Implementation of Butler (2020) for Slug Testing at Willamette River Site

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Step by Step Guidance for Improved Slug Test Data Acquisition and Processing

Our Task:
To determine the groundwater to surface water discharge rate at an uplands property adjacent to an in-river Superfund Site.

Monitoring Well Locations

Improved Methodology: Butler (2020) provides a means to process and interpret non-ideal slug test data. Given the potential wide range of K values and small (2-inch) monitoring well diameters, test success was expected to be variable.

Field Methodology Considerations

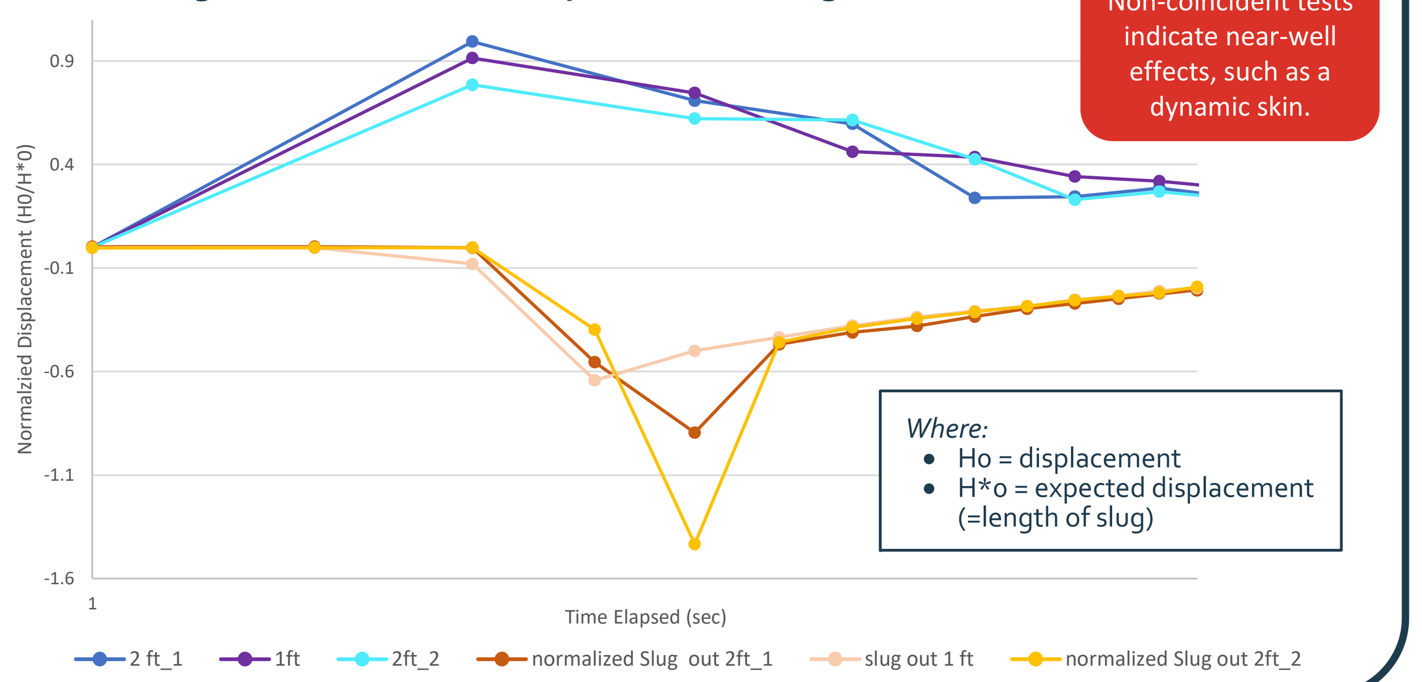
- Minimize near-well disturbances: redeveloped wells with suspected low-K skin observed during sampling. New wells installed with sonic drilling to minimize initial low-K skin formation.
- Multiple slug-in and slug-out tests to assess repeatability and direction-dependent effects.
- Completed with 1-foot and 2-foot solid PVC slugs close to well diameter for best balance of speed of test initiation (easily performed by one team member in one motion) with size of difference in initial displacement.
- Logged water levels with pressure transducers at 0.5-second intervals. Data reviewed immediately in the field to ensure recovery curve was captured; repeated tests in higher-K intervals at 0.1-second intervals because max displacement not apparent at grater logging interval.
- Monitored to ensure static levels pre- and post-test. Recovery was generally rapid with little drift.

Step 1

Plot normalized displacement (Ho/H*o) vs. time to determine whether data coincide and to select the test with the least noise.

Normalized tests should coincide. Non-coincident tests indicate near-well effects, such as a dynamic skin.

MW-104 Slug Test – Normalized Displacement vs Log Time



Step 2

Plot log normalized displacement vs. time to determine damping and filter pack drainage.

Damping is easier to see on a logarithmic plot and informs whether high- or low-K methods are appropriate.

Underdamped response (oscillatory response) -> high K

Overdamped and critically damped response -> low to moderate K

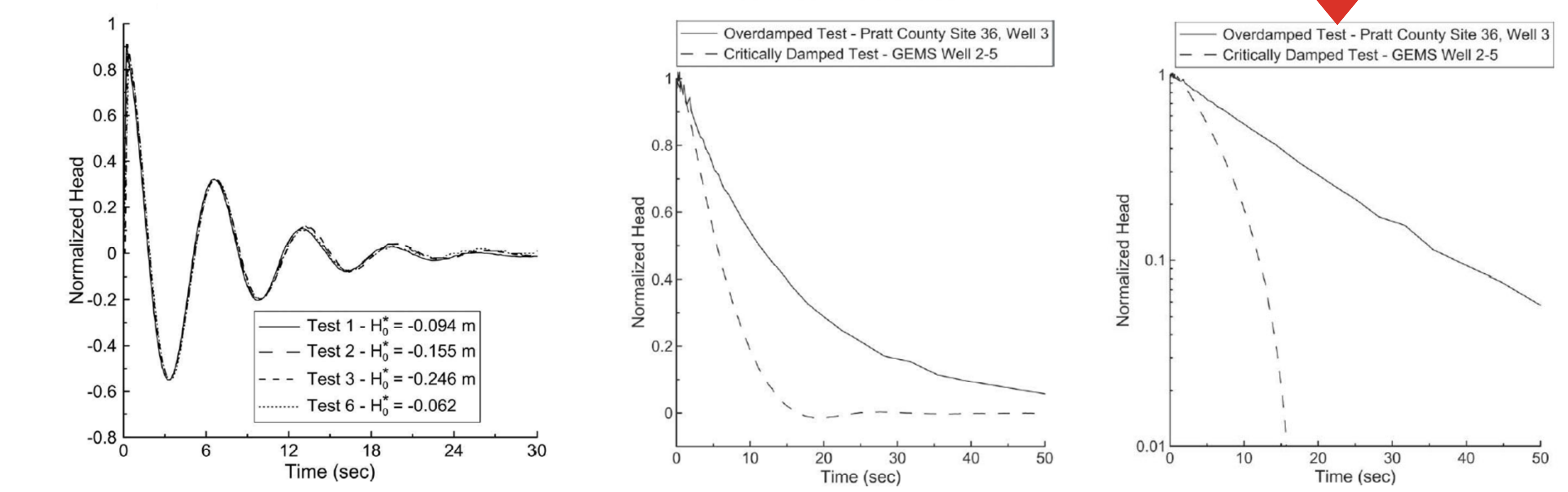
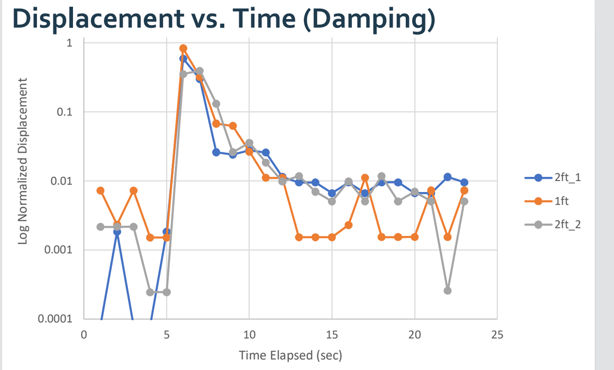


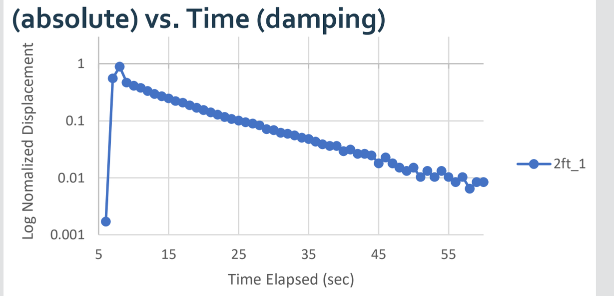
Image Source: The Design, Performance, and Analysis of Slug Tests, Second Editions. James J. Butler, Jr. CRC Press.

Actual Response

MW-02 Slug-In Normalized Log Displacement vs. Time (Damping)



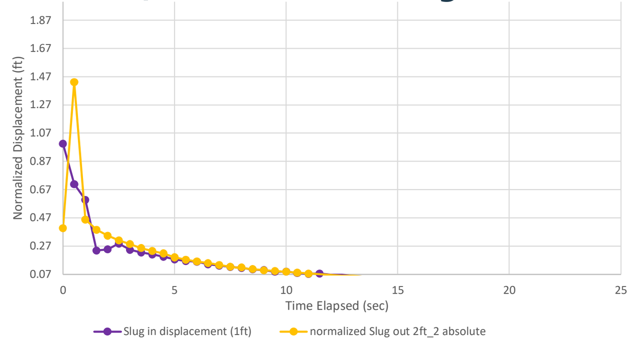
MW-104 Log Normalized Displacement (absolute) vs. Time (damping)



Step 3

Plot normalized displacement vs. time to determine potential filter pack drainage.

MW-104 Filter Pack Drainage



Filter pack drainage: present if steep drop in normalized displacement followed by less steep response.

Fit the solution to the curve after filter pack drainage.

Step 4

Follow flowcharts in Butler (2020) to select analysis method.

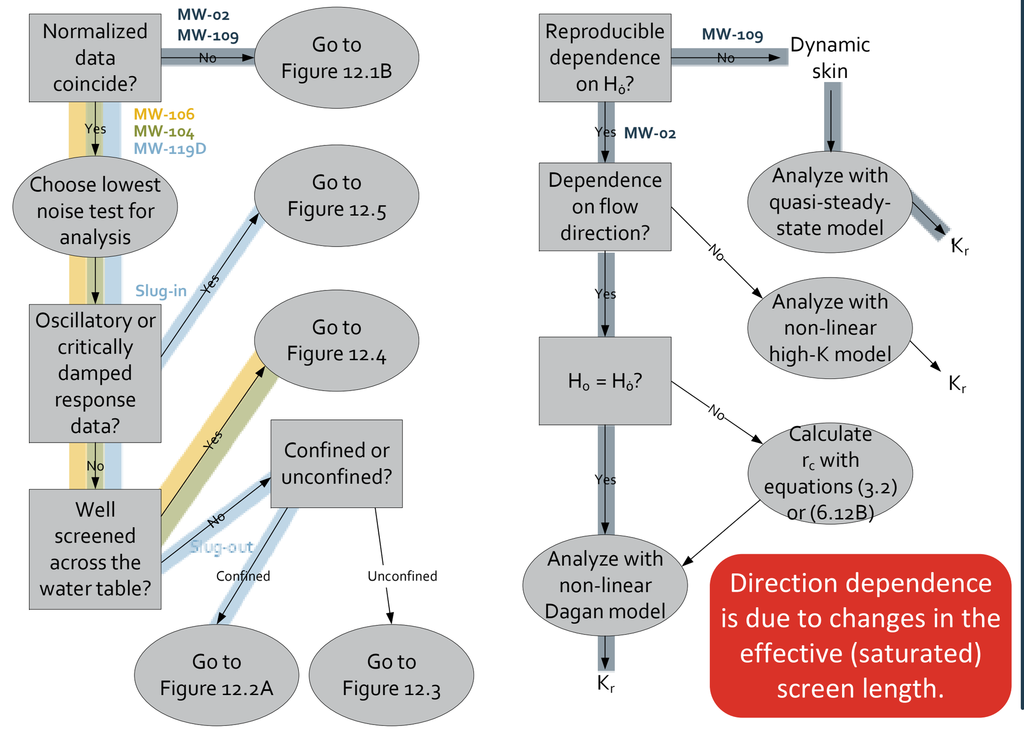
Slug Test Data Analysis Findings

Well ID/ Lithology	Data Coincide?	Direction Dependence	Slug-In Test with Least Noise	Slug-Out Test with Least Noise	Damping	Well Screen	Aquifer Type	Filter Pack Drainage?	Chart
MW-02 (Fill)	No	Yes (1)	2 ft	2 ft	Over (oscillatory)	Water Table	Unconfined	Not apparent	12.1B
MW-104 (Shallow Alluvium)	Yes	--	1 ft	2 ft	Over	Water Table	Unconfined	Yes	12.4
MW-106 (Overbank Deposit)	Yes	--	2 ft	2 ft	Over	Water Table	Unconfined	Yes	12.4
MW-109 (Fill)	No	No	2 ft (2)	2 ft (2)	Critically or Under	Water Table	Unconfined	Not apparent	12.1B
MW-119D (Deep Alluvium)	Yes	--	1 ft	1 ft	Critically or Under (slug-in)	Below Water Table	Semiconfined	Not apparent	12.5
					Over (slug-out)				12.2A

Fill | Shallow Alluvium | Overbank Deposit | Deep Alluvium

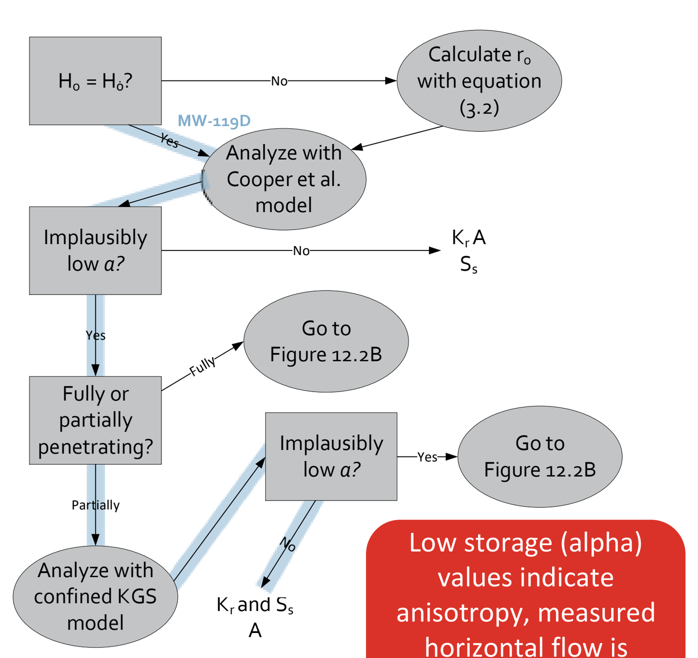
1. Non-coincident data related to shorter slug and differing response curves for slug-in and -out.
2. For quasi-steady state models, the fastest response test was selected.

Follow Butler 2020 **Figure 12.1A/B** to determine which solutions for determining K may apply.



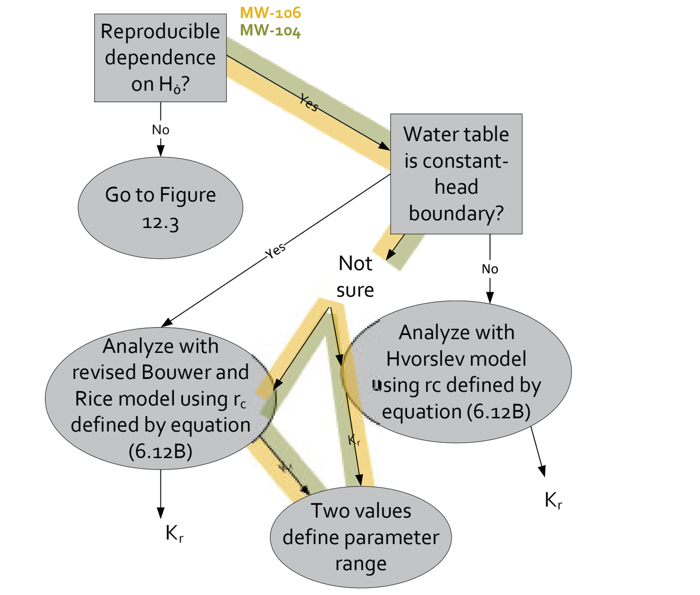
Direction dependence is due to changes in the effective (saturated) screen length.

Butler 2020 **Figure 12.2A** applied for confined/semi-confined unit.



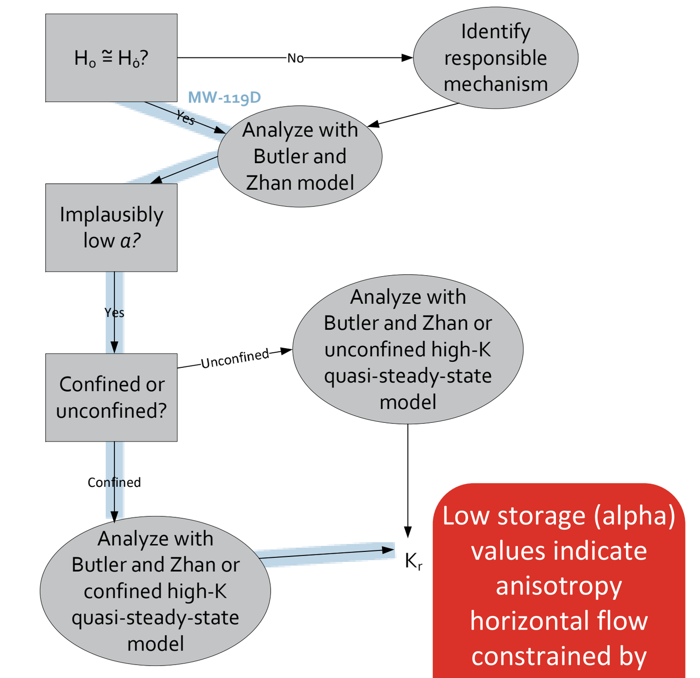
Low storage (alpha) values indicate anisotropy, measured horizontal flow is constrained by the screen interval.

Butler 2020 **Figure 12.4** applied to wells in shallow alluvium.



Linear slug test theory applies.

Butler 2020 **Figure 12.5** applied for confined/semi-confined unit.



Low storage (alpha) values indicate anisotropy horizontal flow constrained by screen interval.

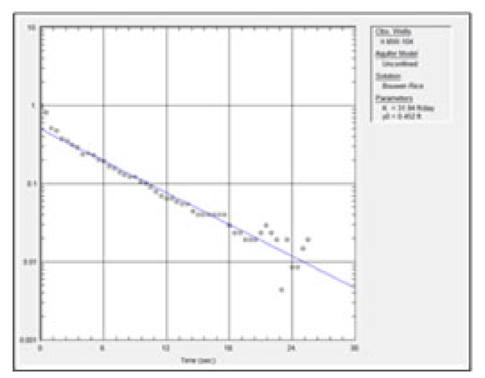
Notes from Data Processing:

- Displacements need to be recorded as absolute values.
- Data processing in Excel is time-consuming but necessary step for evaluation prior to importing data into AQTESOLV.
- Data coincided, except in fill.
- One oscillatory response observed in fill; damping was difficult to determine.
- Filter pack drainage was observed in several wells (fill and alluvium).

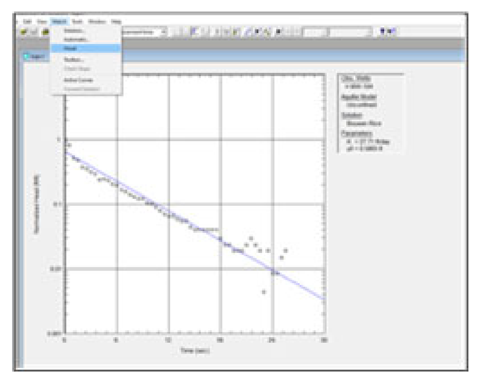
Step 5

Import transducer data into AQTESOLV for finding K solutions. Add data into AQTESOLV as shown below.

Automatic matching



Manual visual solution (drawing line manually)



Hydraulic Conductivity Solutions

Well ID/ Lithology	Analysis Method Per Butler 2020	Slug-In: Analysis Method Used in AQTESOLV	Slug-In: K (ft/day)	Slug-Out: Solution	Slug-Out: K (ft/day)
MW-02 (Fill)	Non-linear Dagan	Dagan	116	Dagan	No match
		Springer-Gelher (1)	130	Springer-Gelher (1)	331
MW-104 (Shallow Alluvium)	Bouwer-Rice	Bouwer-Rice	32	Bouwer-Rice	38
	Hvorslev	Hvorslev	44	Hvorslev	51
MW-106 (Overbank Deposit)	Bouwer-Rice	Bouwer-Rice	9	Bouwer-Rice	10
	Hvorslev	Hvorslev	14	Hvorslev	13
MW-109 (Fill)	Quasi-steady-state	Dagan (2)	136	Springer-Gelhar	164
		Springer-Gelhar (2)	No match	Dagan (2)	No match
MW-119D (Deep Alluvium)	Butler-Zhan	Butler-Zhan (slug-in)	67	Butler-Zhan (slug-in)	96
	Cooper et al.	NA	NA	Cooper et al.	29 – 57
	KGS	NA	NA	KGS	53

1. Used alternate solution because the recommended solution offered no match.
2. Used analysis methods available in software for underdamped formations.

Conclusions:

- Butler's decision trees do not work for every case. Butler 2020 does not provide guide that matches solutions in AQTESOLV in all scenarios.
- Extensive review of Butler 2020 and AQTESOLV software manuals are necessary prior to and during data processing.
- For tests in high-K formations, recommend exploring different solution methods for least noise slug-in and slug-out to verify solution yields an appropriate lower-bound conductivity estimate.
- Recommend exploring automatic and visual matching for solution methods.
- Data analysis using Butler's methodology highlights the limitations and uncertainties in using slug testing in higher conductivity formations. Most K estimates in these formations are considered a lower-bound for calculating discharge rates.