Step-Drawdown–A workbook for analysis of step drawdown tests

A step-drawdown test is a single-well test that is frequently conducted after well development to determine well efficiency and correctly size the production pump. Pumping rates are constant during steps which are of sufficient duration, about 1–4 hours, for water levels to change minimally at the end of each step (Halford and Kuniansky, 2002). Successively greater discharge rates are pumped during subsequent steps, where three to five discharge rates typically are tested. Water levels are measured prior to pumping, during each step, and during recovery so that drawdowns can be estimated.

Transmissivity and well-loss coefficients can be estimated from step drawdown data with the workbook, *Pumping_StepDrawdown-2019.xlsm*. The 2019 workbook accounts for linear and non-linear well losses while using graphical techniques to better estimate transmissivity (Odeh and Jones, 1965). Drawdown (*s*) and flow-rate (*Q*) data are transformed by plotting drawdowns divided by flow rates (*s/Qstep*) against flow-weighted, dimensionless times (Figure 1). Transformed data theoretically should plot in a straight line, where transmissivity is inversely proportional to the slope (Lee, 1982). Discrete steps plot separately because of non-linear, well losses. Measured *s/Qstep* depart from straight lines at the beginning of each step because of wellbore storage. Step drawdowns were analyzed with a flow-normalized drawdown plot in a previously developed workbook (Halford and Kuniansky, 2002). Well-loss model and parameter estimation techniques were improved in the workbook, *Pumping_StepDrawdown-2019.xlsm*.

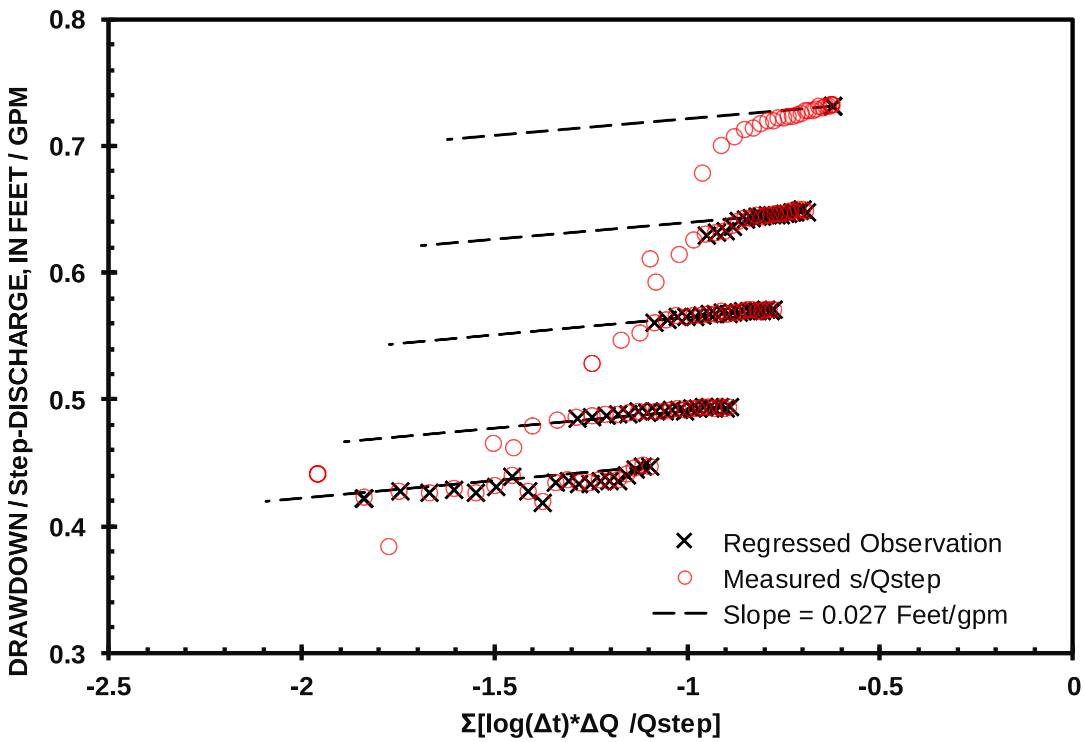


Figure 1.— Example of transformed drawdown (s) and flow-rate (Q) data and interpreted slope of s/Q that is inversely proportional to transmissivity.

Transmissivity estimates are improved with the flow-normalized drawdown plot, because effects of transmissivity on drawdowns are isolated from well-losses (Figure 1). Transmissivity can be adjusted manually to best explain late-time drawdowns during each step, while visually ignoring anomalies from unsteady flow rates and wellbore storage. These anomalies result primarily from the analytical model not simulating wellbore storage. These observations are eliminated from the regression by assigning weights of 0 to minimize their effects on estimates of well-loss coefficients. The flow-normalized drawdown plot also makes other departures between measured drawdowns and analytical model apparent such as the departure between measured and simulated slopes at highest pumping rate of 600 gpm (Figure 1, s/Qstep>0.7). Transmissivity of the aquifer likely was reduced by dewatering transmissive fractures.

The analytical model assumes that the aquifer can be described with the Theis (1935) solution and well losses have linear and non-linear components (Rorabaugh, 1953). Drawdown in the aquifer and well losses are simulated with the equation:

$s_W = B(t)Q(t) + B'Q + CQ^2$, where

s_W is total drawdown in the well,

B(t)Q(t) is time-dependent drawdown in aquifer,

t is the current time,

B´Q is linear well loss during a step,

CQ^2 is non-linear well loss during a step, and

Q is current discharge.

Drawdown in the aquifer, *B(t)Q(t)*, is solved with superimposed Theis (1935) solutions that evaluate all pumping rates from the beginning of the step-drawdown test to the current time (*t*). Well losses are the summation of *B´Q* and CQ^2. This formulation differs from Rorabaugh (1953), where drawdown in the aquifer, *B(t)Q(t)*, and linear well loss, *B´Q*, were combined in the term *BQ*.

Step-drawdown data can be interpreted in the workbook, *Pumping_StepDrawdown-2019.xlsm* to estimate transmissivity and well-loss coefficients (Figure 2). A continuous series of antecedent, pumping, and recovery water levels in the pumped well are specified as depth to water or water level above the transducer. Step discharges are specified in a table. Step-drawdowns, recoveries, and flow rates are plotted on a Cartesian plot and a flow-normalized drawdown plot. Data sets are converted to drawdowns in preferred units of analysis and estimates of *T*, *B´*, and *C* are initialized with the “LOAD” button. Fit between straight line and plotted data can be refined visually to ignore outliers in the flow-normalized drawdown plot by estimating T with scroll bar in cell H34 on the OUTPUT page. Well-loss coefficients *B´* and *C* can be adjusted manually with scroll bars in cells H35 and H36 or regressed with the “FIT” button in cell H32 (Figure 2). Estimated transmissivity, *T*, and well-loss coefficients, *B´* and *C*, are reported in user-specified units and significant digits. Average hydraulic conductivity is reported by assuming screen length adequately approximates aquifer thickness. Well efficiency is reported at the end of each step along with measured and simulated drawdowns.

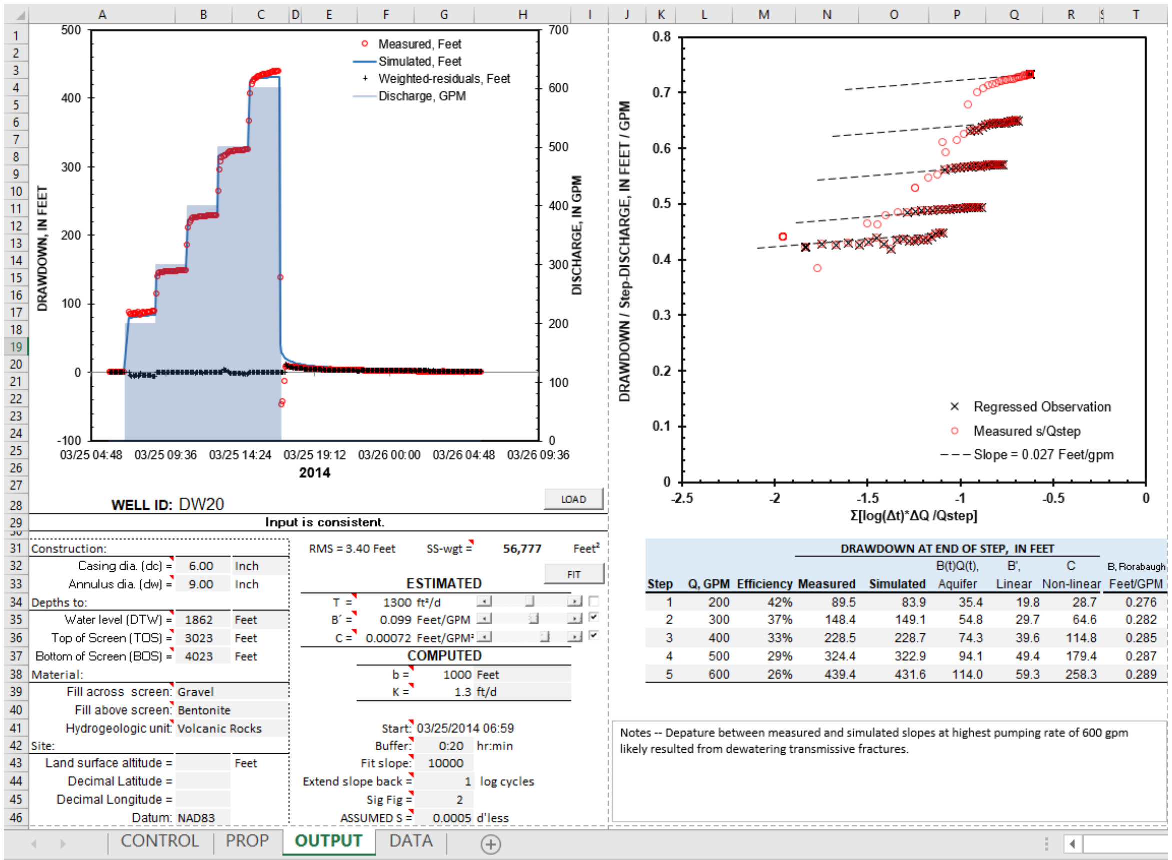


Figure 2.— OUTPUT page in Pumping_StepDrawdown-2019.xlsm with data from well DW20.

Pumping_StepDrawdown-2019.xlsm and explanatory PDF can be downloaded with the following link. This workbook and other workbook applications are better used on local drives instead of a network drive. Pumping_StepDrawdown-2019.xlsm workbook requires that the [Solver](#) is i[nstalled](#) 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 i[nstalled](#). User will be warned and workbook will be closed if opened from within a zip file.

Revisions

May 2, 2020—Revisions in version 2 corrected an error in well loss calculations if negative (-) flow rates were specified. Well loss equation, s-well = B * dQ + C * dQ^2, incorrectly calculates negative loss for B term and positive loss for C term if dQ less than zero. Revision notes if dQ is less than 0 and correctly applies negative to B and C terms.

October 18, 2022—Revisions in version 3 include the following. Safeguards were added to check that the [Solver](#) is i[nstalled](#) and the workbook is not opened from within a zip file.

References

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/

Lee, John, 1982, Well Testing: Society of Petroleum Engineers of AIME: New York, 159 p. https://www.amazon.com/Well-Testing-SPE-textbook-John/dp/0895203170

Odeh, Souad and G.L. Jones, 1965, Pressure Drawdown Analysis, Variable-Rate Case. Journal of Petroleum Technology 17. 960-964 https://www.researchgate.net/publication/240779570_Pressure_Drawdown_Analysis_Variable-Rate_Case

Rorabaugh, M.I., 1953, Graphical and theoretical analysis of step-drawdown test of artesian well: Proceedings of American Society of Civil Engineers, vol. 79, no. 362, 23 p.

Theis, C.V., 1935, The relation between the lowering of the Piezometric surface and the rate and duration of discharge of a well using ground-water Storage: Transactions of the American Geophysical Union, v. 16, no. 2, p. 519–524, https://doi.org/10.1029/TR016i002p00519.

Pumping_StepDrawdown-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 solving drawdown equations and parameter estimation, 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 transmissivities 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 antecedent, pumping, and recovery water levels in the pumped well are specified as depth to water or water level above the transducer in columns A-B from row 7 down (Figure 3). Time is specified as decimal days, which is the convention in Excel. Units of measured water levels are specified in cell B6. Pumping schedule is specified in columns D-E from row 7 down (Figure 3). Time and flow rate at the start of each step are specified in columns D and E, respectively. Units of measured discharges are specified in cell E6. Weights between 0 and 1 are specified for each step, in column F. Blank entries are assigned a weight of 1.

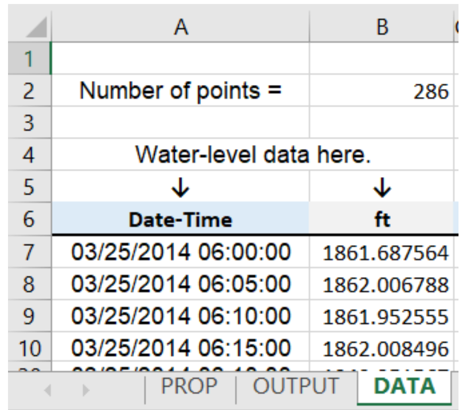
	A	B	C	D	E	F
1						
2	Number of points =	286			7	
3						
4	Water-level data here.			Discharge data here.		
5	↓	↓		↓	↓	
6	**Date-Time**	**ft**		**Date-Time**	**GPM**	**Weight**
7	03/25/2014 06:00:00	1861.687564		03/25/2014 06:59:00	200	1
8	03/25/2014 06:05:00	1862.006788		03/25/2014 08:59:00	300	1
9	03/25/2014 06:10:00	1861.952555		03/25/2014 10:59:00	400	1
10	03/25/2014 06:15:00	1862.008496		03/25/2014 12:59:00	500	1
11	03/25/2014 06:20:00	1861.949821		03/25/2014 14:59:00	600	0
12	03/25/2014 06:25:00	1861.93949		03/25/2014 16:59:00	0	1
13	03/25/2014 06:30:00	1861.811026		03/28/2014 09:30:00	0	1
14	03/25/2014 06:35:00	1861.868579				

PROP | OUTPUT | **DATA**

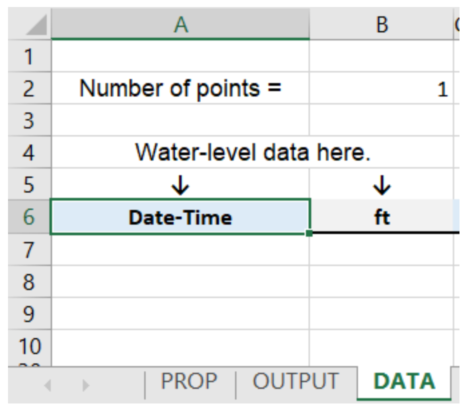
Figure 3.— DATA page in the Pumping_StepDrawdown-2019 workbook where time series of water levels and discharge rates are specified.

Data Page

Clear existing data between columns A and B from row 6 to the last entry.

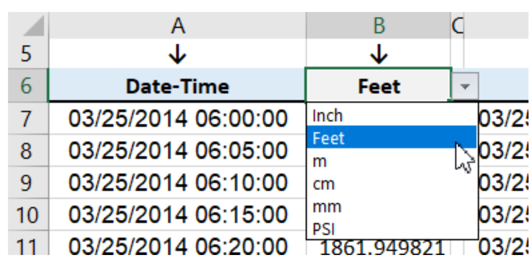


Empty cells before adding your data.

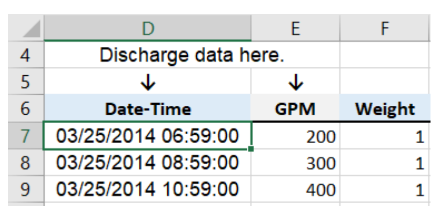


Paste time and water level data in columns A and B starting in row 7.

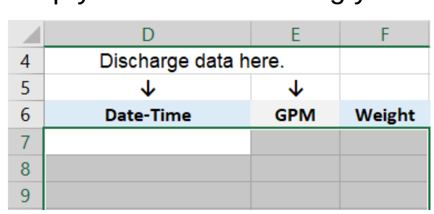
Specify units for measured water levels in cell B6.



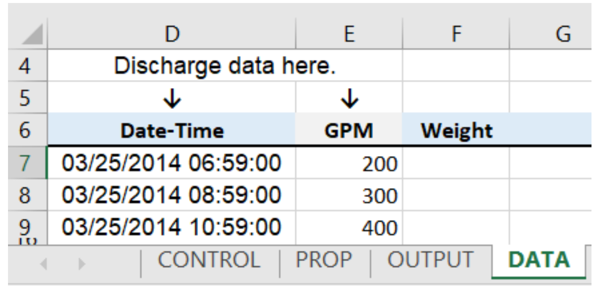
Clear existing data between columns D and F from row 6 to the last entry.



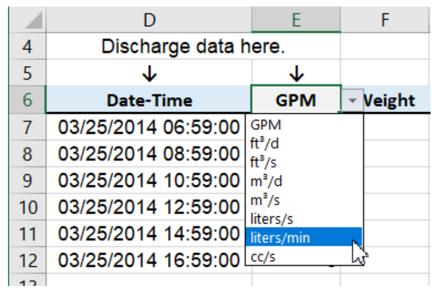
Empty cells before adding your data.



Paste time and discharge data in columns D and E starting in row 7.

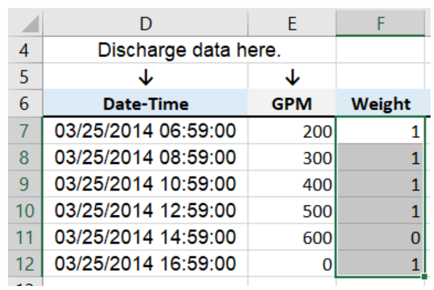


Specify units for measured discharges in cell E6.



Add weights in column F.

Weights should be 1 if the analytical model can explain data in a step and 0 if it cannot.



OUTPUT page—Site Information

Construction, depths, material, and site information are specified on the OUTPUT page (Figure 4). Most of this information is descriptive and does not affect estimated transmissivities. Aquifer material defines broad ranges of permissible transmissivities, which users should expand or replace with site specific limits. Annulus diameter defines radius of the well face in the Theis ([1935]) solution and is specified in cell B33.

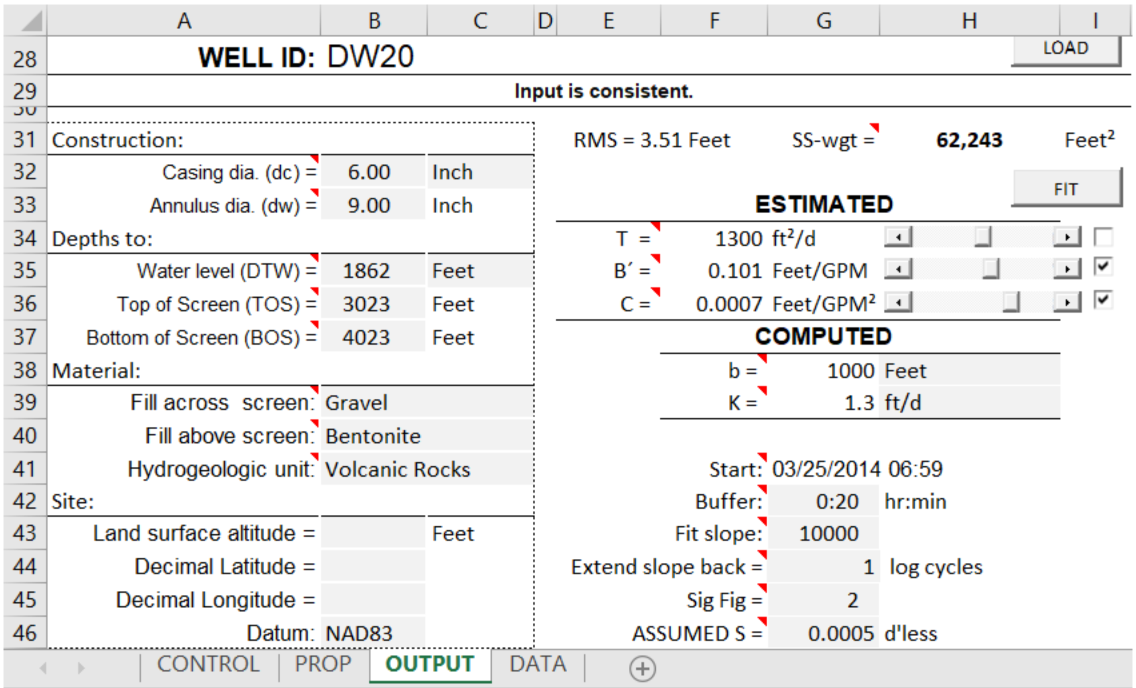
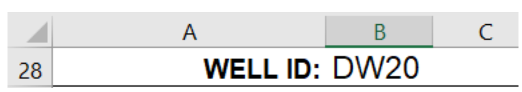
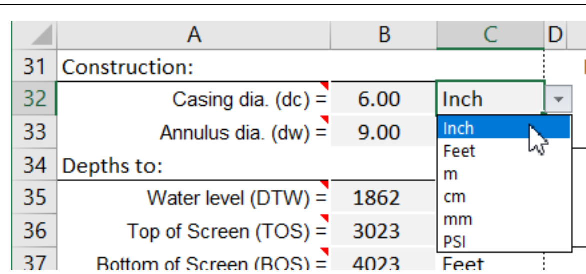
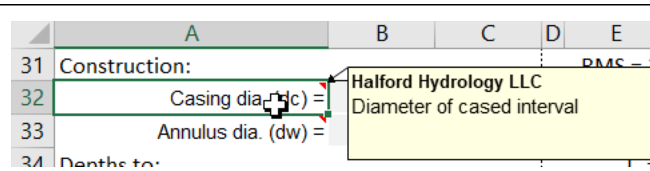
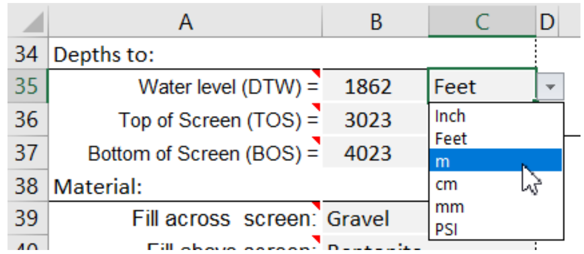


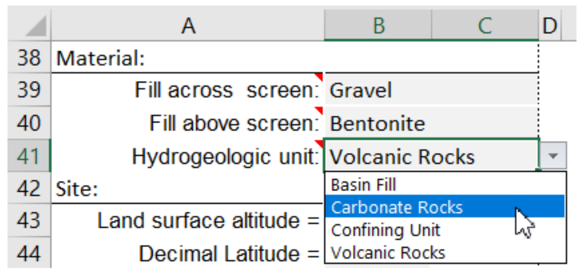
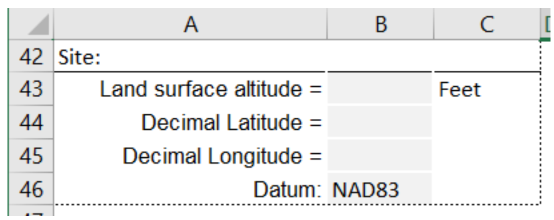
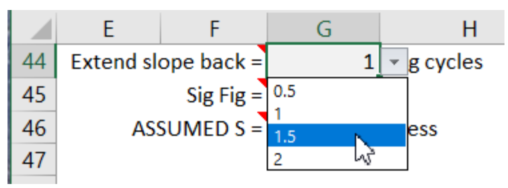
Figure 4.— Site information for single-well aquifer test in the Pumping_StepDrawdown-2019.xlsm workbook.

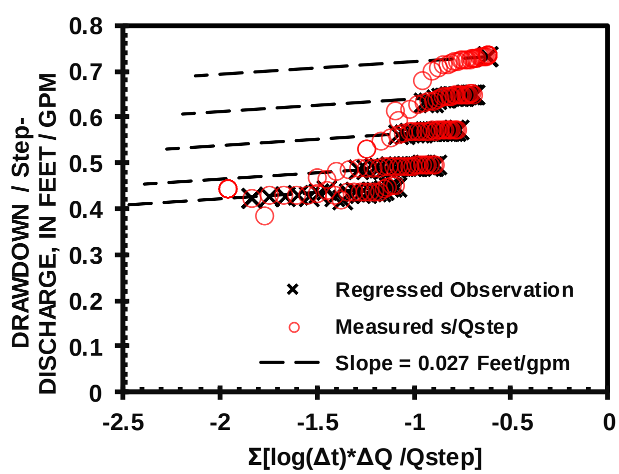
Site Information

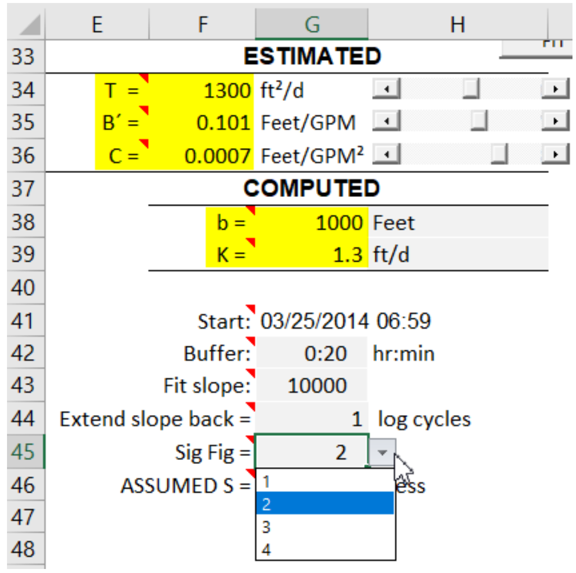
<table>
<tr><td>Enter site identifier in cell B28.</td><td></td></tr>
<tr><td>Diameters of casing and annulus are specified in cells B32 and B33. Select units from pull-down menu in cell C32.</td><td></td></tr>
<tr><td>Commented cells further describe expected input.</td><td></td></tr>
</table>

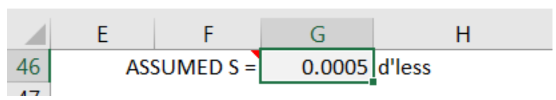
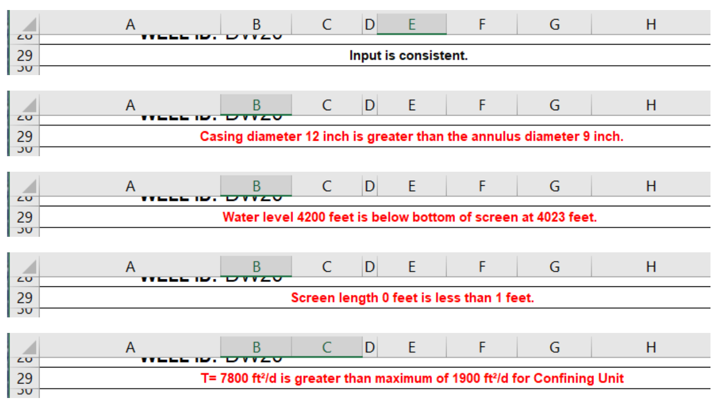
<table>
<tr>
<td>Depths to static water level, top of screen, and bottom of screen are specified in cells B35, B36, and B37. Select units from pull-down menu in cell C35.</td>
<td>
</td>
</tr>
<tr>
<td>Filled annular material across screen and above screen are specified in cells C39 and C40.

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

Select materials from pull-down menus in cells C39:C41.</td>
<td>
</td>
</tr>
<tr>
<td>Site information is for completeness of reporting and is not otherwise used.</td>
<td>
</td>
</tr>
<tr>
<td>Extend flow back specified in cell G44 defines length of linear slopes in the flow-normalized drawdown plot.</td>
<td>

Shows as

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

<table>
<tr>
<td>Significant digits specified in cell G45 affects reported
Transmissivity (T) cell F34,
Linear well-loss coefficient (B´) cell F35,
Non-linear well-loss coefficient (C) F36,
Aquifer thickness (b) cell G38, and
Hydraulic conductivity (K) cell G39.</td>
<td>
</td>
</tr>
<tr>
<td>Assumed storage coefficient (S) for Theis solution. Values should range between 0.00005 and 0.005 for confined aquifers.

S is not estimated because it is highly correlated with the linear well-loss coefficient (B´).</td>
<td>
</td>
</tr>
<tr>
<td>Error conditions are reported in row 29. “Input is consistent,” is reported when no errors exist.</td>
<td>
</td>
</tr>
</table>

OUTPUT page—Estimating transmissivity and well-loss coefficients

Step drawdown and flow-normalized drawdowns are plotted and analyzed on the OUTPUT page (Figure 5). Pumping, measured drawdowns, simulated drawdowns, and weighted residuals are shown on a Cartesian plot. Transmissivity can be estimated visually in the flow-normalized, drawdown plot. Drawdowns that are affected by wellbore storage can be excluded to minimize effects on regressed parameters (*T*, *B´*, and/or *C*). Data sets are converted to drawdowns in preferred units of analysis and estimates of *T*, *B´*, and *C* are initialized with the “LOAD” button. Fit between straight line and plotted data can be refined visually to ignore outliers in the flow-normalized drawdown plot by estimating *T* with scroll bar in cell H34 on the OUTPUT page. Well-loss coefficients *B´* and *C* can be adjusted manually with scroll bars in cells H35 and H36 or regressed with the “FIT” button in cell H32 (Figure 2). Estimated transmissivity, *T*, and well-loss coefficients, *B´* and *C*, are reported in user-specified units and significant digits. Average hydraulic conductivity is reported by assuming screen length adequately approximates aquifer thickness.

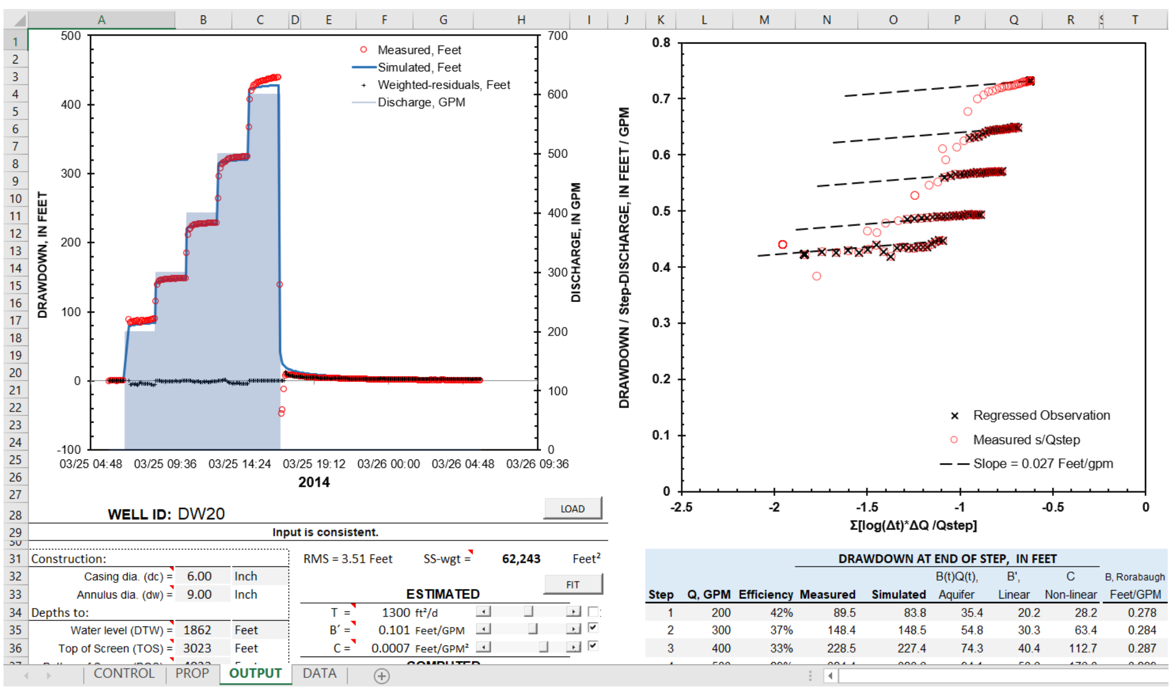


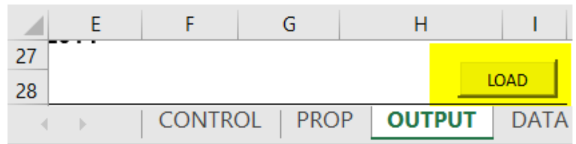
Figure 5.— Estimating transmissivity and well-loss coefficients from step-drawdown test in the Pumping_StepDrawdown-2019.xlsm workbook.

Estimating Transmissivity and well-loss coefficients

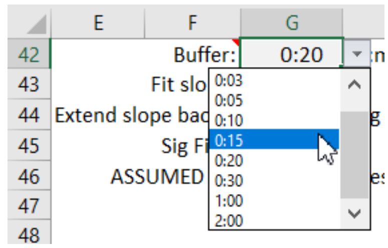
Press the “LOAD” button in cell H27 to

Convert input water levels to drawdowns in preferred units of analysis and

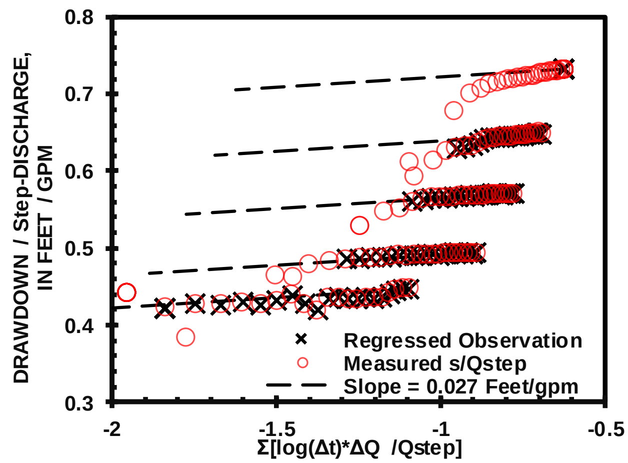
Initialize estimates of *T*, *B´*, and *C*.



Buffer period in cell G42 changes analyzable data, where drawdowns in the buffer periods at the beginning of each step and recovery are excluded from analysis.

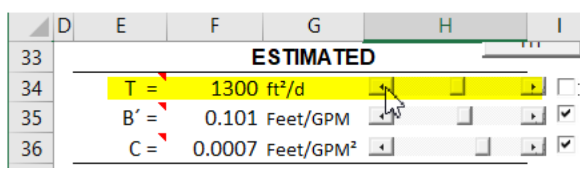


Buffered drawdowns that are not analyzed appear as open circles on the flow-normalized drawdown plot.

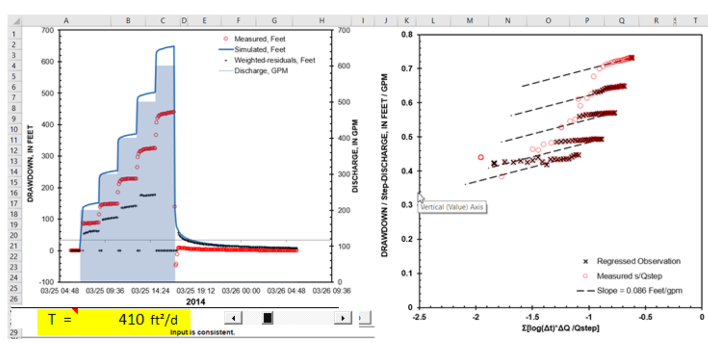


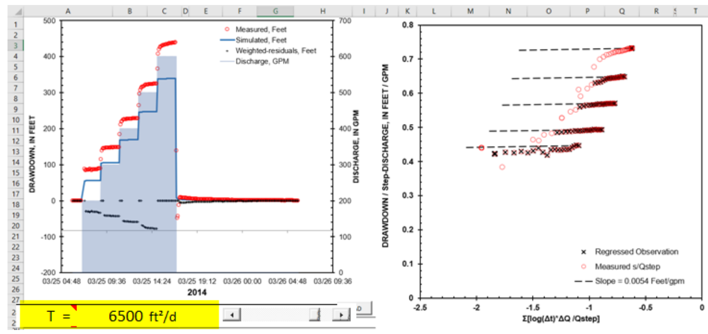
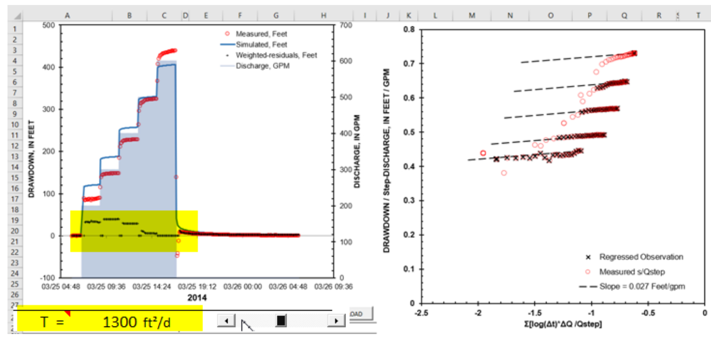
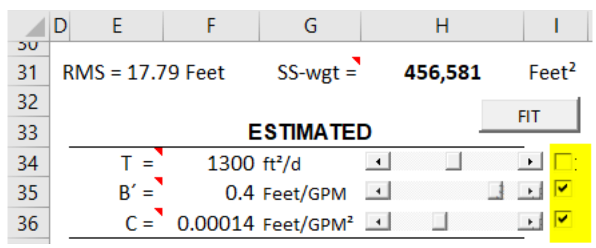
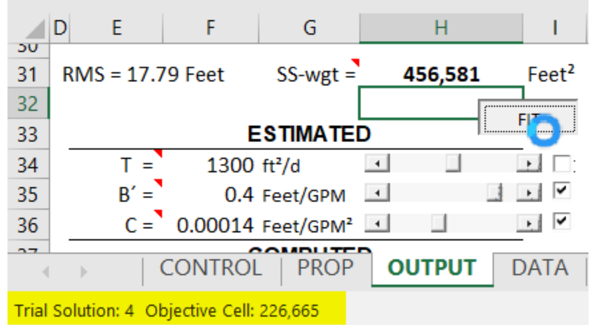
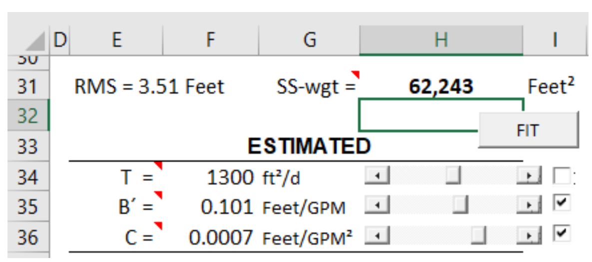
T can be estimated manually with the scroll bar in cell H34.

Similarly, coefficients *B´* and *C* can be estimated manually with scroll bars in cells H35 and H36, respectively.



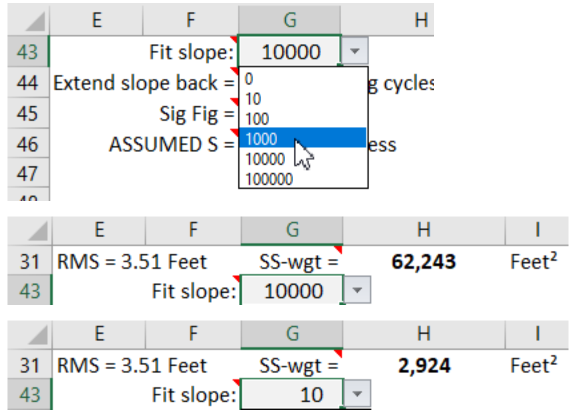
Reducing *T* from 1,300 to 410 ft²/d increases simulated drawdowns in the Cartesian plot and slopes of analytical solution in the flow-normalized, drawdown plot.



Increasing *T* from 1,300 to 6,500 ft²/d decreases simulated drawdowns in the Cartesian plot and slopes of analytical solution in the flow-normalized, drawdown plot.	
Slopes of analytical solution and measured s/Qstep in the flow-normalized, drawdown plot agree with *T* = 1,300 ft²/d, while misfit exists between measured and simulated drawdowns in the Cartesian plot. This is because coefficients *B´* and *C* are misestimated.	
Pressing "FIT" button (cell H32) starts the regression for estimating coefficients *B´* and *C*. These coefficients are estimated because check boxes in cells I35 and I36 are checked. Regression minimizes the weighted sum-of-squares in cell H31 with the Excel add-in Solver.	
Progress by Solver is reported in the lower, left corner of the Excel window.	
Changes in RMS and SS errors and revised estimates of coefficients *B´* and *C* are results from Solver.	

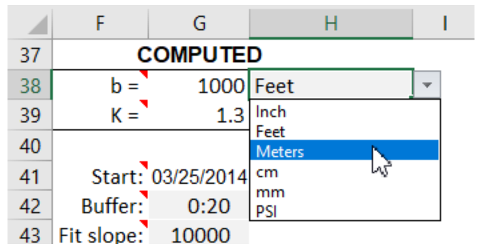
T also can be estimated with Solver. The objective function contains terms to emphasize matching late-term slopes of measured drawdowns.

The term "Fit slope" in cell G43 weights slope-matching component of SS error, where increasing "Fit slope" value increases emphasis on matching slopes.



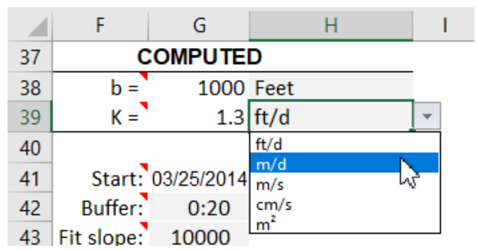
Units of reported length are selected from pull-down menu in cell G38.

This selection affects both plots, RMS and SS errors, and coefficients *B´* and *C*, in addition to assumed aquifer thickness (*b*).



Units of reported hydraulic conductivity (*K*) are selected from pull-down menu in cell H39.

Units of reported transmissivity are tied to this selection and limited to ft²/d, m²/d, or m²/s.



OUTPUT page—Well efficiency by step

Well efficiency is reported at the end of each step along with measured and simulated drawdowns on the OUTPUT page (Figure 6). Well efficiency is drawdown from the aquifer (column P) divided by total simulated drawdown (column O). B from the Rorabaugh (1953) equation, $s_W = BQ + CQ^2$, also is reported (column T).
B is equal to ($B(t)Q(t) + B'Q$)/Q and is evaluated at the end of each step. B is not constant, but perhaps constant enough for the user.

	K	L	M	N	O	P	Q	R	T
31				DRAWDOWN AT END OF STEP, IN FEET					
32						B(t)Q(t),	B',	C	B, Rorabaugh
33	**Step**	**Q, GPM**	**Efficiency**	**Measured**	**Simulated**	Aquifer	Linear	Non-linear	Feet/GPM
34	1	200	42%	89.5	83.8	35.4	20.2	28.2	0.278
35	2	300	37%	148.4	148.5	54.8	30.3	63.4	0.284
36	3	400	33%	228.5	227.4	74.3	40.4	112.7	0.287
37	4	500	29%	324.4	320.6	94.1	50.6	176.0	0.289
38	5	600	27%	439.4	428.1	114.0	60.7	253.5	0.291
39									

CONTROL | PROP | **OUTPUT** | DATA

Figure 6.— Reported discharges, well efficiencies, and drawdowns by step in the Pumping_StepDrawdown-2019.xlsm workbook.

PROP page

Annular fill, grouts, and hydrogeologic units are specified on the PROP page (Figure 7). 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 transmissivities for each hydrogeologic unit. The default list was defined for southern Nevada in the Death Valley system from 269 aquifer tests and specific-capacity estimates (Figure 8). The list of hydrogeologic units should be adapted to specific information from a user's study area.

	A	B	C	D	E	F	G
1	Annular Fill	GROUTS		Hydrogeologic Unit	Tmin, ft²/d	Tmax, ft²/d	
2	Gravel	Bentonite		Basin Fill	5	60,000	
3	Coarse Sand	Cement		Carbonate Rocks	2	400,000	
4	Medium Sand	Backfill		Confining Unit	0.00002	1,900	
5	Fine Sand	Open Hole		Volcanic Rocks	0.0001	200,000	
6	Open Hole						
7							

PROP | OUTPUT | DATA

Figure 7.— Annular fills, grouts, and ranges of transmissivities on the PROP page in the Pumping_StepDrawdown-2019.xlsm workbook.

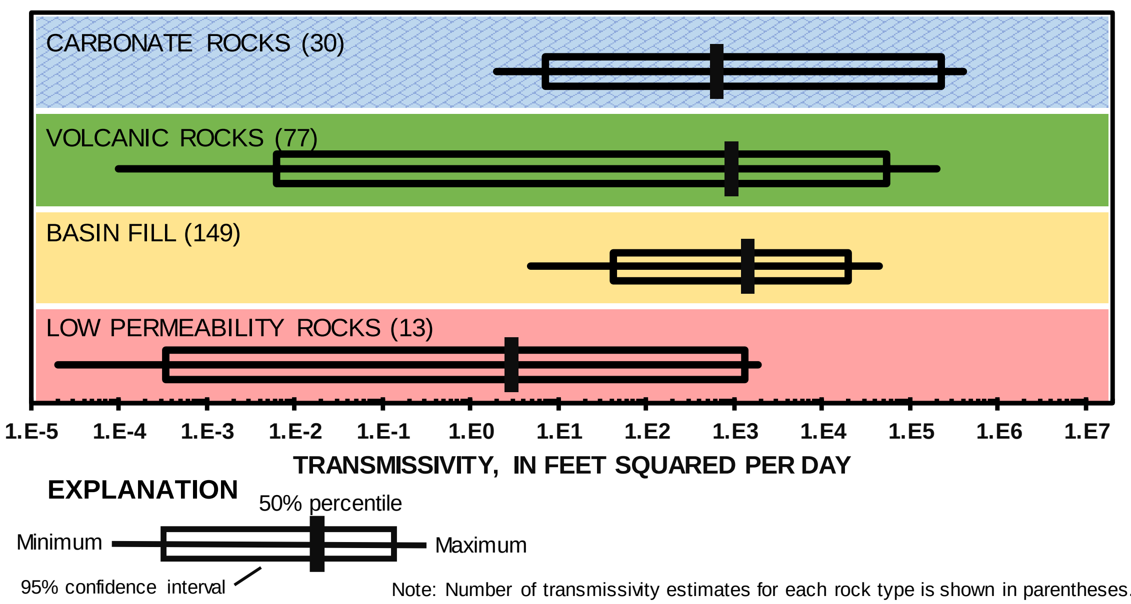


Figure 8.— Minimum, maximum, median, and 95-percent confidence interval of log-transmissivities in four rock-type categories from 269 field estimates of transmissivity in the Death Valley regional flow system (Halford and Jackson, 2019).

Halford, K.J., and T.R. Jackson, 2019, Groundwater Characterization and Effects of Pumping in the Death Valley Regional Groundwater Flow System, Nevada and California, with Special Reference to Devils Hole: U.S. Geological Survey Professional Paper 2019–XXXX, xx p.