}$$

In Eq. (D.6), $N$ = number of time increments during the baildown test, $\Delta t_i = t_{i+1} - t_i$, $t_{i+1/2} = (t_i + t_{i+1})/2$, and $\Delta t_a$ = time adjustment factor that may be applied (see discussion in Section 6.2). The LNAPL transmissivity is estimated by minimizing the SSD in Eq. (D.6).

Fitting of data and estimation of LNAPL transmissivity is based on comparing the measured volume inflow to the well versus the calculated inflow using the Cooper and Jacob equation. It is of some interest to see how the data compares directly with the Cooper and Jacob equation. For this purpose, the ratio $Q_n/s_n$ is plotted as a function of time, as shown in Figure D.1. The red-dashed curve shown in this figure is calculated using the following:

$$\frac{Q_n}{s_n} = \frac{4\pi T_n}{\ln(2.25T_n(t-\Delta t_a)/r_e^2 S_n)} \quad \text{(D.7)}$$

In Figure D.1, the vertical dotted and dashed lines show the Time Adjustment $\Delta t_a$ and cut-off time, respectively. This figure is produced in the lower part of the C&J worksheet.

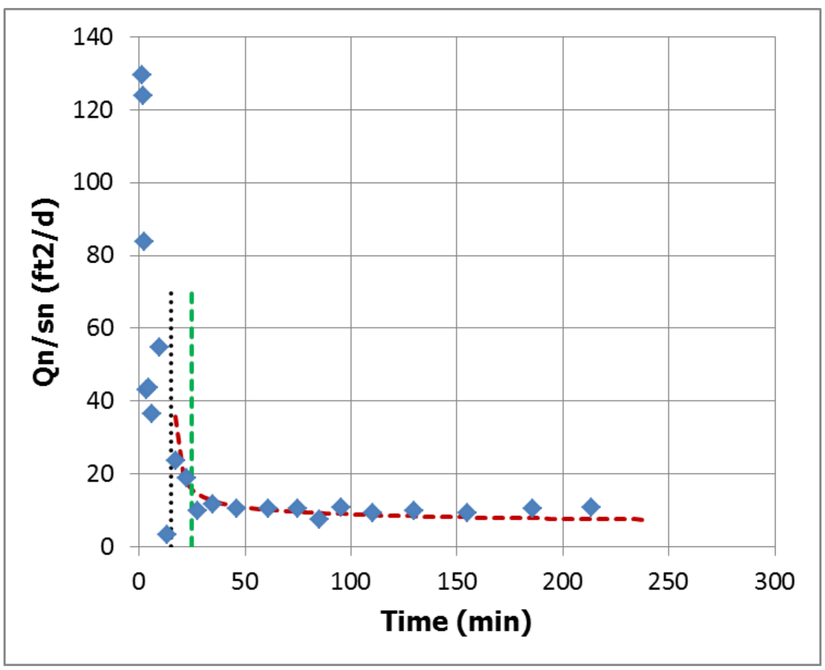



**Figure D.1. Comparison of Cooper&Jacob equation with baildown test data. Red-dashed curve = C&J equation; green-dashed line (vertical) = cutoff time; black-dotted line (vertical) = time adjustment**

# Appendix E: Cooper, Bredehoeft and Papadopulos Method

A third model that can be used to estimate LNAPL transmissivity is based on the work of Cooper, Bredehoeft and Papadopulos (1967). The model assumes that a slug of fluid is added to the casing of a well in a confined aquifer, and the change in fluid levels is monitored. The configuration is shown in Figure E.1. The initial height of the water column above equilibrium, $H_0$, is related to the volume of water, $V_w$, added through

(E.1) $$H_0 = \frac{V_w}{\pi r_c^2}$$

The boundary conditions at the well are specified as

(E.2) $$h(r_s^+, t) = H(t)$$

(E.3) $$2\pi r_s T \frac{\partial h(r_s^+, t)}{\partial r} = \pi r_c^2 \frac{dH(t)}{dt}$$

The first of these equations states that the formation head just outside of the well screen is equal to the water column head above equilibrium within the well. The second of these equations equates the water volume flux into the formation to the change in water volume storage within the well casing. The following solution is presented by Cooper et al. (1967):

(E.4) $$\frac{H(t)}{H_0} = F\left(\frac{r_s^2 S}{r_c^2}, \frac{Tt}{r_c^2}\right)$$

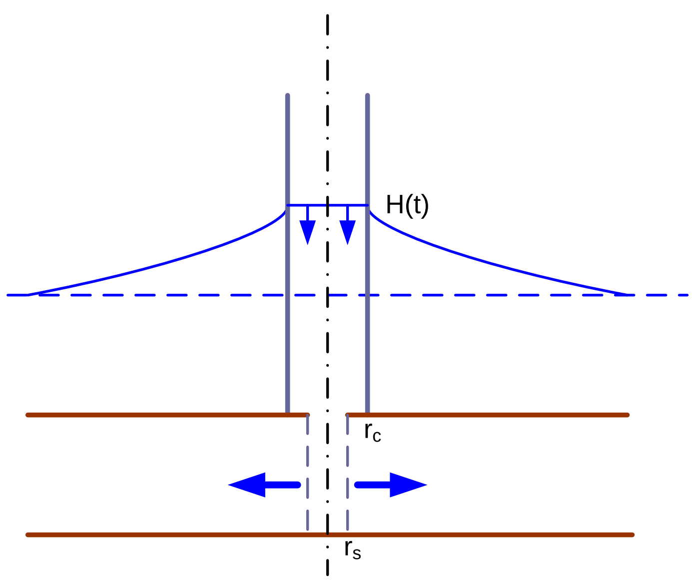



**Figure E.1. Configuration for the Cooper et al. (1967) slug test**

When applied to LNAPL in a well, the form of Eq. (E.4) and the boundary conditions specified by Eqs. (E.2) and (E.3) must be modified. Cooper et al. (1967) use the casing radius $r_c$ in calculation of changes in well-bore storage. The screen radius $r_s$ is used to designate the (radial) location where the LNAPL head (or drawdown) in the well-bore is equal to that in the formation. In analysis of LNAPL bail-down tests the effective radius $r_e$ plays the same role as $r_c$. The presence of the filter pack in a bail-down test makes identification of an equivalent radius to $r_s$ less obvious. A simple assumption is that $r_e$ plays an equivalent role to $r_s$ as well. Furthermore, the solution is written in term of the LNAPL drawdown, $s_n$. With Eq. (A.1), the boundary condition Eq. (E.3) can be written

(E.5) $$Q_n = -2\pi r_e T_n \frac{\partial s_n}{\partial r} = \pi\, r_e^{\,2} \frac{db_n}{dt} = \frac{\pi\, r_e^{\,2}}{J} \frac{ds_n}{dt}$$

These changes imply that Eq. (E.4) must be modified to

(E.6) $$\frac{s_n(t)}{s_n(0)} = F\left( S_n, \frac{(-J) T_n\, t}{r_e^{\,2}} \right)$$

Using the LNAPL drawdown ($s_{ni}$) versus time ($t_i$) data, a measure of how well the model fits the data is provided by the sum-square error specified by

(E.7) $$\sum_{i=1}^{N} \left[ \frac{s_{ni}(t_i)}{s_n(0)} - F\left( S_n, \frac{(-J) T_n\, t_i}{r_e^{\,2}} \right) \right]^2$$

In Eq. (E.7), the summation is over all data included in the analysis.

# Appendix F: Confined LNAPL

Figure F.1 (a) shows LNAPL confined beneath a fine-grain soil layer. The initial LNAPL thickness in an observation well, $b_{nR}$, depends on the water table elevation, $z_{aw}$, the LNAPL/water density ratio, $\rho_r$, and the initial elevation of the confined LNAPL-water interface in the formation and well, $z_{nw}$. During a baildown test the LNAPL discharge from the formation to the well is expected to initially be large, associated with rapid drainage of the filter pack and immediate well vicinity, and then the discharge should reach a constant magnitude that is determined by the radial LNAPL head difference experienced by the confined LNAPL. This head difference is equal to $(1 - \rho_r)(b_{nR} - b_{nW})$, and remains constant until the LNAPL column thickness in the well $b_n = b_{nW}$. For $b_n > b_{nW}$, the LNAPL head difference equals $(1 - \rho_r)(b_{nR} - b_n)$, and this magnitude decreases to zero ($b_n \rightarrow b_{nR}$) with further LNAPL inflow to the well. For this analysis it is assumed that the water table elevation remains constant and $J = -(1 - \rho_r)$. This is reasonable because for LNAPL under confined conditions, it is expected that the water transmissivity of the well will be much greater than the LNAPL transmissivity.

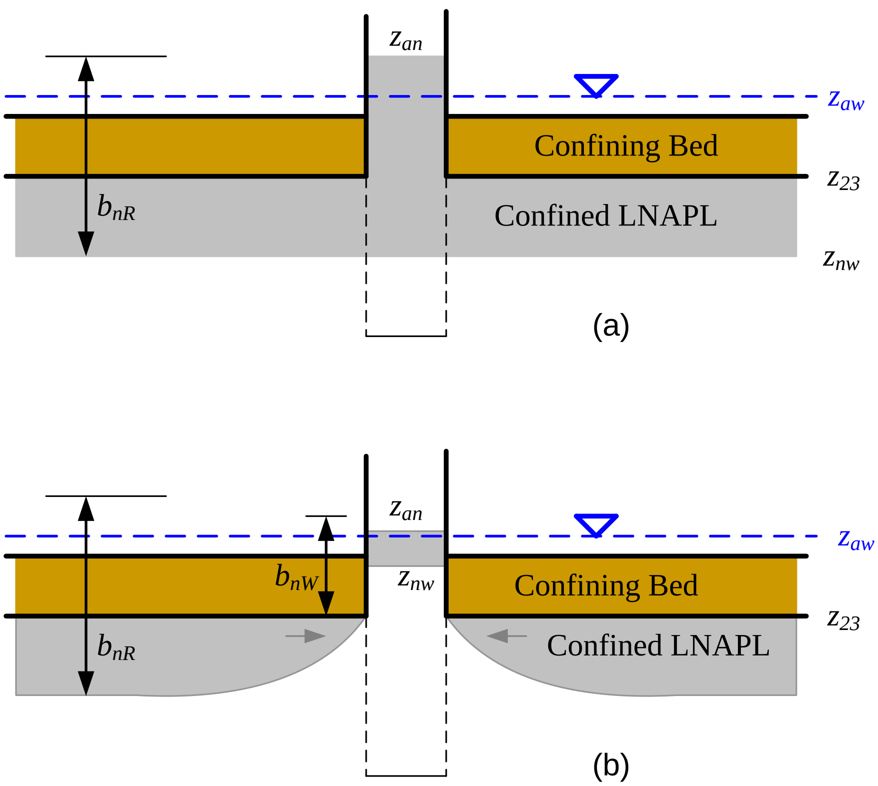



**Figure F.1 Confined LNAPL conditions**

The constant LNAPL discharge magnitude $Q_n$ for the period with $b_n < b_{nW}$ can be used to estimate the LNAPL transmissivity:

(F.1) $$T_n = \frac{Q_n \ln(R/r_w)}{2\pi(1-\rho_r)(b_{nR} - b_{nW})}$$

With the configuration shown in Figure F.1, the limiting effective well thickness is

(F.2) $$b_{nW} = \frac{z_{aw} - z_{23}}{\rho_r}$$

The corresponding LNAPL drawdown is

(F.3) $$s_{nW} = (1-\rho_r)\left(b_{nR} - \left(\frac{z_{aw} - z_{23}}{\rho_r}\right)\right)$$

Figure F.1 (b) shows the well and LNAPL configuration under conditions with $b_n < b_{nW}$, and suggests that the effective LNAPL thickness at the well is equal to $b_{nW}$. Actually, under these cut-off conditions for the LNAPL column in the well, there will be a seepage face extending downward from the facies contact at elevation $z_{23}$. The thickness of the seepage face is unknown, but it may be anticipated that the limiting effective LNAPL thickness at the well might be greater than calculated using Eq. (F.2). Correspondingly, the effective elevation $z_{23}$ as determined from the plot of $z_{nw}$ (DTW) vs. LNAPL discharge (Fig. 6 on the "Figures" worksheet) might have a lower elevation from that estimated using a geologic log.

# Appendix G: Perched LNAPL

Figure G.1 shows LNAPL perched upon a low-permeability unit. Analysis of perched LNAPL is essentially the same as that for confined LNAPL. The initial depth to product is $DTP_0$ and the depth to the top of the perching layer is $DZ_{12}$ (the top of the perching layer is at elevation $z_{12}$). During a baildown test the LNAPL discharge from the formation to the well is expected to initially be large, associated with rapid drainage of the filter pack and immediate well vicinity, and then the discharge should reach a constant magnitude that is determined by the radial LNAPL head difference experienced by the perched LNAPL. This head difference is equal to $DZ_{12} - DTP_0$, and remains constant until the LNAPL column thickness in the well, $b_n$, increases in magnitude because of LNAPL inflow from the formation, until $z_{an} = z_{12}$. For $z_{an} > z_{12}$, the LNAPL head difference equals $DTP - DTP_0$, and this magnitude decreases to zero ($DTP \rightarrow DTP_0$) with further LNAPL inflow to the well.

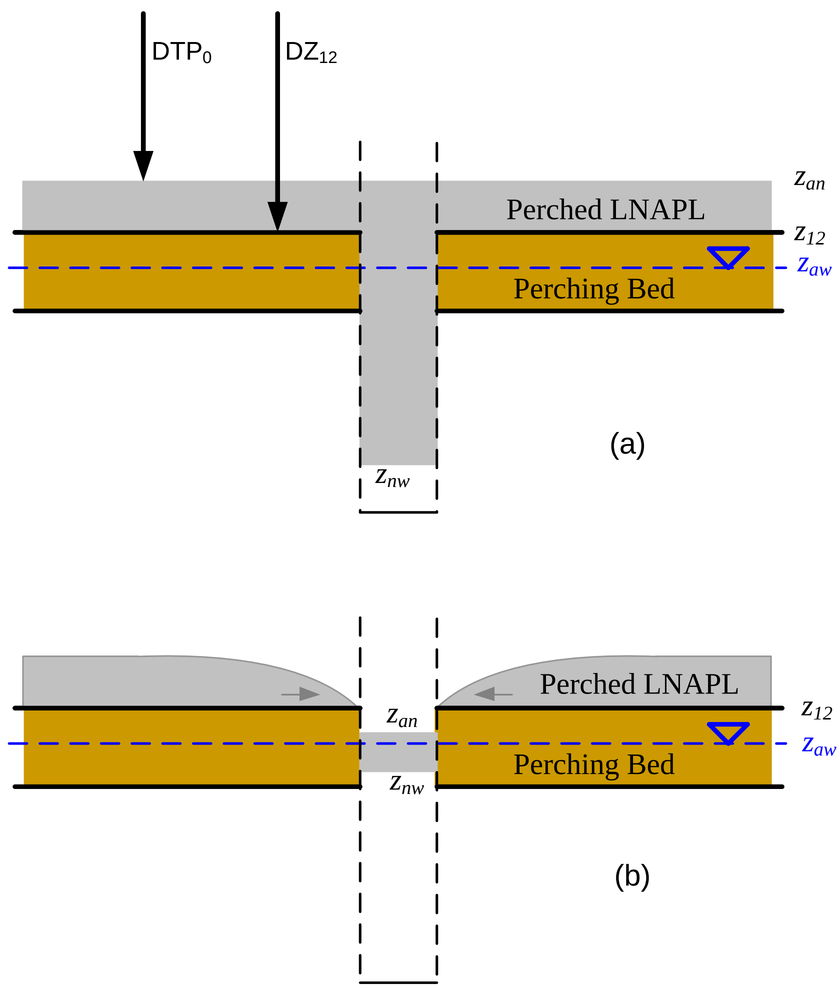



**Figure G.1. Perched LNAPL conditions**

The constant LNAPL discharge magnitude $Q_n$ for the period with $DTP > DZ_{12}$ can be used to estimate the LNAPL transmissivity:

(G.1) $$T_n = \frac{Q_n \ln\left(R/r_w\right)}{2\pi\left(DZ_{12} - DTP_0\right)}$$

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