HIGH RESOLUTION MOBILE NAPL INTERVAL IDENTIFICATION AND TRANSMISSIVITY CALCULATIONS FOR DNAPL (PATENT PENDING)

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BACKGROUND

Dense Non-Aqueous Phase Liquid (DNAPL) can be persistent in the saturated zone, and complex in terms of its distribution with multiple mobile NAPL intervals separated by lenses of lower permeability soils. These multiple MNIs can result in perched DNAPL separated by lower permeability rock and/or soils that yields exaggerated thicknesses of DNAPL in wells relative to the actual MNI thicknesses in the formation. To date, no method has satisfactorily accounted for these complexities in the measurement of DNAPL transmissivity, thus yielding artificially low DNAPL transmissivity values due to falsely large assumed drawdowns.

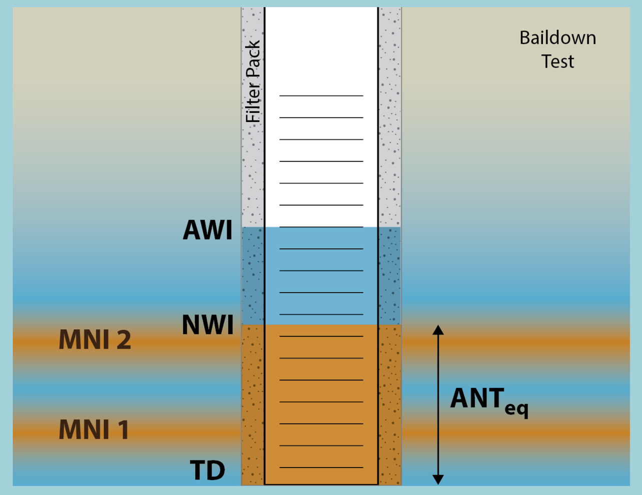


Figure 1. Conceptual diagram of DNAPL in a monitoring well at equilibrium. The measured thickness in the well will equilibrate from the top of the upper most MNI to the bottom of the well. This thickness does not necessarily correlate to the thickness of mobile DNAPL in the formation. Frequently, the mobile DNAPL is present in multiple, distinct seams. Assuming the DNAPL is continuous in the formation over the thickness measured in the well leads to an overestimation of the thickness in the formation, overestimation of the potential DNAPL drawdown during testing, and under estimation of DNAPL transmissivity.

The authors have developed patent pending procedures to identify each individual MNI across a given well screened interval, and to accurately calculate DNAPL transmissivity values for each MNI and for the well in the aggregate. The resulting information provides precise determination of the elevation and thickness of each MNI as well as the associated DNAPL transmissivity value for each MNI. This information can be used in a variety of ways to augment the conceptual site model (CSM) to better quantify potential DNAPL migration risk and pathway identification and design improved remedies. Perhaps more importantly, this information can be used to justify cessation of DNAPL recovery and site closure where no other risk driver exists and DNAPL recovery is the only driver for continued work.

EVALUATION METHOD

The DNAPL transmissivity measurement and calculation method is a modification of the baildown test presented in ASTM E2856, Standard Guide for Estimation of LNAPL Transmissivity.

Modifications to the ASTM E2856 methodology are required to account for the presence of multiple mobile LNAPL intervals as well as the DNAPL density, which is denser rather than lighter than water.

Drawdown versus Discharge Curve Interpretation for Single Mobile NAPL Interval

This interpretation methodology is presented in ASTM E2856 and is applicable where a single mobile NAPL interval is in connection with the well screen. This condition is common, though not universal, for LNAPL, but less common for DNAPL.

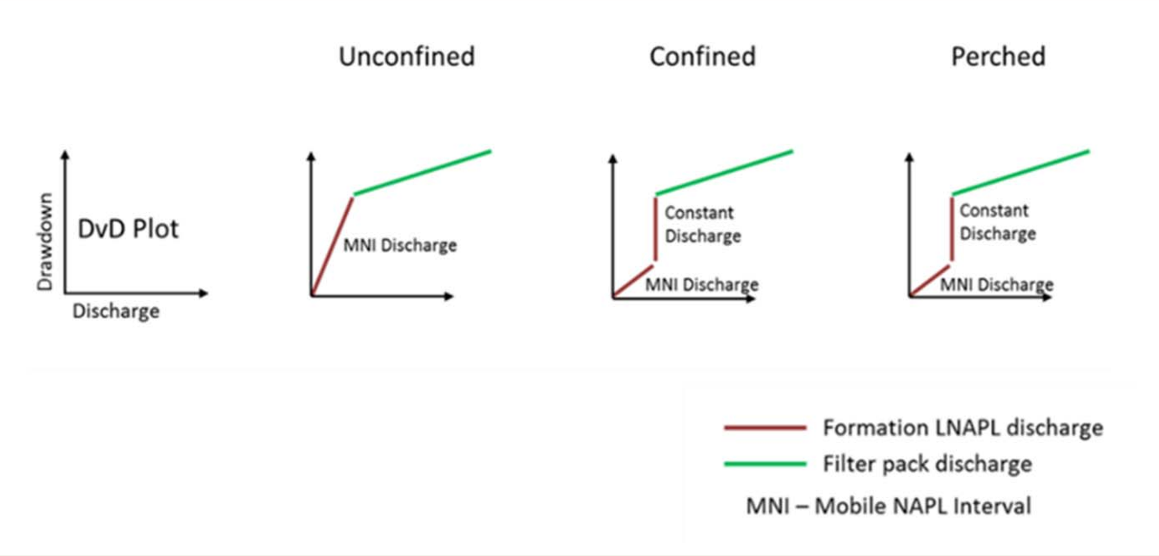
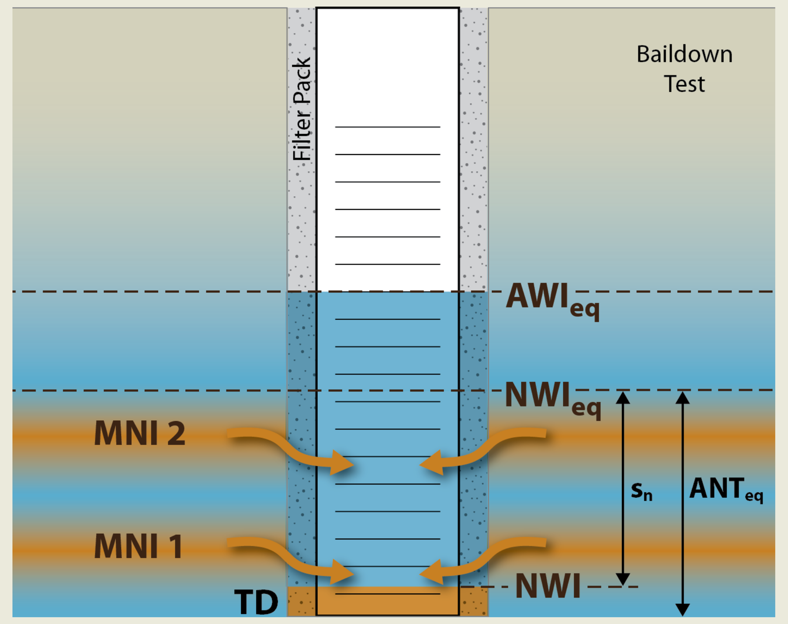


Figure 2. Conceptualized drawdown versus discharge plot for LNAPL recharging into a well from a single MNI under unconfined, confined, and perched conditions. Recharge begins in the upper right portion of the graph and proceeds to completion of the recharge dataset at the graph origin. NAPL drawdown and discharge are initially large, gradually decrease as the test proceeds, and are zero when equilibrium is achieved. Periods of decreasing drawdown with constant discharge are characteristic of perched and confined NAPL where the NAPL in the well is above or below MNI. Under all hydrogeological conditions, the sloping line at the end of the test represents the MNI. The thickness of the MNI is determined from the change in drawdown from the beginning to the end of the sloped line. The vertical location of the MNI can also be determined from the drawdown range.

Drawdown versus Discharge Curve Interpretation for Multiple Mobile DNAPL Intervals

Interpretation of the drawdown versus discharge curve is the critical modification that allows for accurate interpretation for multiple mobile DNAPL intervals. Interpretation of this curve provides the thickness of each mobile DNAPL interval as well as its individual discharge rate. With this data, transmissivity can be estimated via the Theim equation, as described in ASTM E2856.



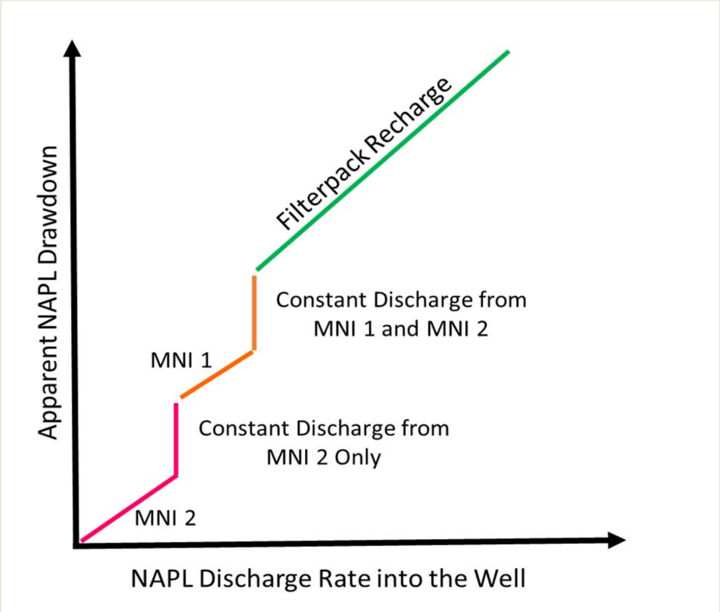


Figure 3 (left) and **4** (right). Conceptualized drawdown versus discharge plot for DNAPL recharging into a well screened across multiple mobile NAPL intervals separated by low permeability zones after the DNAPL was removed for a baildown test. Recharge begins in the upper right portion of the graph and proceeds to completion of the recharge dataset at the graph origin in the lower left because as DNAPL recharges into the well, both the discharge and the drawdown gradually return to zero (equilibrium) values. Vertical lines represent periods of constant discharge in between mobile NAPL intervals (Kirkman et al. 2012). Sloping lines connecting the constant discharge segments represent individual mobile NAPL intervals. The right-most constant discharge represents the maximum formation LNAPL discharge observed, which is the total discharge from MNI 1 and MNI 2. The left-most constant discharge represents the maximum discharge for MNI 2 only. The maximum discharge for MNI 1 can be obtained by subtracting the MNI 2 discharge from the total discharge. The thickness of each MNI is determined from the change in drawdown from the beginning to the end of each MNI sloping discharge line. The vertical location of each MNI can also be determined from this drawdown range.

RESULTS

DNAPL transmissivity was estimated for a site located in Massachusetts. The only remaining risk driver preventing site closure was the presence of DNAPL in wells. Historic recovery data was reviewed, and the recovery rate was below the regulatory de minimis threshold for all but one location. A baildown test was conducted to confirm the practicality of continuing DNAPL recovery in that well.

Data Interpretation

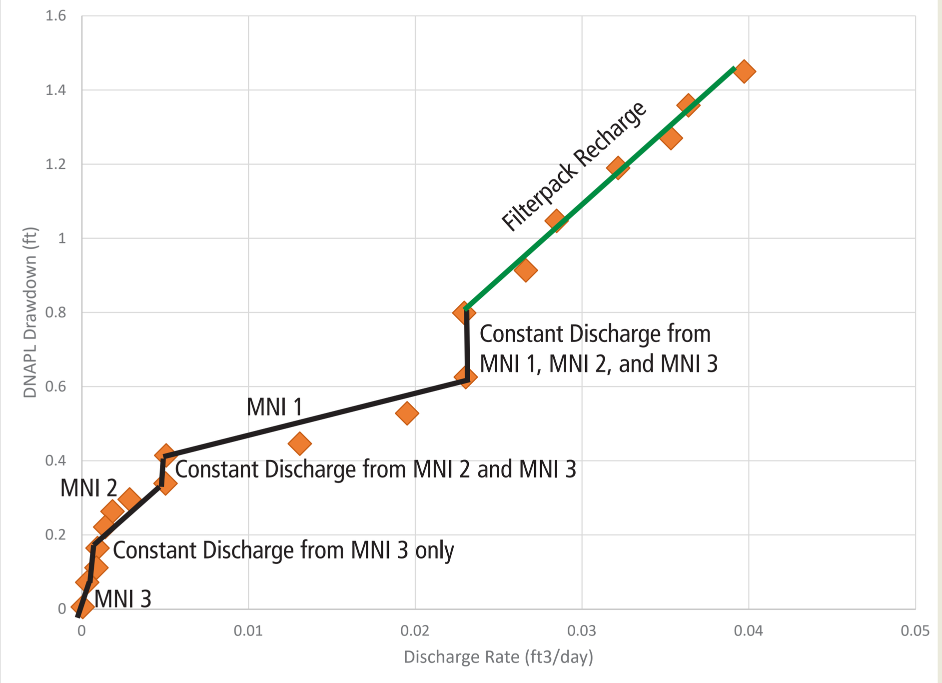


Figure 4 above). Annotated real-world DvDs of DNAPL recharge into the test well. Note that recharge begins in the upper right and proceeds to zero values for discharge and drawdown in the lower left at the completion of LNAPL recharge to equilibrium conditions at the conclusion of the baildown test. Three MNIs were identified based on alternating periods of constant discharge with decreasing drawdown and linearly decreasing discharge with decreasing drawdown. The geometries, discharge rates, and calculated LNAPL transmissivities for each MNI and for the well in aggregate are provided in Table 1.

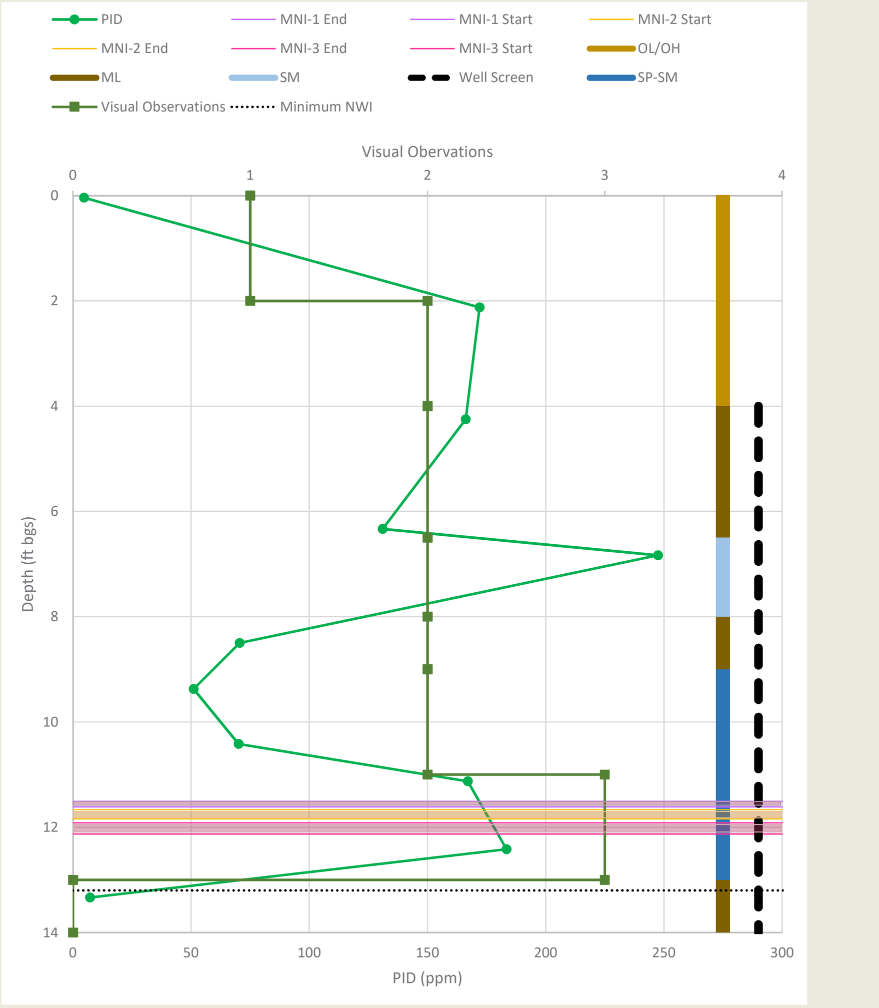


Figure 5 (above). Annotated well conceptual model presenting the MNI locations along with the well construction and qualitative / semi-quantitative data on the DNAPL presence and saturation. The three MNI locations are located within the more permeable soil consistent with the elevation of the elevated PID results and visual observations of DNAPL. The log described the presence of seams of DNAPL within a 2-foot segment from 11 to 13 ft bgs. The test was able to identify three, distinct mobile NAPL intervals with a total thickness of 0.5 feet.

Interval	Discharge Rate (ft^3/day)	MNI Top (ft bgs)	MNI Bottom (ft bgs)	MNI (ft)	Transmissivity (ft^2/day)
MNI-3	0.001	11.51	11.61	0.11	0.01
MNI-2	0.004	11.67	11.84	0.17	0.02
MNI-1	0.018	11.92	12.13	0.21	0.06
Aggregate	0.023	N/A	N/A	0.49	0.03

Table 1. Mobile LNAPL Interval discharges, geometries, and calculated LNAPL transmissivity values for the test wells

Site Closure

The test results indicated that the DNAPL transmissivity was well below the recoverable range. While DNAPL thicknesses of several feet accumulated in the well due to the well construction, the thickness of mobile DNAPL in the formation was only about 0.5 feet. Therefore, ongoing hydraulic recovery was not warranted. A Site Closure report was issued and all DNAPL wells on the property have been properly abandoned.

CONCLUSIONS

DNAPL transmissivity estimation via baildown testing can be successfully implemented where one or more mobile NAPL intervals are present in the formation based on careful interpretation of the drawdown versus discharge curve to identify the number, location, and thickness of individual mobile NAPL intervals as well as the DNAPL discharge rate and maximum drawdown associated with each.

Keys to successful implementation include:

- Understanding equilibrium conditions (equilibrium DNAPL thickness in the well) to predict test timeframe and endpoint.
- Collection of high resolution gauging data during the test (preferably using transducers) to identify small scale mobile NAPL intervals.
- Gauging the well until full equilibrium is achieved to allow for identification of each mobile NAPL interval as well as accurately identify its vertical position.
- Plan for extended test timeframes (months) for high viscosity / low recoverability locations.

Transmissivity is an increasingly accepted metric for sites with LNAPL to identify the endpoint of effective hydraulic recovery of LNAPL. Multiple states have written specific, numerical standards into their guidances and many more state agencies are accepting transmissivity thresholds on a site-specific basis. No guidances have been issued to date specifically for DNAPL transmissivity. While the fundamental physics are consistent for LNAPL and DNAPL mobility and recoverability, additional discussion and negotiation is anticipated with regulators until the practices are more widely utilized.

REFERENCES

ASTM. 2013. ASTM E2856-13, Standard Guide for Estimation of LNAPL Transmissivity, ASTM International, West Conshohocken, PA, 2013, www.astm.org., 68 pp.

Kirkman, Andrew J, Mark Adamski and J. Michael Hawthorne. 2012. Identification and Assessment of Confined and Perched LNAPL Conditions. Groundwater Monitoring and Remediation 33, no. 1:105-110.