Developing Better Regional Groundwater Flow Models with Effective Use of Step-Drawdown Test Results

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The assessment of regional ground water resources often depends on limited hydrogeological data and information, such as single-well tests instead of multiple-well constant rate discharge tests. Single-well tests provide limited hydrogeologic parameters and are often greatly influenced by well losses, but they can still provide valuable information for resource assessment.

A step-drawdown test performed after well construction provides a range of specific capacities at various pump rates. It is also used to determine the well efficiency at various rates and the effectiveness of the development process.

The calculated specific capacity values from step-drawdown tests often are used to estimate transmissivity, which is a measure of the amount of water that can be transmitted through the aquifer. Generally, these transmissivity estimates are made without taking into account the well losses in the specific capacities measured during the test. If these estimated transmissivity values are used in the construction of regional groundwater flow models, the results from such models will overestimate the potential withdrawal impacts.

The results from the step-drawdown tests can be used to correct the specific capacities to a 100-percent efficiency condition. When these corrected specific capacity values are used in equations to estimate transmissivity, the calculated values of transmissivity are much closer to values determined through multiple-well aquifer performance tests. The analytical models used to estimate transmissivity can be refined once a general number is calculated by using a refined constant for the analytical model, resulting in a solution that approaches closer to the values calculated from multiple-well aquifer performance tests.

Well Losses & Well Efficiency

Drawdown in a well is equal to the difference between the static water level and the pumping water level. Aquifer losses and well losses combine to contribute to the total drawdown observed in a pumped well. The aquifer losses are the linear head losses that occur in the aquifer where the flow is laminar (Kruseman & de Ridder, 1991). The extra head losses associated with partial penetration of a well into an aquifer are included in the aquifer losses.

If a well is not in steady-state flow, drawdown will increase gradually over time. Depending upon the aquifer characteristics and the selected pump rate, the time to reach steady-state flow can vary from minutes to several weeks.

The well losses observed in a pumping well include both linear and non-linear head losses. Linear well losses are the result of well construction, including the reduction of permeability near the bore hole and head losses in gravel packs and screens (Kruseman & de Ridder, 1991). Non-linear well losses include friction losses due to turbulent flow associated with the well screen, suction pipe, and the flow zone adjacent to the well.

Flow within an aquifer is typically laminar because of the presence of high frictional forces within the pore spaces and flow pathways, as well as the low inertia of flow; however, as groundwater moves toward a pumping well and flow lines converge, inertia increases with an increase in head pressure differentials and turbulent flow can occur.

Well construction also can add to the non-linear well losses by reducing the aquifer permeability within a portion of the production zone, thereby causing more flow lines to converge into fewer flow paths. An increase in turbulent flow around the well is the result.

The drawdown associated with the aquifer losses is considered the theoretical drawdown. Well efficiency is the ratio of the theoretical drawdown to the observed drawdown for a particular flow rate. It can also be considered a measure of the extent of aquifer restoration through well development. Well losses associated with well diameter, filter pack, and screen openings can be controlled through proper well design prior to construction.

Once development of the well is completed, a step-drawdown test should be performed to determine well efficiency. A step-drawdown test consists of pumping a well at a minimum of four escalating rates for equal lengths of time (usually at least one hour). The highest pump rate should be 25 to 50 percent higher than the design pump rate, if possible. Jacob (1947) performed the first step-drawdown test and related the following equation for drawdown in the pumped well:

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$$s = B_{(rew,t)}Q + CQ^2$$

Where:
s = drawdown
$B_{(rew,t)} = B_{1(rw,t)} + B_2$
$B_{1(rw,t)}$ = linear aquifer-loss coefficient
B_2 = linear well-loss coefficient
C = non-linear well-loss coefficient
Q = pump rate
r_{ew} = effective well radius
r_w = actual well radius
t = pumping time

Jacob combined the various linear head losses into the effective radius of the well term, defined as the distance from the axis of the well at which theoretical drawdown equals the drawdown just outside the well screen or well. It is not possible to determine the effective radius of the well from step-drawdown test data without knowing the storativity of the aquifer (Kruseman & de Ridder, 1991); this can be determined only from observations in nearby piezometers or wells.

Bierschenk (1963) presented a simple graphical method for determining B and C by dividing the above equation by Q. There is a linear equation in s/Q and Q—that is, by plotting s/Q versus Q, the resultant graph is a straight line with slope C and intercept B. The following formula is a representation of the described graph:

$$s/Q = B + CQ$$

By plotting the drawdown divided by flow rate versus the flow rate, one can get an estimate of the turbulent well losses and the aquifer losses plus laminar well losses. An approximation of the true well efficiency then can be obtained by calculating the linear head losses (BQ) for each step (n) divided by the observed drawdown times 100.

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Estimated Transmissivity (T_e) (gpd/ft)	Storage Coefficient				
	0.10	0.01	0.001	0.0001	0.00001
500	633	897	1,161	1,425	1,689
1,000	713	977	1,241	1,505	1,769
5,000	897	1,161	1,425	1,689	1,953
10,000	977	1,241	1,505	1,769	2,033
50,000	1,161	1,425	1,689	1,953	2,217
100,000	1,241	1,505	1,769	2,033	2,297
500,000	1,425	1,689	1,953	2,217	2,481
1,000,000	1,505	1,769	2,033	2,297	2,561
5,000,000	1,689	1,953	2,217	2,481	2,745

Table 1. Transmissivity factors (F_T) for estimating transmissivity from specific capacity at 100-percent efficiency.

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Well Efficiency (%) = $100 \times BQ_n / s_n$

Hantush (1964) expresses drawdown in a well during the n-th step of a step-drawdown test as a sum of the incremental drawdown for a fixed interval of time. The drawdown for the previous step is extrapolated out to the next step drawdown curve. This is necessary because of the unsteady state of flow to the well. Drawdown will continue to increase over time to some fixed point in time when it reaches steady state.

To calculate the true well efficiency, the aquifer parameters determined through analysis of observation well data must be calculated. Since this additional well test information is often not available and the turbulent flow well losses are often significant, the step-drawdown test is a useful tool in determining approximate well efficiency.

This article estimates specific capacity (Q/s) at 100-percent efficiency by the following equation:

$$Q/s_{100} = Q_n / BQ_n$$

<u>Equation 1: $Q/s_{100} = 1 / B$</u>

This equation allows for the calculation of drawdown in the aquifer at the point of withdrawal with the non-linear well losses removed from the equation, so the 100-percent specific capacity is equal to the inverse of the y-intercept of the s/Q versus Q step-drawdown graph.

Estimating Transmissivity

The transmissivity of an aquifer can be estimated using the specific capacity of the well and multiplying it by an analytical coefficient derived from the Cooper and Jacob (1946) equation. The analytical method correlating the potential specific capacity to transmissivity is detailed in Driscoll (1986) and here below. The analytical equations are derived by assuming an average well diameter, average pumping duration, and typical storage coefficients for the aquifer. The analytical equations are based on the following Cooper and Jacob (1946) equation:

$$s = \frac{264\,Q}{T} \log \frac{0.3\,Tt}{r^2 S}$$

Where:
s = drawdown in the well (ft)
T = transmissivity (gpd/ft)
S = aquifer storage coefficient
Q = pump rate (gpm)
t = pumping time (days)
r = well radius (ft)

By rearranging terms in the equation, specific capacity can be determined by:

$$\frac{Q}{s} = \frac{T}{264 \log \frac{0.3\,Tt}{r^2 S}}$$

Analytical models have been derived using assumed variables in the log function of the equation such as t = 1 day, r = 0.5 ft, T = 30,000 gpd/ft, and S = 0.001 for a confined aquifer and S = 0.075 for an unconfined aquifer (Driscoll, 1986). For a confined aquifer, the potential specific capacity is calculated by:

$$\frac{Q}{s} = \frac{T}{2{,}000}$$

and for an unconfined aquifer:

$$\frac{Q}{s} = \frac{T}{1{,}500}$$

These in turn have been modified to estimate transmissivity from a known specific capacity. Unfortunately, the specific capacity most often known and used is one for which the well efficiency is not corrected. A better estimate of transmissivity is one that incorporates the specific capacity at 100-percent efficiency (Q/s_{100}). For a confined aquifer the equation is:

<u>Equation 2: $T_e = Q/s_{100} \times 2{,}000$</u>

Once transmissivity is estimated using the above equation, it can be refined by using better calculations of the log function. Table 1 allows the user to look up the estimated transmissivity (T_e) previously calculated and the known or approximated storage coefficient for the aquifer being tested. Using the derived transmissivity factor F_T from the table refines the transmissivity estimate; therefore the following equation can be used for any aquifer:

<u>Equation 3: $T = Q/s_{100}\ F_T$</u>

Estimated transmissivity values using the specific capacity at 100-percent efficiency and the transmissivity factor (F_T) will result in values closer to measured values from multiple-well constant rate discharge tests.

Case Study

The city of Port St. Lucie has constructed 20 Floridan Aquifer wells within the last 10 years. A step-drawdown test was performed on each of these wells and results from those tests are provided in Table 2.

The tests yielded uncorrected specific capacity values from 25 gallons per minute per foot of drawdown (gpm/ft) to 857 gpm/ft. The average specific capacity from these tests is 202 gpm/ft and the geometric mean is 154 gpm/ft. When corrected for well efficiency, the 100-percent specific capacity (Q/s100%) ranges from 41 gpm/ft to 9,677 gpm/ft.

The average and geometric mean values of Q/s100% are 1,268 gpm/ft and 550 gpm/ft, respectively. Because of the range of values calculated, the geometric mean values were used for comparison purposes as a more reasonable measure of the regional value.

The estimated transmissivity of the Floridan Aquifer in the area using the geometric mean uncorrected specific capacity value and the simplified analytical model is approximately 309,000 gpd/ft (41,300 ft^2/day). Three different multiple-well aquifer performance tests in the area resulted in an average transmissivity of the Floridan Aquifer to be about 1,253,000 gpd/ft (167,500 ft^2/day). Since the estimated transmissivity from the uncorrected specific capacity values were about 25 percent of the values derived from the multiple-well

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WELL	PUMPAGE (gpm)	TOTAL OBSERVED DRAWDOWN (ft)	SPECIFIC CAPACITY (gpm/ft)	s/Q (ft/gpm)	AQUIFER AND LINEAR WELL LOSSES (ft)	WELL EFFICIENCY (%)	100% EFFICIENCY SPECIFIC CAPACITY (gpm/ft)	WELL	PUMPAGE (gpm)	TOTAL OBSERVED DRAWDOWN (ft)	SPECIFIC CAPACITY (gpm/ft)	s/Q (ft/gpm)	AQUIFER AND LINEAR WELL LOSSES (ft)	WELL EFFICIENCY (%)	100% EFFICIENCY SPECIFIC CAPACITY (gpm/ft)
F1	1,250	37.2	34	0.02976	30.68	82%	41	F11	1,982	4.3	461	0.00217	0.20	5%	9,677
F1	1,500	46.2	32	0.03080	36.81	80%	41	F11	2,583	7.2	359	0.00279	0.27	4%	9,677
F1	1,750	56.4	31	0.03223	42.95	76%	41	F11	3,150	10.8	292	0.00343	0.33	3%	9,677
F1	2,000	65.6	30	0.03280	49.08	75%	41	F11	3,750	15.0	250	0.00400	0.39	3%	9,677
F2	817	6.6	124	0.00808	5.08	77%	161	F12	1,867	6.3	296	0.00337	0.41	6%	4,571
F2	1,333	10.9	122	0.00818	8.29	76%	161	F12	2,333	11.0	212	0.00471	0.51	5%	4,571
F2	1,767	17.1	103	0.00968	10.98	64%	161	F12	2,843	17.4	163	0.00612	0.62	4%	4,571
F2	2,700	30.7	88	0.01137	16.78	55%	161	F12	3,804	28.3	134	0.00744	0.83	3%	4,571
F3	900	4.7	191	0.00522	2.72	58%	331	F13	1,040	1.7	623	0.00161	0.58	34%	1,808
F3	1,300	9.9	131	0.00762	3.93	40%	331	F13	2,000	5.5	364	0.00275	1.11	20%	1,808
F3	1,800	16.0	113	0.00889	5.44	34%	331	F13	2,945	10.5	280	0.00357	1.63	16%	1,808
F3	2,700	30.0	90	0.01111	8.16	27%	331	F13	3,780	17.2	220	0.00454	2.09	12%	1,808
F4	833	2.9	287	0.00348	1.74	60%	478	F14	1,745	7.3	241	0.00415	4.45	61%	392
F4	1,333	8.1	165	0.00608	2.79	34%	478	F14	2,267	11.5	197	0.00507	5.78	50%	392
F4	1,800	12.1	149	0.00672	3.77	31%	478	F14	2,982	17.5	170	0.00587	7.60	43%	392
F4	2,700	22.6	119	0.00837	5.65	25%	478	F14	3,836	26.0	148	0.00678	9.78	38%	392
F5	850	3.5	243	0.00412	0.91	26%	937	F15	1,133	2.5	453	0.00221	1.28	51%	884
F5	1,350	9.9	136	0.00733	1.44	15%	937	F15	2,000	6.3	316	0.00317	2.26	36%	884
F5	1,917	18.7	103	0.00975	2.05	11%	937	F15	3,109	13.2	236	0.00423	3.52	27%	884
F5	2,733	33.7	81	0.01233	2.92	9%	937	F15	3,891	19.2	202	0.00494	4.40	23%	884
F6	717	3.0	239	0.00419	2.05	68%	349	F16	1,017	2.3	444	0.00225	0.91	40%	1,123
F6	1,650	11.0	150	0.00667	4.72	43%	349	F16	1,982	7.5	264	0.00378	1.76	24%	1,123
F6	2,367	18.5	128	0.00782	6.78	37%	349	F16	2,907	14.6	199	0.00502	2.59	18%	1,123
F6	3,050	28.0	109	0.00918	8.73	31%	349	F16	3,709	22.5	165	0.00606	3.30	15%	1,123
F7	900	1.1	857	0.00117	0.65	62%	1,384	F17	1,000	4.7	214	0.00467	3.09	66%	324
F7	1,733	3.3	533	0.00188	1.25	39%	1,384	F17	1,960	12.8	153	0.00655	6.06	47%	324
F7	2,417	4.4	547	0.00183	1.75	40%	1,384	F17	3,080	25.7	120	0.00833	9.52	37%	324
F7	3,050	7.6	401	0.00249	2.20	29%	1,384	F17	3,533	31.5	112	0.00892	10.92	35%	324
F8	783	2.5	314	0.00318	1.64	66%	477	F18	600	10.3	58	0.01715	6.23	61%	96
F8	1,567	6.8	229	0.00437	3.29	48%	477	F18	1,125	28.5	39	0.02533	11.68	41%	96
F8	2,300	12.4	186	0.00538	4.83	39%	477	F18	1,729	54.9	31	0.03178	17.94	33%	96
F8	2,833	17.3	164	0.00609	5.94	34%	477	F18	2,359	92.9	25	0.03940	24.48	26%	96
F9	850	1.6	531	0.00188	0.74	46%	1,144	F21	2,100	16.5	128	0.00783	8.24	50%	255
F9	1,700	5.0	340	0.00294	1.49	30%	1,144	F21	2,560	21.9	117	0.00854	10.04	46%	255
F9	2,450	9.3	263	0.00380	2.14	23%	1,144	F21	3,060	30.0	102	0.00979	12.00	40%	255
F9	3,033	13.7	221	0.00452	2.65	19%	1,144	F21	3,680	39.3	94	0.01067	14.44	37%	255
F10	950	9.9	96	0.01042	7.38	75%	129	EW2	855	7.0	122	0.00819	1.07	15%	796
F10	1,933	25.1	77	0.01298	15.01	60%	129	EW2	1,108	11.2	99	0.01011	1.39	12%	796
F10	2,867	46.0	62	0.01604	22.27	48%	129	EW2	1,516	20.1	75	0.01326	1.90	9%	796
F10	3,767	68.2	55	0.01810	29.26	43%	129	EW2	1,679	25.0	67	0.01489	2.11	8%	796

Table 2. Step-drawdown test results from twenty Floridan aquifer wells for the City of Port St. Lucie, Florida.

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aquifer performance tests, the groundwater flow models constructed with these transmissivity values to simulate potential future impacts would be estimating four times the drawdown and overall impact from pumpage.

The transmissivity estimate (T_e) value, using the specific capacity value at 100-percent efficiency ($Q/s_{100\%}$) of 550 gpm/ft and Equation 2, is equal to 1,100,000 gpd/ft (147,059 ft^2/day). Taking this transmissivity estimate with a storage value of 0.0001 for the Floridan Aquifer in this area, a transmissivity factor (F_T) of 2,297 is obtained from Table 1. A refined transmissivity is then obtained using Equation 3 with a result of 1,264,162 gpd/ft (169,006 ft^2/day), which is about 1 percent greater than the value determined through aquifer performance testing.

Conclusion

Single-well tests provide limited hydrogeologic parameters and are often greatly influenced by well losses; however, the results from step-drawdown tests can be used to calculate good estimates for transmissivity by accounting for well efficiency. By calculating the specific capacity at 100-percent efficiency ($Q/s_{100\%}$), an estimate of transmissivity (T_e) can be obtained. Using the table of transmissivity factors (F_T) provided here, a more refined transmissivity value can be calculated.

The case study showed a very good correlation (within 1 percent) of the refined transmissivity value calculated for the region studied and the average value of transmissivity calculated from three multiple-well constant rate discharge tests. The greater number of tests available in an area will also improve the chances of getting a regional value as opposed to a localized condition, as often is encountered.

Regional groundwater flow models which are developed using strictly limited single-well test information that is not corrected for well efficiency will lead to an overestimation of the potential withdrawal impacts. The refined values of transmissivity taking into account the aquifer and linear well losses determined in the step-drawdown test analysis and incorporated into regional models will lead to the development better models, which will help in water resource planning and sustainability.

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