Slug_KGS-BnR-2019–A workbook for analyzing slug tests with Bouwer-Rice and KGS solutions

Slug tests frequently are analyzed with Bouwer and Rice (*1976*) to estimate hydraulic conductivities. Hydraulic conductivity is estimated by fitting a straight line to normalized displacements on a logarithmic axis vs. time on an arithmetic axis in a semi-log plot (Halford and Kuniansky, 2002). This approach works well for overdamped responses where water levels monotonically return to initial conditions.

Slug tests with oscillating or underdamped responses can be analyzed with the KGS model (Butler and Garnett, 2000), which simulates oscillating water levels. These oscillations result from the momentum of a water column in a well not being damped because the aquifer is transmissive. The KGS model smoothly simulates slug-test responses from underdamped to overdamped conditions and can be used in place of Bouwer and Rice (*1976*).

Multiple slug tests frequently occur in a well to verify repeatability and detect errors during data collection. More sequential slug tests typically occur where water levels can recover quickly (less than 5 minutes). These repeated tests create a time series of perturbed water levels (Figure 1). Water-level changes are normalized by dividing all changes during a test by the peak displacement. Peak displacement is the difference between maximum change and initial water level during each test. Absolute values of normalized displacements will be 1 or less.

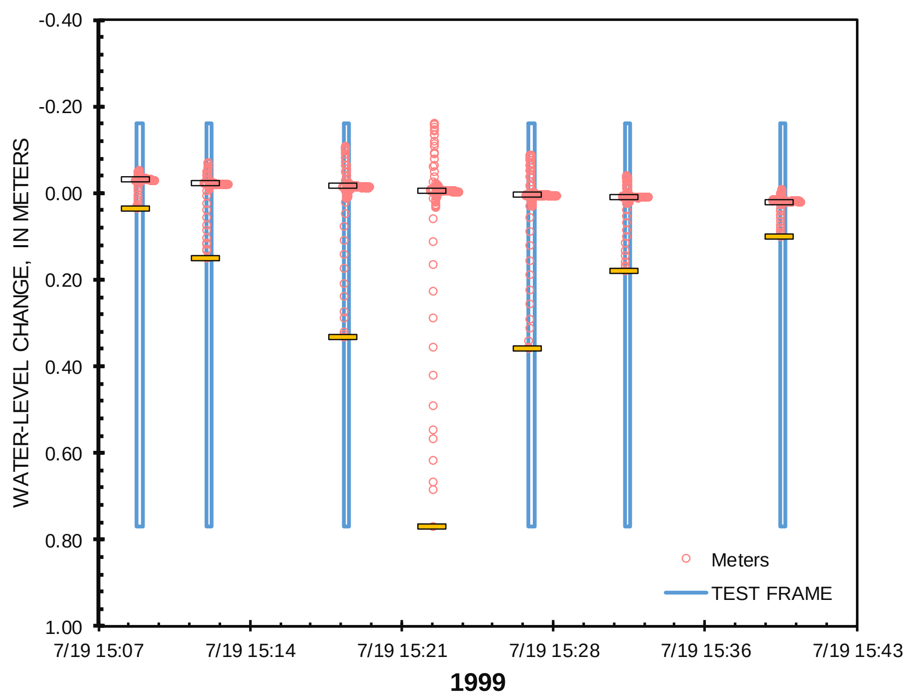


Figure 1.— Measured water-level displacements in well BB426 D3-6 from Butler and Garnett (2000) and periods for analyzing each slug test.

Measurement errors can occur during a slug test when transducer depth is affected by adding or removing a slug. Transducers can be lifted momentarily during slug removal, which increases apparent water-level change. For example, maximum measured displacement was overestimated during the 4th slug test in well BB426 D3-6 (Figure 2). This error can be corrected by adjusting estimated maximum water-level change or negated by not analyzing this slug test.

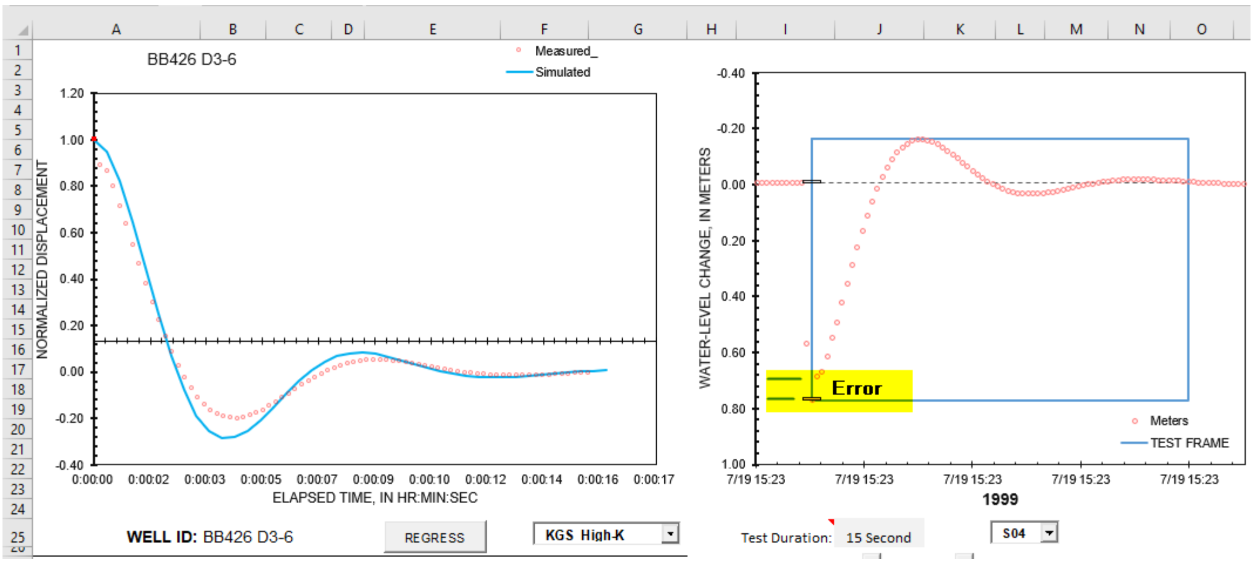


Figure 2.— Measurement error in peak displacement of 4th slug in well BB426 D3-6 (Butler and Garnett, 2000).

All normalized slug-test responses overlie one another and can be analyzed simultaneously (Figure 3). Slug-test responses coincide regardless of initial displacement during each test. Discrepancies between slug-test responses primarily result from misestimated initial displacements. A single simulated response is fit to all measured displacements and can be simulated with either Bouwer and Rice (*1976*) or KGS model (Butler and Garnett, 2000).

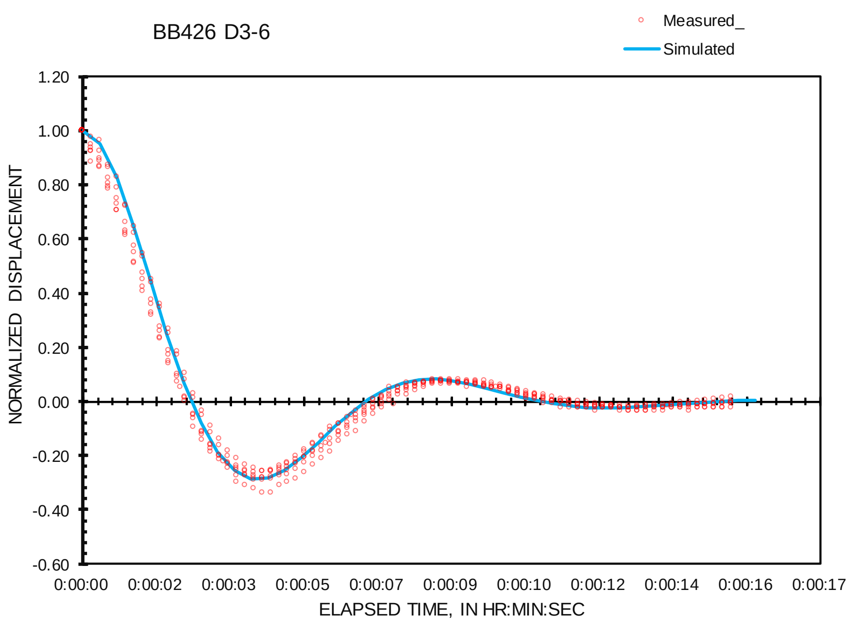


Figure 3.— Normalized displacements of 6 of 7 slug tests in well BB426 D3-6 and simulated displacement with the KGS solution (Butler and Garnett, 2000).

Interpretation of repeated slug tests with Bouwer and Rice (*1976*) or KGS models (Butler and Garnett, 2000) has been implemented in the workbook Slug_KGS-BnR-2019.xlsm (Figure 4). A continuous series of water levels with slug displacements are specified as depth to water or water level above the transducer. Measured water levels are plotted as a time series with periods of analysis superimposed (Figure 4). Individual slug tests and normalized displacements can be viewed to assess initial reference and maximum water-level estimates (Figure 2). These defining water levels can be changed for each slug test or analysis of a slug test can be rejected. Normalized displacements to be analyzed are plotted on semi-log or cartesian plots for analysis with Bouwer and Rice (*1976*) or KGS model (Butler and Garnett, 2000), respectively (Figure 4). Hydraulic conductivity (K) initially is estimated from a linear regression and refined graphically when interpreted with Bouwer and Rice (*1976*). Hydraulic conductivity and modulation factor (MF) are estimated simultaneously with Solver to fit the KGS model (Butler and Garnett, 2000). Hydraulic conductivity and modulation factor can be adjusted manually with spin buttons. Hydraulic conductivity is reported with a user defined number of significant digits.

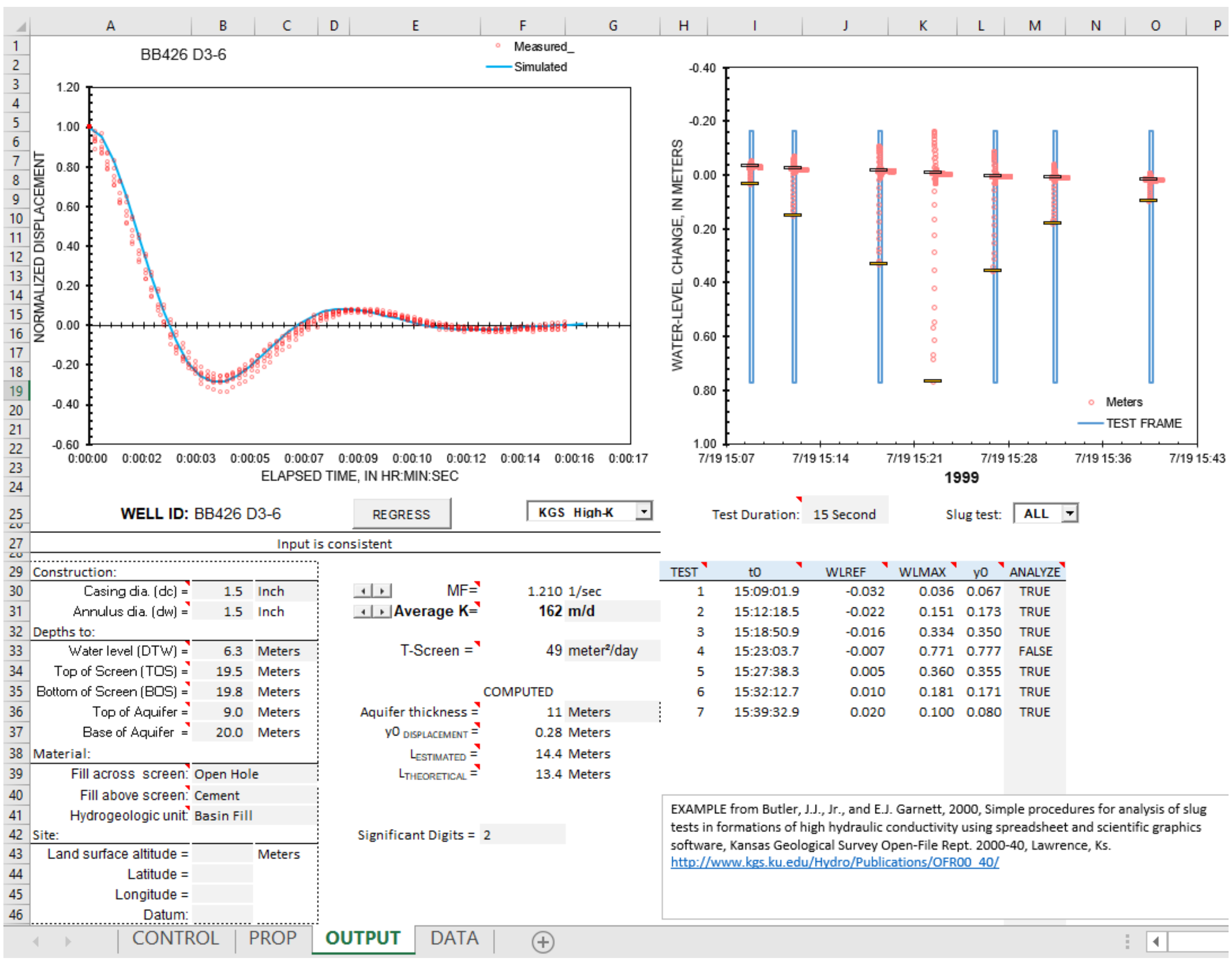


Figure 4.— OUTPUT page in Slug_KGS-BnR-2019.xlsm with data from well BB426 D3-6 from Butler and Garnett (2000).

Slug_KGS-BnR-2019.v3.xlsm and explanatory PDF can be downloaded with the following link. Another copy of the workbook, Slug_KGS-BnR-2019_BnR.v3.xlsm, is included with an overdamped response that was interpreted with Bouwer and Rice (*1976*). This workbook and other workbook applications are better used on local drives instead of a network drive. Slug_KGS-BnR-2019_*.v3.xlsm workbooks require that the Solver is installed and the workbook is not opened from within a zip file. The fitting routine will stop and warn the user if the Solver is not installed. User will be warned and workbook will be closed if opened from within a zip file.

Revisions

October 6, 2022—Revisions in version 2 include the following. Workbook was revised to accommodate response from a single slug without initial static water levels in the continuous measurements. Reference water level on data page changed from average of all values to last 5 percent if single slug measured. Reference remains average of all measurements if multiple slugs measured. Initialization macro called from DATA page revised so first entry is initial time and maximum water-level displacement for analyzing a single slug without initial static water levels.

October 18, 2022—Revisions in version 3 include the following. Safeguards were added to check that the Solver is installed and the workbook is not opened from within a zip file.

References

Bouwer, H., and R.C. Rice. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resour. Res. 12, no. 3: 423-428. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/WR012i003p00423

Butler, J.J., Jr., and E.J. Garnett, 2000, Simple procedures for analysis of slug tests in formations of high hydraulic conductivity using spreadsheet and scientific graphics software, Kansas Geological Survey Open-File Rept. 2000-40, Lawrence, Ks. http://www.kgs.ku.edu/Hydro/Publications/OFR00_40/

Butler, J. J., Garnett, E. J. and Healey, J. M. (2003), Analysis of Slug Tests in Formations of High Hydraulic Conductivity. Groundwater, 41: 620-631. doi:10.1111/j.1745-6584.2003.tb02400.x https://ngwa.onlinelibrary.wiley.com/doi/abs/10.1111/j.1745-6584.2003.tb02400.x

Halford, K.J. and E.L. Kuniansky 2002, Documentation of spreadsheets for the analysis of aquifer pumping and slug test data, USGS OF 02-197 https://pubs.usgs.gov/of/2002/ofr02197/

Slug_KGS-BnR-2019.xlsm Workbook

The workbook consists of three pages, DATA, OUTPUT, and PROP, and one hidden page, CONTROL. The hidden CONTROL page contains lookup tables and code for translating coordinates, which users should not need to edit. Aquifer test information, analysis, and results are summarized on the OUTPUT page. Well construction, aquifer thickness, aquifer material, site identifier, and remarks about the test are specified on the OUTPUT page. Additional information such as a well construction diagram and pictures of the site also could be pasted on the OUTPUT page. Time series of water-level changes from data loggers or manual measurements are entered on the DATA page. Ranges of hydraulic conductivities for hydrogeologic units are specified on the PROP page. The list should be modified to include more specific information about local hydrogeologic units in a study area.

DATA page

A continuous series of water levels with slug displacements are specified as depth to water or water level above the transducer in columns A-B from row 6 down (Figure 5). Time can be specified as decimal days, which is the convention in Excel, or as elapsed time in seconds, minutes, or hours as specified in cell A5. Units of measured water levels are specified in cell B5. An initial date and time (cell D3) are specified only if water levels are paired with elapsed times. Units of analyzed water-level changes can differ as specified in cell E5.

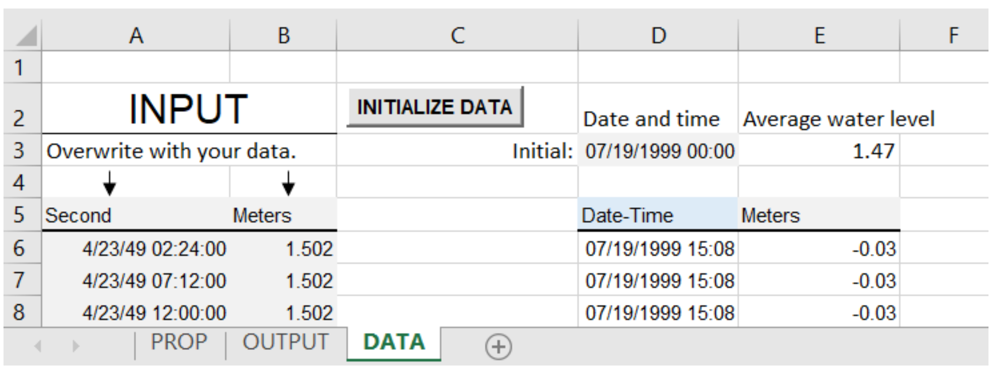
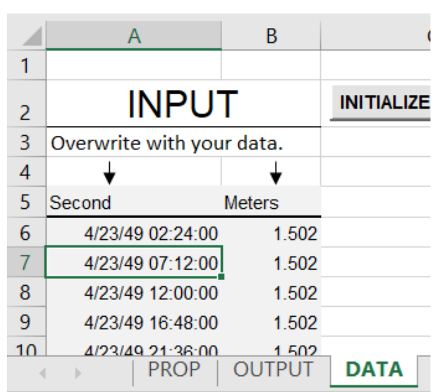
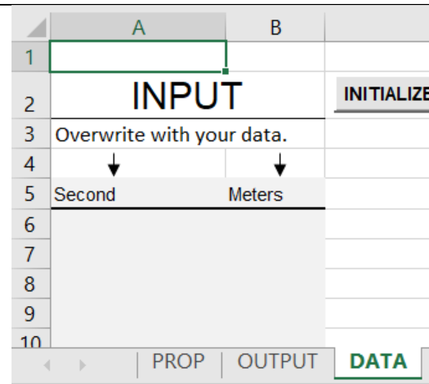
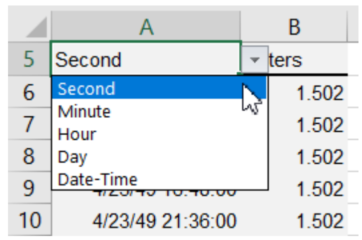
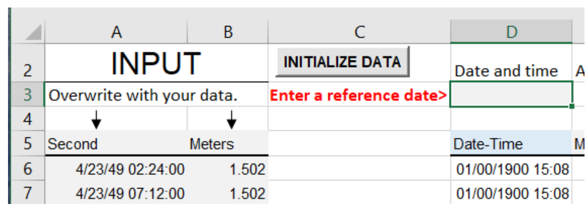


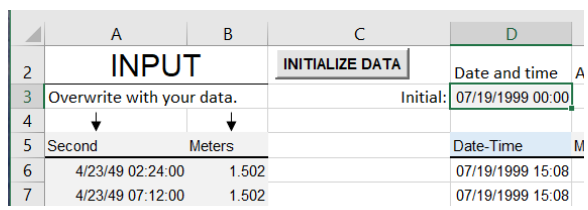
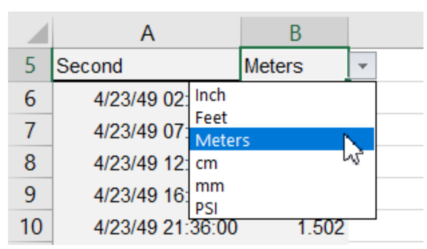
Figure 5.—DATA page in the Slug_KGS-BnR-2019 workbook where time series of water levels are specified.

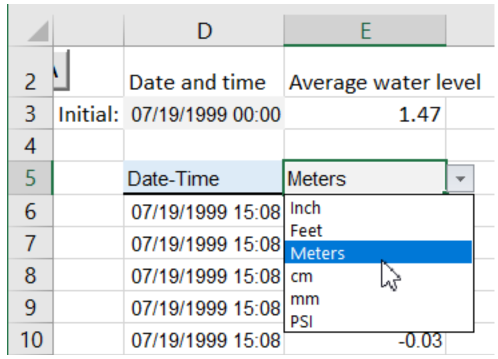
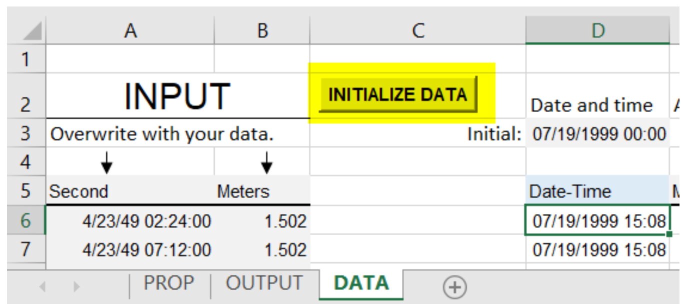
Data Page

Clear existing data between columns A and B from row 6 to the last entry.	 Empty cells before adding your data.

<table>
<tr>
<td></td>
<td>
</td>
</tr>
<tr>
<td>Specify units for time in cell A5.</td>
<td>
</td>
</tr>
<tr>
<td>A reference date is specified in cell D3 if elapsed times are specified in column A.

Error message changes to “Initial:” after filling cell D3.</td>
<td>

Changes to,

</td>
</tr>
<tr>
<td>Specify units for measured water levels in cell B5.</td>
<td>
</td>
</tr>
</table>

Specify units for depths to water that are analyzed in cell E5.	
Before returning to OUTPUT page, Press INITIALIZE DATA button in cell C2, which 1. Pairs equations on DATA and CONTROL pages with time-series data. 2. Identifies initial time, reference water level, and maximum water-level change for each slug. 3. Uniquely labels each slug.	

OUTPUT page—Site Information

Construction, depths, material, and site information are specified on the OUTPUT page (Figure 6). Most of this information is descriptive and does not affect estimated hydraulic conductivities, except for well construction. Aquifer material defines broad ranges of permissible hydraulic conductivities, which users should expand or replace with site specific limits. Hydraulic conductivity estimates are affected by casing diameter (cell C30) and screen length as specified by depths to top and bottom of screen (cells B34:B35).

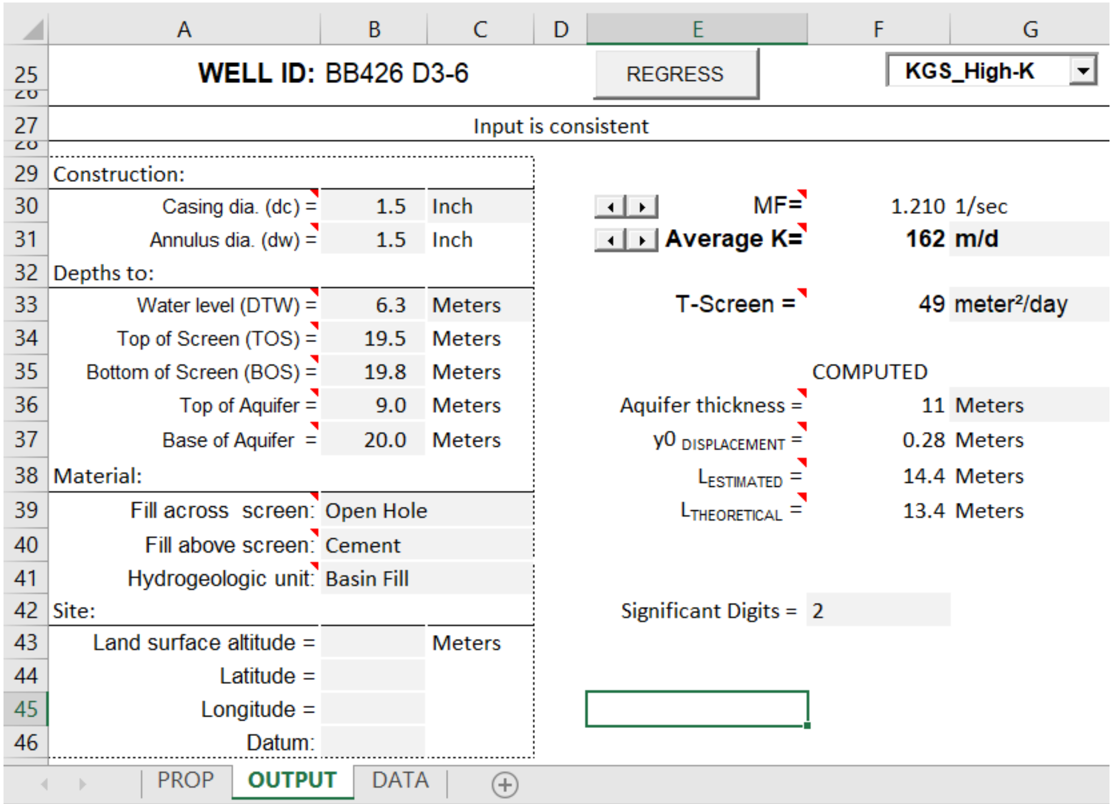
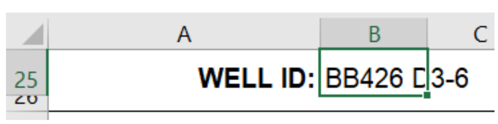
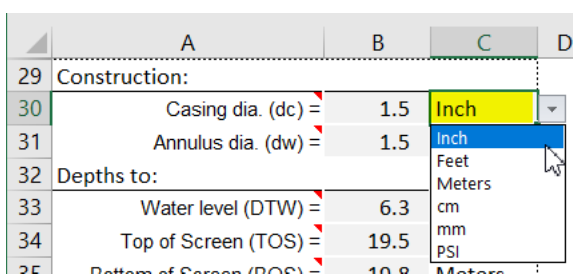
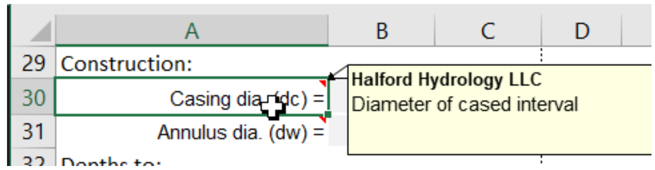


Figure 6.—Site information for slug-test analysis in the Slug_KGS-BnR-2019.xlsm workbook.

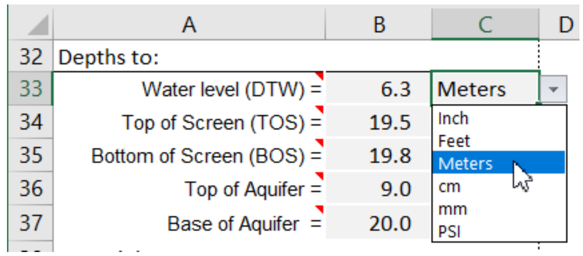
Site Information

Enter site identifier in cell B25.	
Diameters of casing and annulus are specified in cells B30 and B31. Select units from pull-down menu in cell C30.	

Commented cells further describe expected input.



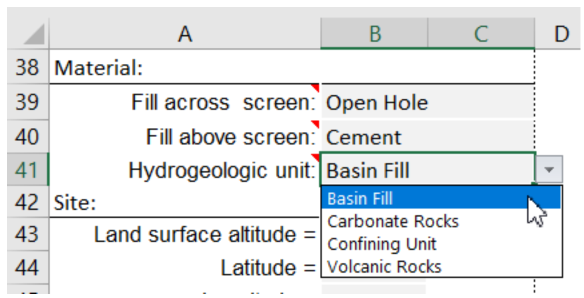
Depths to static water level, top of screen, bottom of screen, top of aquifer, and bottom of aquifer are specified in cells B33:B37. Select units from pull-down menu in cell C33.



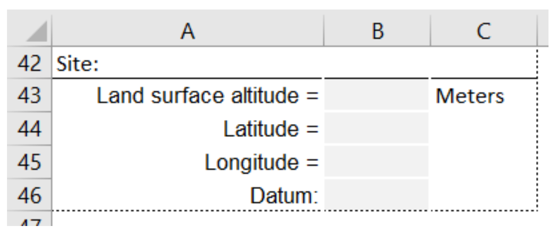
Filled annular material across screen and above screen are specified in cells C39 and C40.

Hydrogeologic unit is specified in cell C41 and defines range of permissible hydraulic conductivities.

Select materials from pull-down menus in cells C39:C41.



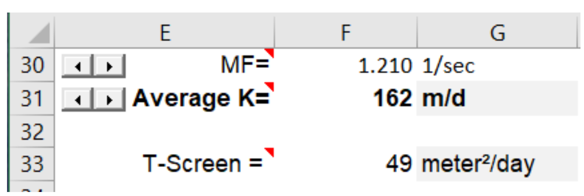
Site information is for completeness of reporting and is not otherwise used.



Hydraulic conductivity (K, cell F31) adjusted to fit Bouwer-Rice and KGS models. Modulation factor (MF, cell F30) adjusted to fit KGS model.

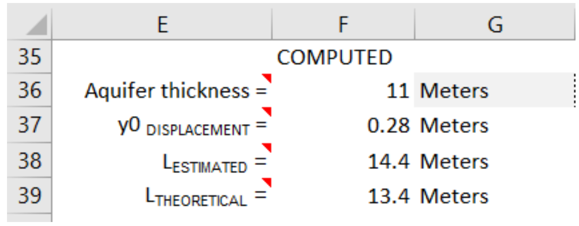
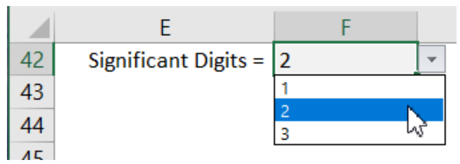
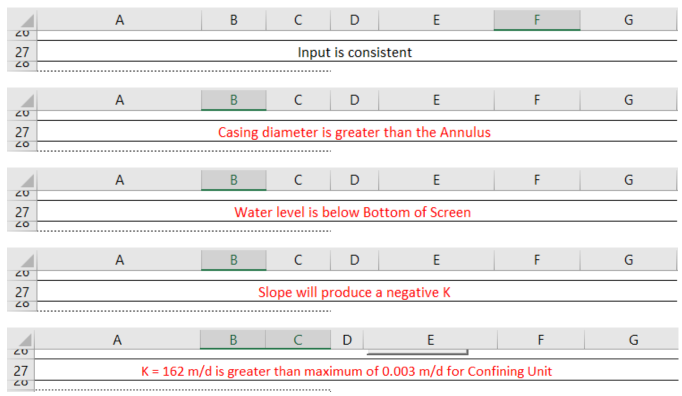
K and MF parameters are estimated with regression tools or manually with spin buttons (cells E30:E31). K and MF parameters in cell F30:F31 are ***NOT*** changed directly.

Transmissivity is limited to length of screened interval because slugs typically displace small volumes of water, relative to pumping tests.



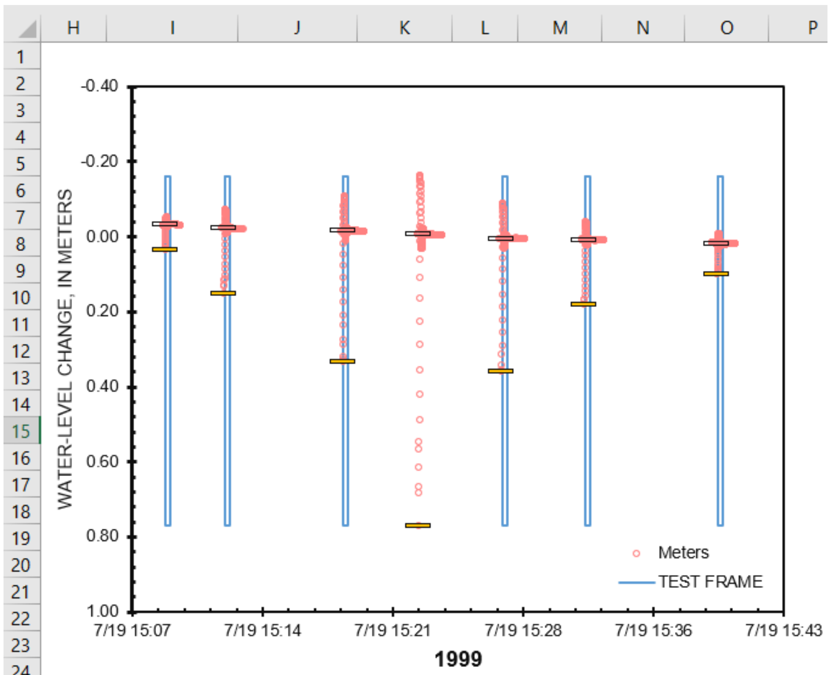
<table>
<tr>
<td>Aquifer thickness (F36) used for empirical factors in Bouwer and Rice.

y0 (F37) is average of all measured displacements.

$L_{ESTIMATED}$ (F38) and $L_{THEORETICAL}$ (F39) are water-column lengths from fitting KGS model and well construction, respectively.</td>
<td>
</td>
</tr>
<tr>
<td>Significant digits specified in cell F42 affects reported hydraulic conductivity (K) and transmissivity of screened interval (T) in cells F31 and F33.</td>
<td>
</td>
</tr>
<tr>
<td>Error conditions are reported in row 27. “Input is consistent,” is reported when no errors exist.</td>
<td>
</td>
</tr>
</table>

OUTPUT page—Review Slug Tests

Measured water levels are plotted as a time series with periods of analysis superimposed on the OUTPUT page (Figure 6). Test duration for analysis is specified from a pull-down menu in cell J25. Initial time, reference water level, maximum water-level change, and decision to analyze are tabulated for each slug test below row 29. Initial time, reference water level, and maximum water-level change are estimated automatically with INITIALIZE DATA button on DATA page. Each slug test can be selected and reviewed individually with pull-down menu in cell M25 (Figure 6). Reviewing each slug test response is recommended strongly because automatic estimates of initial time, reference water level, and maximum water-level change can be erroneous.



Test Duration: 15 Second   Slug test: ALL

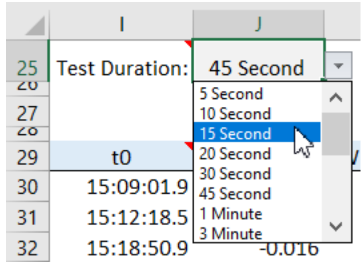
TEST	t0	WLREF	WLMAX	y0	ANALYZE
1	15:09:01.9	-0.032	0.036	0.067	TRUE
2	15:12:18.5	-0.022	0.151	0.173	TRUE
3	15:18:50.9	-0.016	0.334	0.350	TRUE
4	15:23:03.7	-0.007	0.771	0.777	FALSE
5	15:27:38.3	0.005	0.360	0.355	TRUE
6	15:32:12.7	0.010	0.181	0.171	TRUE
7	15:39:32.9	0.020	0.100	0.080	TRUE

PROP OUTPUT DATA

Figure 7.—Information for reviewing each slug test in the Slug_KGS-BnR-2019.xlsm workbook.

Review Slug Tests

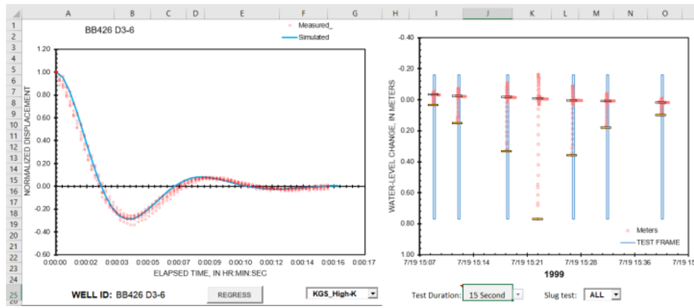
Test duration specified from pull-down menu in cell J25. This is period where slug-test data are normalized and compered to simulated responses for interpretation.



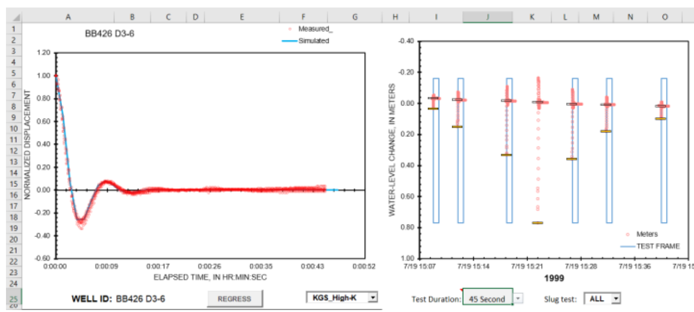
Test duration is indicated by test frames in the time-series of water-level changes and visible data in the normalized-displacement plot. See differences between 15 and 45 second test durations.

Automatic estimates of initial time, reference water level, and maximum water-level change will be wrong if significant mismatch exits between test duration in cell J25 and duration of slug recovery.

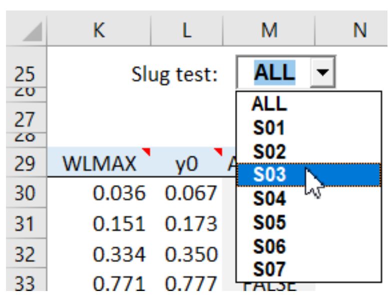
Change test duration in cell J25 to a representative period and press INITIALIZE DATA button on DATA page to revise estimates.



Test duration increases from 15 to 45 seconds,

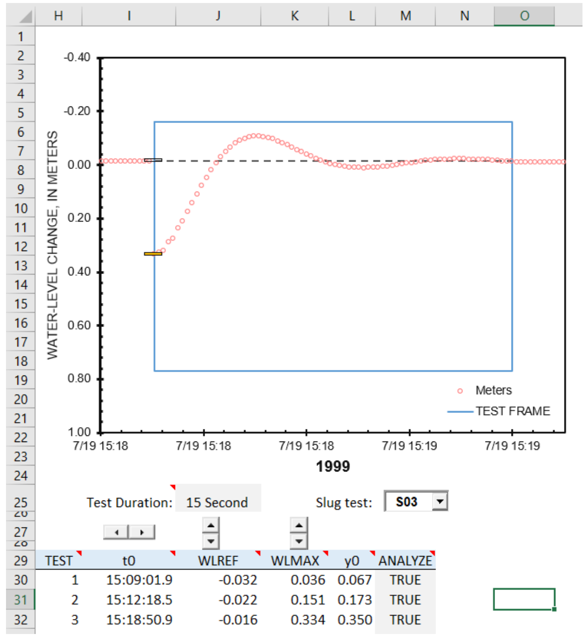


Select a slug test with pull-down menu in cell M25.



Time series will be windowed to period around test duration, which is the third slug, S03, in this example.

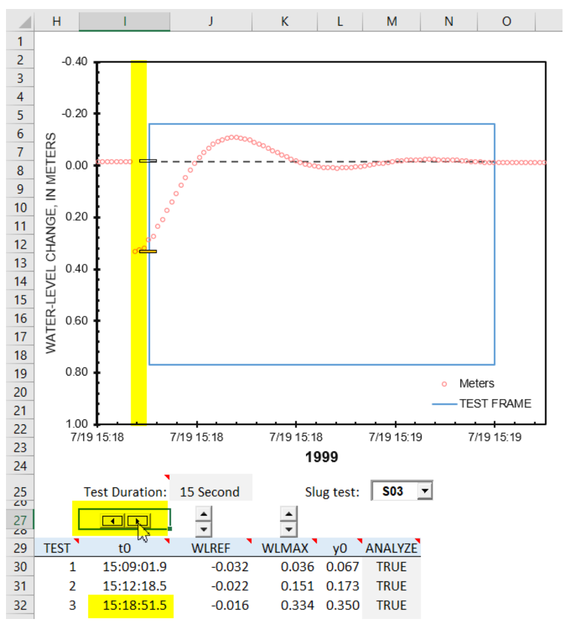
Spin buttons appear in row 27 for adjusting initial time, reference water level, and maximum water-level change.



Initial time, t0, can be adjusted with the spin button in column I.

Adjustments change t0 in cell I32 in this example because slug test S03 is selected.

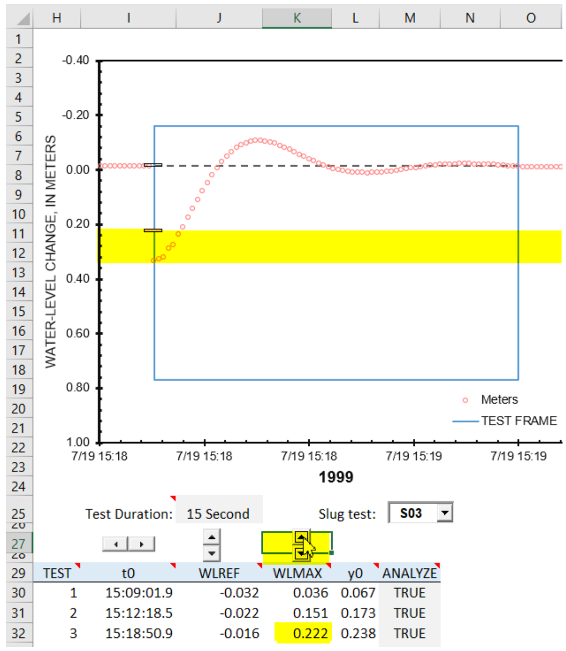
Initial time, t0, in cell I32 also could be edited directly.



Maximum water-level change, WLMAX, can be adjusted with the spin button in column I.

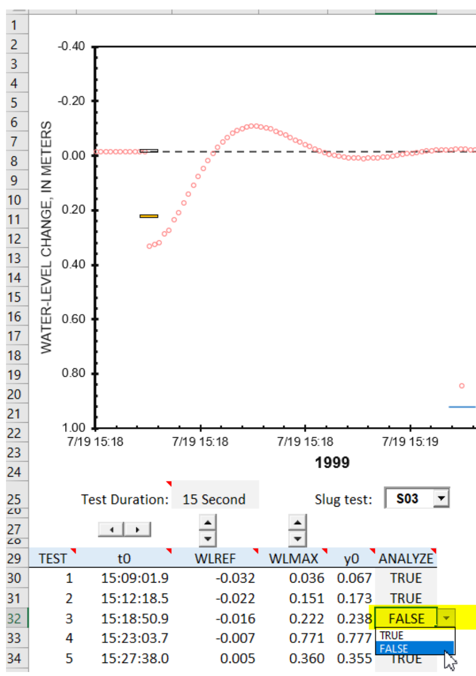
Adjustments change WLMAX in cell K32 in this example because slug test S03 is selected.

Maximum water-level change, WLMAX, in cell K32 also could be edited directly.



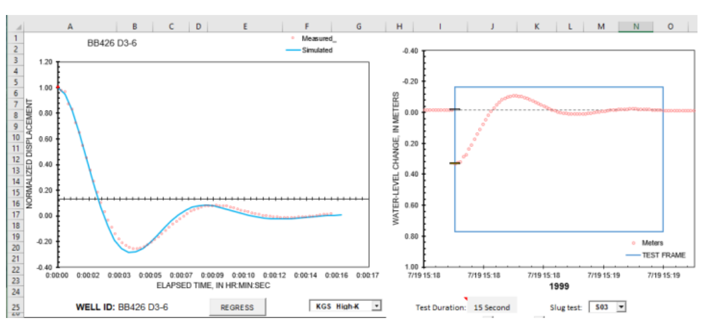
Test frame for slug test S03 will disappear when cell L32 is changed from TRUE to FALSE.

Displacement data from slug test S03 will ***NOT*** be normalized or analyzed when cell L32 is FALSE.



Normalization and analysis are limited to a single slug test as specified in cell M25.

Change cell M25 to ALL to analyze slug tests *en masse*.



OUTPUT page—Estimating hydraulic conductivity

Normalized displacements are plotted on semi-log or cartesian plots for analysis with Bouwer and Rice (*1976*) or KGS model (Butler and Garnett, 2000), respectively (Figure 8). Hydraulic conductivity (K) initially is estimated from a linear regression and refined graphically when interpreted with Bouwer and Rice (*1976*). Hydraulic conductivity and modulation factor (MF) are estimated simultaneously with Solver to fit the KGS model (Butler and Garnett, 2000). Hydraulic conductivity and modulation factor can be adjusted manually with spin buttons. Hydraulic conductivity is reported with a user defined number of significant digits.

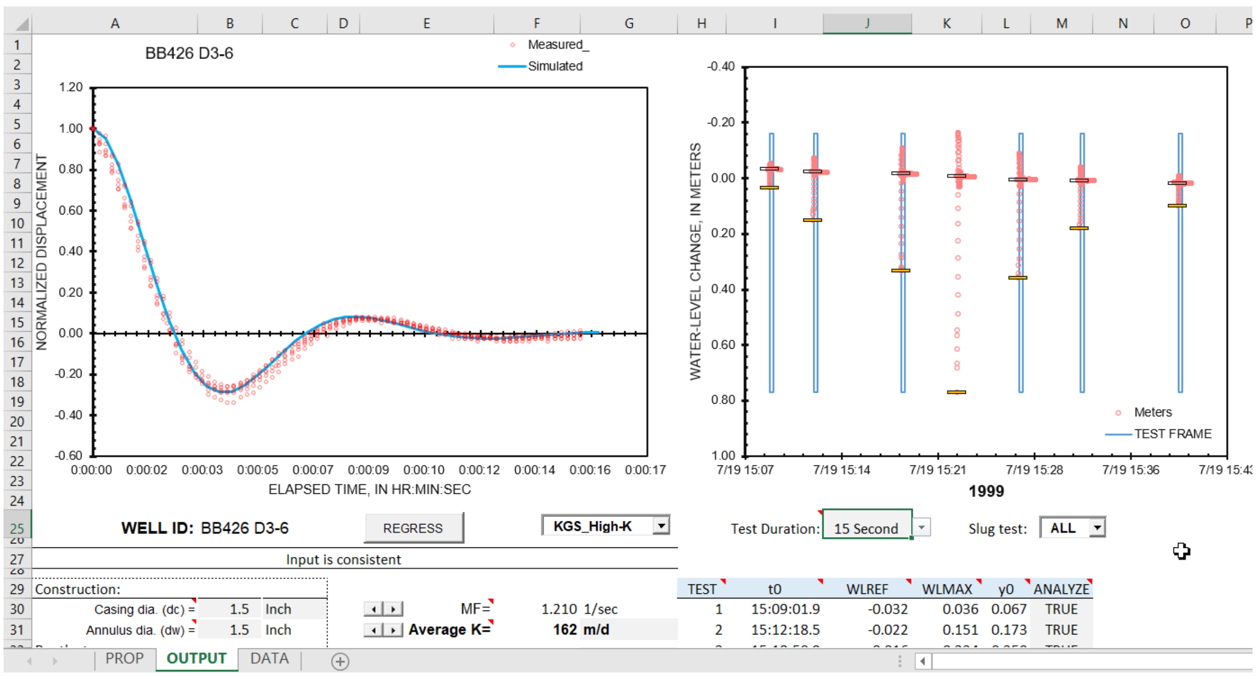
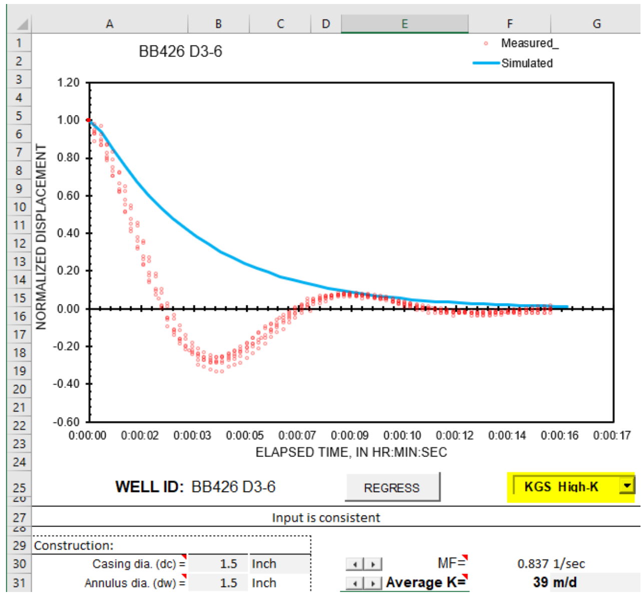
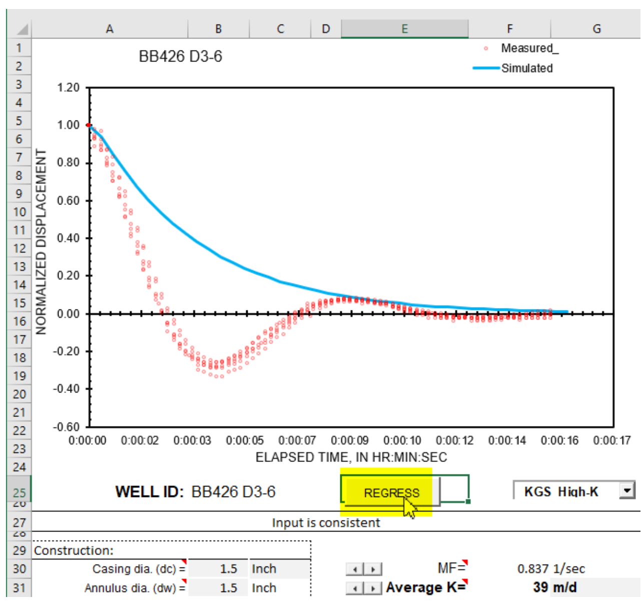
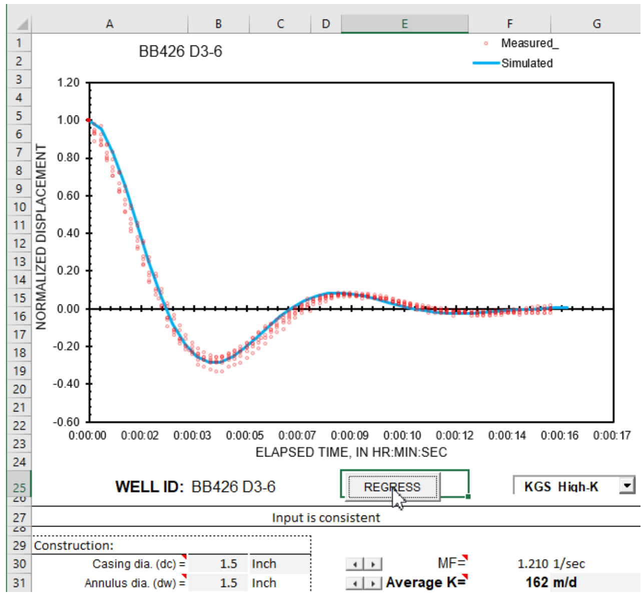


Figure 8.—Estimating hydraulic conductivity from slug tests in well BB426 D3-6 with the KGS model (Butler and Garnett, 2000) in the Slug_KGS-BnR-2019.xlsm workbook.

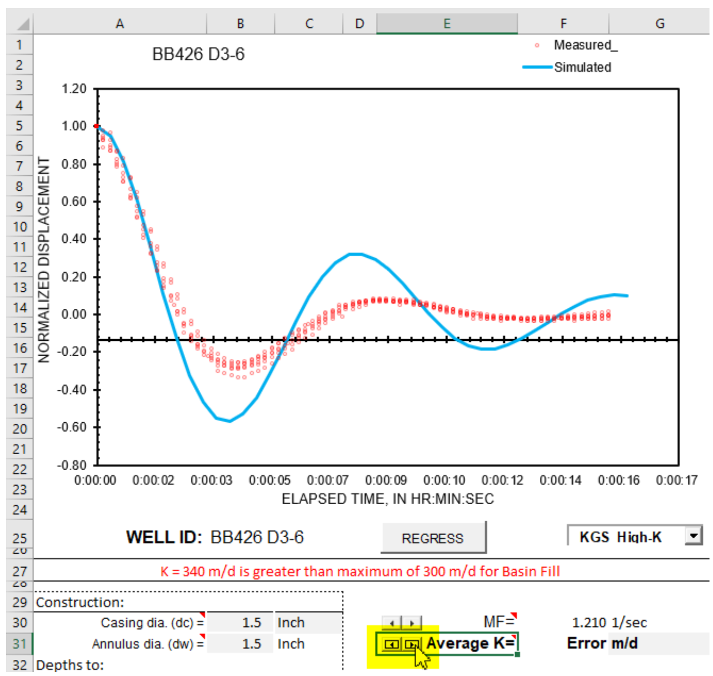
Estimating Hydraulic Conductivity—KGS model

Select KGS model with KGS_High-K from pull-down menu in cell F25.	
Press "REGRESS" button (cell E25) to estimate hydraulic conductivity (K, cell F31) and modulation factor (MF, cell F30).	

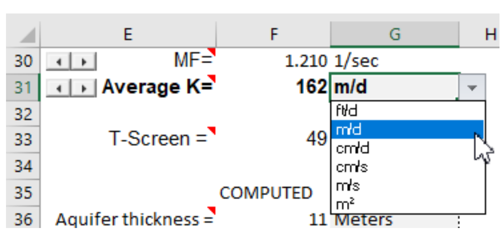
After pressing “REGRESS” button in (cell E25), hydraulic conductivity (K, cell F31) and modulation factor (MF, cell F30) have been estimated simultaneously with the Solver.



Hydraulic conductivity (K, cell F31) and modulation factor (MF, cell F30) can be changed manually with spin buttons in cells E31 and E30.



Units of reported hydraulic conductivity (K) are selected from pull-down menu in cell G31.

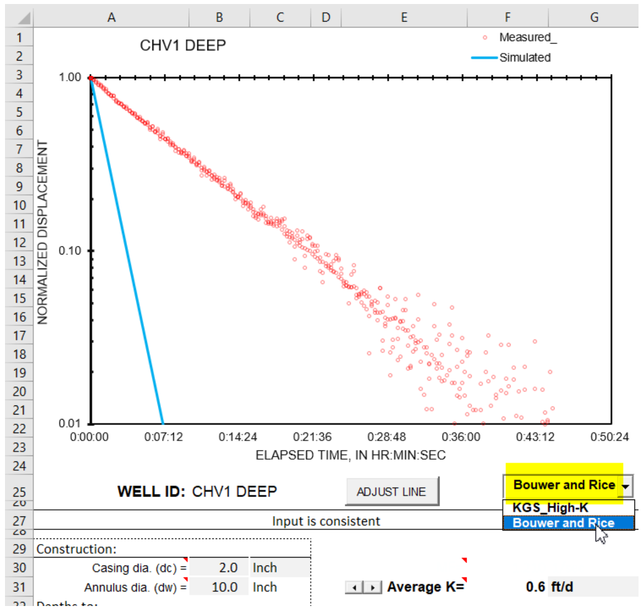


<table>
<tr>
<td>

Select “Bouwer and Rice” from pull-down menu in cell F25.

Hydraulic conductivity (K) initially will be estimated with a linear regression.

</td>
<td>



</td>
</tr>
<tr>
<td>

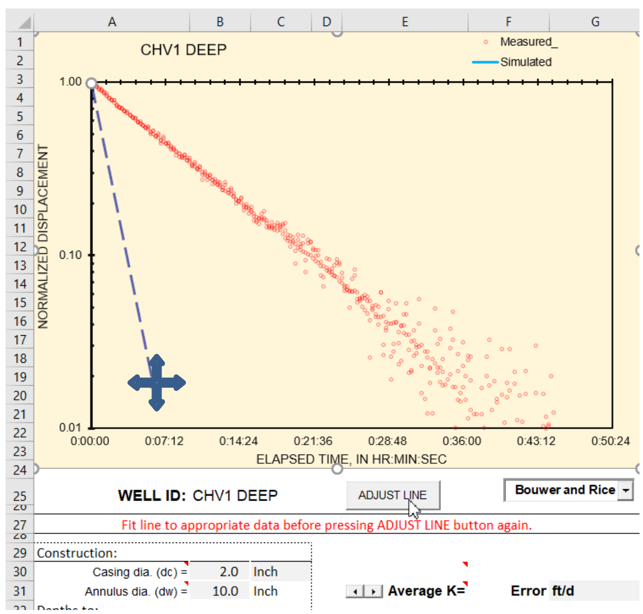
Press “ADJUST LINE” button (cell E25) to visually modify fit of line.

Regression line in chart converted to a graphical line that can be moved and adjusted.

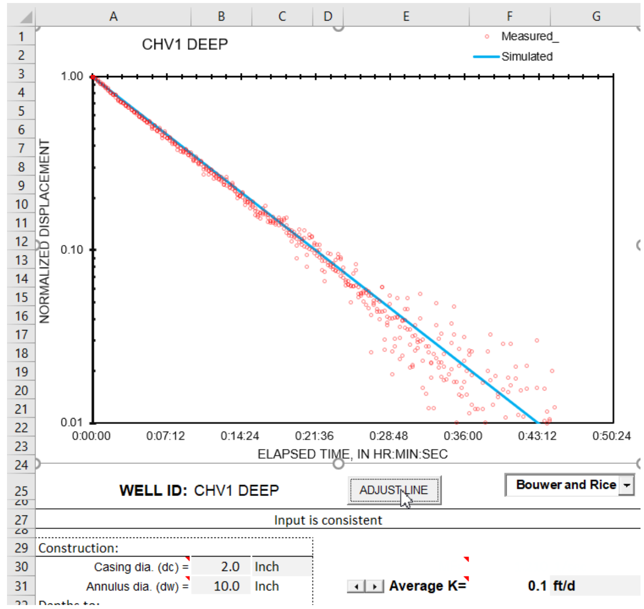
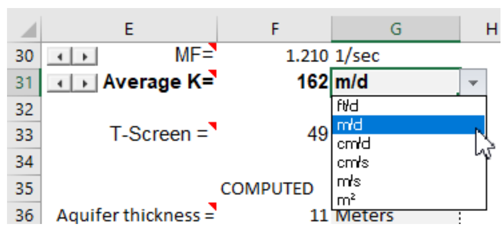
Background color changes and remains changed while in fitting mode.

An error condition exists while graphically fitting line.

</td>
<td>



</td>
</tr>
</table>

Pressing “ADJUST LINE” button (cell E25) again. Reverts graphical line to regression line and restores background color of chart.	
Units of reported hydraulic conductivity (K) are selected from pull-down menu in cell G31.	

PROP page

Annular fill, grouts, and hydrogeologic units are specified on the PROP page (Figure 9). Annual fill and grout are descriptive lists in columns A and B that can be edited by the user. Hydrogeologic units define a range of permissible hydraulic conductivities for each hydrogeologic unit. The default list was generalized from aquifer-test results and specific-capacity estimates in southern Nevada. The list of hydrogeologic units should be adapted to specific information from a user’s study area.

	A	B	C	D	E	F
1	Annular Fill	GROUTS		Hydrogeologic Unit	Kmin, ft/d	Kmax, ft/d
2	Gravel	Bentonite		Basin Fill	0.001	1,000
3	Coarse Sand	Cement		Carbonate Rocks	0.001	5,000
4	Medium Sand	Backfill		Confining Unit	1.00E-06	1.00E-02
5	Fine Sand	Open Hole		Volcanic Rocks	1.00E-07	3,000
6	Open Hole					

PROP | OUTPUT | DATA

Figure 9.—Annular fills, grouts, and ranges of transmissivities on the PROP page in the Slug_KGS-BnR-2019.xlsm workbook.