A Department of Ecology Report

A Comparison of Horizontal Hydraulic Conductivity Values Derived from Aquifer Test and Well Specific-Capacity Data for the Sequim-Dungeness Area

Abstract

Transmissivity results from eight aquifer tests were used to derive horizontal hydraulic conductivity values for hydrogeologic units underlying the Sequim-Dungeness Peninsula in Clallam County. Specific-capacity information for the tested production wells also was analyzed to obtain a second hydraulic conductivity value for comparison against the "aquifer test" results. These paired estimates differed by less than a factor of 2, which is comparable to the "internal" variability in hydraulic conductivity noted for the individual aquifer tests. This evaluation suggests that, for the Sequim-Dungeness area, well specific-capacity data provide comparable hydraulic conductivity values to those values estimated through more intensive aquifer testing methods.

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April 2002

Publication No. 02-03-017
Waterbody No. WA-18-1020

Publication Information

This report is available on the Department of Ecology home page on the World Wide Web at http://www.ecy.wa.gov/biblio/0203017.html

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Introduction

The Sequim-Dungeness peninsula in northeastern Clallam County experienced significant changes in both water and land use over the past several decades, as the local economy shifted from irrigated agriculture toward rural residential and municipal development. In anticipation of these changes, resource management agencies at the state and local level funded several studies during this period to define the hydrogeology and water development potential of the Sequim-Dungeness area (Noble, 1960; Drost, 1983; Jones, 1996; and Thomas et al., 1999). The near-term culmination of these efforts is expected to be the development of a transient three-dimensional, groundwater flow model of the Dungeness peninsula. The model will be used to evaluate future water-supply development proposals, irrigation-efficiency measures, and other "hydraulically" significant land-use changes.

Model development and calibration, of the sort envisioned, requires detailed knowledge about the magnitude and spatial variability of hydraulic properties for each of the study area geologic units. To fill this need, Drost (1983) and Thomas (1999) collectively evaluated specific-capacity[1] data for approximately 770 wells to define horizontal hydraulic conductivity (hydraulic conductivity) values for five hydrogeologic units underlying the Sequim-Dungeness area. While specific-capacity techniques are a convenient and straightforward means of estimating hydraulic conductivity, they suffer from several significant limitations (most notably well loss[2] and partial penetration[3] effects) and commonly provide hydraulic conductivity estimates that are too low (in Bentall, 1963, p.245-Jacobs). This evaluation was undertaken to determine if the hydraulic conductivity estimates provided by Drost (1983) and Thomas (1999) are comparable to those obtained from more technically rigorous aquifer test methods, and thus appropriate for use during future modeling efforts.

In undertaking this comparison, the implicit assumption is that aquifer tests generally provide better estimates of hydraulic conductivity than do specific-capacity techniques. While this is probably true, all of these analysis methods are subject to numerous simplifying assumptions. In addition, none of these techniques provide a unique solution; thus, the hydraulic properties of the geologic materials underlying the study area may never be precisely known by any of these analysis methods.

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1 Specific capacity is a rough measure of a well's water production potential and is defined as the well pumping rate divided by the resultant drawdown.
2 Well loss refers to the component of measured drawdown that originates from turbulent water flow through the well screen, well perforations, or well face, plus friction loss from water movement within the well casing itself.
3 The observed drawdown in wells that are not screened or open across the full thickness of an aquifer (a partially penetrating well) typically deviates from theoretical drawdown predictions due to vertical flow gradients that occur near the well. To obtain valid test results, a correction factor must be applied to compensate for this deviation.

Study Methods

Numerous aquifer tests have been conducted within the study area during the installation and testing of production wells for the City of Sequim, Clallam County Public Utility District, and other large users of groundwater. A review of the available summary reports for these tests identified two single well and six multiple well tests that were sufficiently well documented that they could be used for this evaluation (Figure 1) (Grimstad, 1973; Pacific Groundwater Group, 1992, 1995a, 1995b, 1996, 1998; Robinson and Noble, 1974). For information about the field procedures and analysis methods used during the individual aquifer tests, consult the appropriate summary report(s).

The aquifer tests selected for comparison generally consist of three parts: 1) an initial "step" test to evaluate well efficiency, 2) a constant-rate drawdown test, and 3) post-test monitoring of water level recovery. The transmissivity value(s) reported in the aquifer test reports were developed via standard curve matching techniques and were used "as is" for this analysis. The reported transmissivity values were divided by the aquifer thickness to define a range of hydraulic conductivity values for each of the aquifer tests (Tables 1 and 2).

Where possible, data from the initial step tests were evaluated via the method of Csallany and Walton (1963) to estimate well loss for each of the production wells (Table 1 and Appendix). A computerized technique by Bradbury and Rothschild (1985) that incorporates corrections for well loss and partial penetration was then used to estimate hydraulic conductivity values from the production well specific-capacity data (Table 2). These "corrected" hydraulic conductivity values are presented in Table 2, along with "uncorrected" values from Thomas (1999).

Results

For the eight wells evaluated, the difference between analysis methods (aquifer test and specific capacity) differed by less than a factor of 2, and was less in several cases than the internal variability of the individual aquifer tests (Table 2). While this difference may at first glance seem large, hydraulic conductivity can vary over several orders of magnitude; thus, the noted variability between methods is within acceptable limits.

The hydraulic conductivity estimates developed from corrected specific-capacity data deviated from the aquifer test value by a somewhat smaller margin than the uncorrected data provided by Thomas et al. (1999). Direct comparisons against the hydraulic conductivity values estimated by Drost (1983) were not possible since he did not publish well-by-well estimates. There was no apparent bias in the specific-capacity test results. Three wells revealed higher hydraulic conductivity values from specific-capacity data, three wells had lower values, and two wells had approximately the same values from both the aquifer test and specific-capacity test methods.

This evaluation suggests that, for this area, specific-capacity techniques provide comparable hydraulic conductivity estimates to those obtained from more intensive aquifer test procedures.

In addition, specific-capacity tests are far more common than aquifer tests and can thus provide a better spatial distribution of hydraulic conductivity within the study area. Used in tandem, these analysis techniques are complementary and provide both certainty in and cost effective estimates of hydraulic conductivity.

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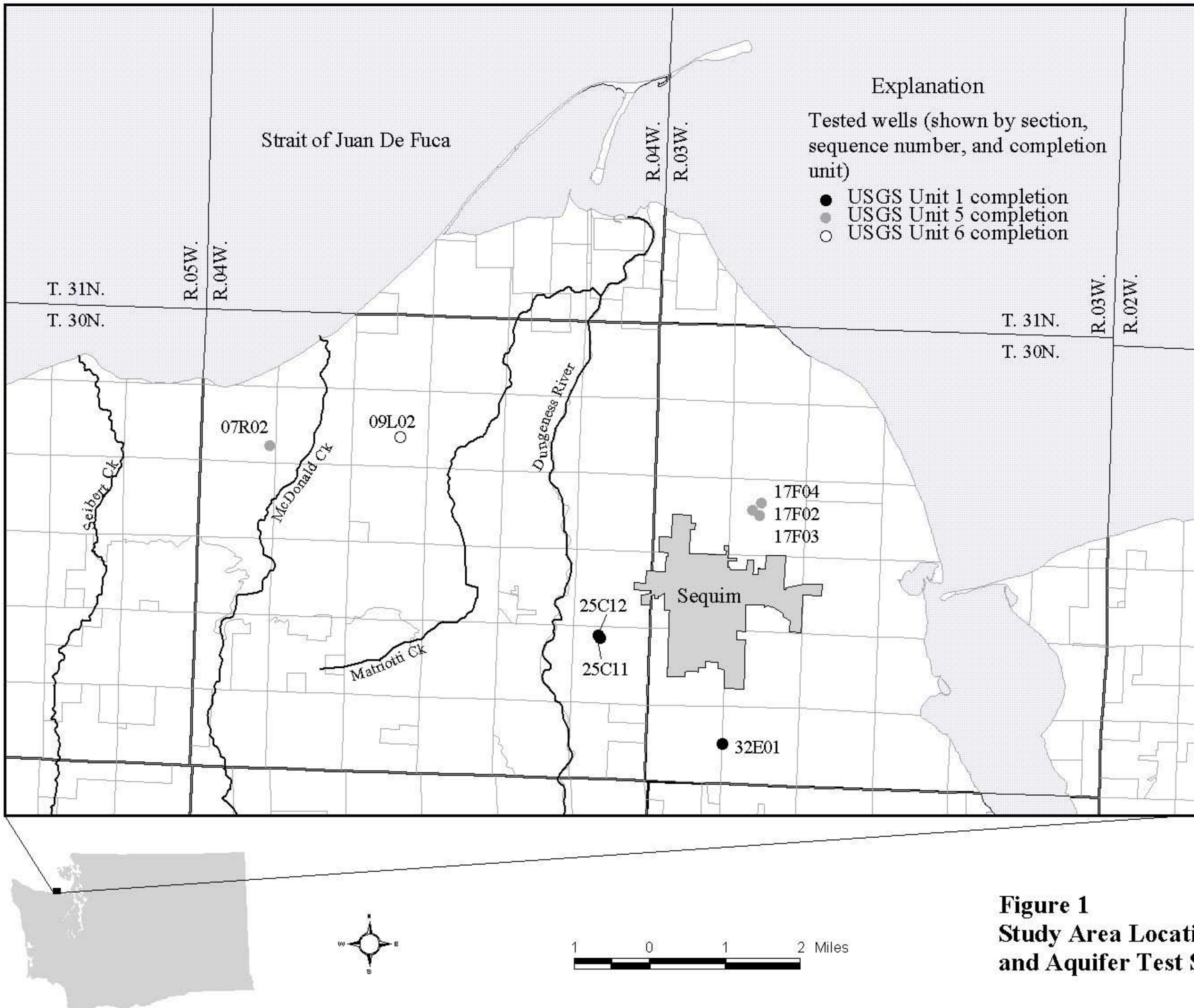

Figure 1
Study Area Location and Aquifer Test Sites

Table 1 - Well descriptions and summary of aquifer test results

Well number	Well depth (feet)	Casing diameter (inches)	Screen diameter (inches) and open interval (feet below land surface)	Hydro-geologic unit [A]	Average pumping rate during aquifer test (gpm)	Aquifer test method and duration [B] (hours)	Total drawdown in pumping well during aquifer test (feet)	Estimated well loss (feet)	Well specific-capacity (gpm/ft)	Storage coefficient [C] (unit less)	Summary of aquifer test results [D]	Data Source [E]
30N/03W-17F02	320	10	(8-in) 279-320	5	228	P(48hr)	77.9	45	2.9	0.0002*	Multiple well test, T ranged from 15,000 to 15,400 gpd/ft	PGG, 1995a
30N/03W-17F03	417	12	(6-in) 283.5-310, 367-384,395.5-411	5	540	P(24hr)	79	18.4	6.8	0.00012	Multiple well test, T ranged from 17,600 to 25,900 gpd/ft Average of all T values is 21,500 gpd/ft	PGG, 1995b
30N/03W-17F04	379	12	(6-in) 291-373	5	600	P(24hr)	138	43.2	4.3	0.0003	Multiple well test, T ranged from 35,000 to 52,600 gpd/ft Log average of all T values is 40,000 gpd/ft	PGG, 1998
30N/03W-32E01	118	6	(6-in) 107-118	1	25	F(24hr)	NA	NA	NA	0.00046	Multiple well test, T = 2,579 gpd/ft	Grimstad, 1973
30N/04W-07R02	468	8	(8-in) 428-458	5	106	P(6.85hr)	111	65.8	0.95	0.0002*	Single well test, T= 11,000 gpd/ft	PGG, 1992
30N/04W-09L02	842	12	(6-in) 800-830	6	715	P(5hr)	29	5	24.7	0.0001*	Single well test, T = 160,000 gpd/ft	R&N, 1974
30N/04W-25C11	186	10	(10-in) 148-186	1	301	P(24hr)	48	39.8	6.3	0.00007	Multiple well test, T ranged from 45,400 to 137,000 gpd/ft Log average of all T values is 86,000 gpd/ft Storage coefficient (S) ranged from 2X10-4 to 1X10-5	PGG, 1996
30N/04W-25C12	172	10	(10-in) 132-172	1	367	P(24hr)	55	43.5	6.7	0.0001	Multiple well test, T ranged from 37,200 to 116,300 gpd/ft Log average of all T values is 72,900 gpd/ft Storage coefficient (S) ranged from 5X10-4 to 2X10-5	PGG, 1996

[A] After Thomas et al, 1999
[B] P (well tested by pumping at a constant rate), F (artesian well, tested by allowing it to flow at a constant rate)
[C] Values denoted with an * were assumed for analysis purposes. The assumed value represents the average storage coefficient for that unit as measured during the aquifer tests.
[D] T (aquifer transmissivity), S (aquifer storage coefficient)
[E] PGG (Pacific Groundwater Group), R&N (Robinson and Noble)

Table 2 - Comparison of horizontal hydraulic conductivity values derived from aquifer test and well specific-capacity data

Well number	Hydro-geologic unit [A]	Transmissivity estimated from aquifer test (ft^2/day)	Aquifer thickness (ft)	Horizontal hydraulic conductivity (ft/day)		
				Aquifer test	Specific capacity (Thomas et al., 1999)	Corrected [B] specific capacity
30N/03W-17F02	5	2005	170 [C]	12	23	15
30N/03W-17F03	5	2353 to 3463	175	13 to 20	-	37
30N/03W-17F04	5	4680 to 7032	88	53 to 80	-	35
30N/03W-32E01	1	345	16	22	45	-
30N/04W-07R02	5	1470	137	11	9.2	5.2
30N/04W-09L02	6	21390	64	334	220	317
30N/04W-25C11	1	6069 to 18315	112	54 to 164	32	49
30N/04W-25C12	1	4973 to 15548	78	64 to 199	-	76

[A] After Thomas et al., 1999.
[B] The indicated values were derived using a computerized technique developed by Bradbury and Rothschild (1985) which incorporates correction factors for partial penetration and well loss.
[C] Aquifer thickness estimated from cross-section B-B' in Thomas et al., 1999.

Appendix

Summary of Specific-capacity Methods

Drost Study

Drost, 1983, used specific-capacity data from approximately 530 wells to define hydraulic conductivity values for the study area aquifers. Of this total, 485 wells were completed in the water table aquifer (unit 1), 46 in the upper confined aquifer (unit 3), and three in the lower confined aquifer (unit 5). The specific-capacity data were first adjusted using the Jacob method (in Bentall, 1963) to account for partial penetration effects. The corrected data for unit 1 wells were then used to calculate transmissivity values via the Theis method (in Bentall, 1963). The resultant transmissivity estimates were then divided by the aquifer saturated thickness to obtain horizontal hydraulic conductivity values. For wells completed in units 3 and 5, transmissivity values were estimated using the Brown method (in Bentall, 1963).

Thomas Study

Thomas et al. (1999) evaluated specific-capacity data for 229 wells. Of these wells, 167 were completed in unit 1; 7 in unit 2; 36 in unit 3; 17 in unit 5; and 1 in unit 6. For wells with screened, perforated, or open hole (uncased bedrock) completions, Thomas used a modified version of the Theis equation (Ferris et al., 1962) to estimate transmissivity using Newton's iterative method (Carnahan et al., 1969).

$$T = \frac{Q}{4\pi s} \ln \frac{2.25Tt}{r_w^2 S} \qquad \text{(Equation 1)}$$

Where

T	is the transmissivity of the hydrogeologic unit contained within the open interval of the well, in square feet per day
Q	is the well discharge rate, in cubic feet per day
s	is drawdown in the well (at pumping rate Q), in feet
t	is the duration of pumping, in days
r_w	is the effective well radius, in feet
S	is the formation storage coefficient, dimensionless

Based on previous modeling work by Drost (1983), Thomas used an assumed storage coefficient of 0.12 for unit 1 wells and a value of 0.00001 for wells completed in units 3, 5, 6, and 7. The resulting transmissivity estimates were then used to derive hydraulic conductivity values using the following equation.

$$K_h = \frac{T}{b} \quad \text{(Equation 2)}$$

Where

K_h	is the horizontal hydraulic conductivity of the unit, in feet per day
T	is the estimated transmissivity derived using equation 1
b	is the length of the well screen, perforations, or open interval (as appropriate), in feet

The assumption that the open interval for a well is equal to the total aquifer thickness may yield high estimates of hydraulic conductivity. However, the amount of error introduced by this assumption is probably small, due to natural layering within and between aquifers which favors horizontal flow.

Hydraulic conductivity values for open-ended wells (those without screens, casing perforations, or uncased-open intervals) were calculated using Bear's (1979) equation for hemispherical flow to an open-end well that just penetrates (barely enters) an aquifer. When modified to describe spherical flow to an open-ended well completed within an aquifer, the equation becomes:

$$K_h = \frac{Q}{4\pi s r} \quad \text{(Equation 3)}$$

Where

K_h	is the horizontal hydraulic conductivity of the unit, in feet per day
Q	is the well discharge or pumping rate, in cubic feet per day
s	is the drawdown in the well (at pumping rate Q), in feet
r	is the well radius, in feet

This Evaluation

During this evaluation a computerized technique developed by Bradbury and Rothschild (1985) was used to estimate hydraulic conductivity values from corrected specific-capacity data. The Bradbury program is based on Ferris's modification of the Theis equation (equation 1) but also includes drawdown corrections for well loss and partial penetration effects proposed by Csallany and Walton (1963) and Brons and Marting (1961).

$$T = \frac{Q}{4\pi (s - s_w)} \left[\ln\left(\frac{2.25\,Tt}{r_w^2 S}\right) + 2\,s_p\right] \quad \text{(Equation 4)}$$

Where

T	transmissivity (L^2/t)
Q	the well discharge or pumping rate (L^3/t)
s	drawdown in the well (at pumping rate Q) (L)
t	the duration of pumping (t)
S	the formation storage coefficient (dimensionless)
r_w	the radius of the well (L)
Tt	the initial estimate of transmissivity used by the program (L^2/t)
s_w	the well loss correction factor (L)
s_p	a factor to correct for partial penetration

The transmissivity values estimated by the program were divided by the aquifer thickness to obtain hydraulic conductivity values in units of feet per day.