RGDSS Memorandum
Final

To:	Mike Sullivan, P.E.	Colorado Division of Water Resources
	James Heath, P.E.	Colorado Division of Water Resources
From:	Eric J. Harmon, P.E.	HRS Water Consultants, Inc.
Subject:	Review of Water Level Layer Assignment Protocol in Confined Layers	
Date:	June 22, 2015	

Introduction

This analysis was done at the request of the RGDSS Peer Review Team ("PRT") to assess whether the present protocol used to assign measured water levels to confined aquifer layers in the SLV for use in RGDSS calibration is appropriate. The PRT asked HRS to review the current protocol for head assignment and suggest any needed refinements or improvements to this procedure.

Current Protocol: Criteria for Assignment of Measured Water Levels

In the RGDSS, measured head in a well used for water level monitoring and model calibration is assigned according to the following protocol:[1]

1) If the aquifer layer assigned to a particular well used for water level monitoring has been selected by others (e.g. RGWCD, RGDSS Piezometers, designated in the GRSA Dunes model, or provided by Davis Engineering) the head measurements are assigned to that layer.

2) If a perforated interval is defined, the bottom of the well is defined as the bottom of the perforations, otherwise total depth (TD) is used as the bottom of the screened or perforated interval.

3) If the bottom of the screened interval is known, it is used to determine the layer as follows:
   a) If the bottom is in layer 1 or layer 5, no adjustment is made, and the measurements are assigned to that layer.
   b) If the bottom of the screened interval is less than 6 feet below the top of a layer, the head measurements are assigned to represent the next shallower layer.

[1] Schrueder, W., August 2013, email communication to E. Harmon.

4) If the bottom of the screened interval is unknown:
    a) Head measurements for wells labeled “Unconfined wells” are assigned to layer 1.
    b) Head measurements for wells labeled “Confined wells” are assigned to layer 2.

5) If no information can be found as to total depth or screened interval, the well is not used.

Correction of Water Levels in a Multiply-Completed Monitoring Well

In many situations the only monitoring wells available are screened across two or more aquifer layers. Oftentimes the aquifer layers each have a distinct confined potentiometric head due to the presence of vertical gradients between layers. The head measured in the well (h_w) is a composite head of all aquifer layers screened. The dilemma is whether it is appropriate to use the measured composite head to estimate what the true head is in any one aquifer layer, and whether the current layer assignment protocol is appropriate.

If we have a non-pumping well that is screened across two (or more) confined aquifers; if it is reasonable to estimate that the well is nearly at a steady-state, if there is minimal leakance between aquifer layers, and if we know or can reasonably estimate the T and thickness of each aquifer layer, then the method of Sokol (1963)[2] can be used as a simple method to estimate the actual head in each layer based on the single, composite head measurement in the multi-layer well (see figure 1).

[2] Sokol, D., February 15, 1963, Position and Fluctuations of Water Level in Wells Perforated in More Than One Aquifer. Journal of Geophysical Research, Vol. 68, No. 4, pp. 1079-1080.

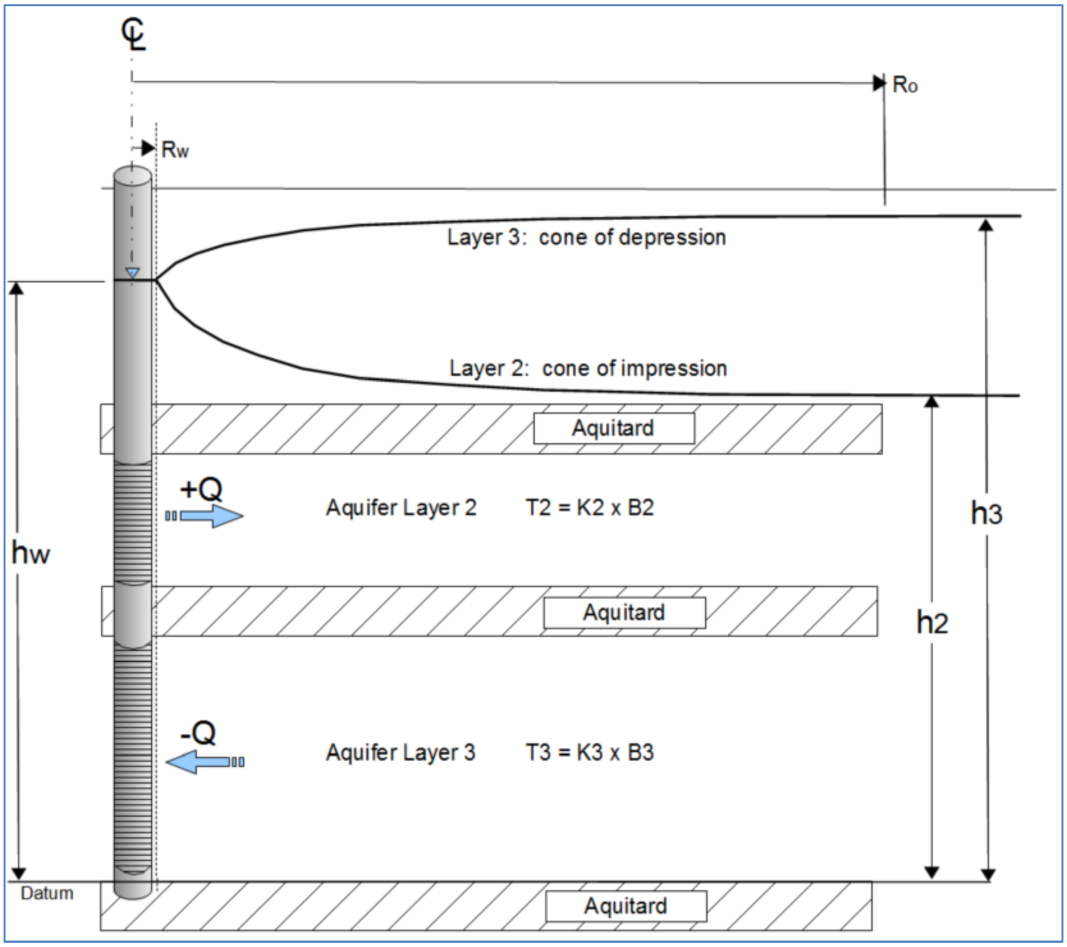

Figure 1: After Figure 1 of Sokol (1963), water level in a well perforated in two aquifers. B2 and B3 are the thicknesses of Layer 2 and Layer 3, respectively

For a multiply-completed confined aquifer well that is either capped (shut in and not allowed to flow or in which the head is not sufficiently high to flow, Sokol proposed using the Thiem equation. Sokol's method use the facts that, 1) the net flow rate from the well is zero, and 2) the head in each aquifer layer at some distance (R_0) are the true heads in the confined aquifer layers screened. In this example, they are shown as Layer 2 and Layer 3, respectively (h_2 and h_3).

Figure 1 shows a situation where Layer 1 (unconfined) is ignored; the aquitards are ideal (nonleaky), Layers 2 and 3 are confined, and there is an upward gradient. Due to movement of water up the well, a cone of depression will form in Layer 3 due to discharging at a rate of –Q, and a cone of impression will form in Layer 2 due to recharging at a rate of +Q.

The fact that the net discharge (Q) from the well is zero in this situation can be expressed as follows for an n-layered system of aquifer layers, even if the flow up or down the casing from one layer to another is non-zero:

$$Q_1 + Q_2 + \cdots + Q_n = 0 \tag{1}$$

$$\sum_{L=0}^{n} Q_i = 0 \tag{2}$$

(Note that if needed this relationship can be generalized for a flowing well [∑Q > 0]).
In simple form the Thiem equation, which describes drawdown at any distance from a pumped well in a steady-state condition, (and homogeneous, isotropic, and infinite in areal extent) can be expressed as:

$$Q = \frac{2\pi T(h - h_w)}{ln(\frac{r}{r_w})} \tag{3}$$

By substitution:

$$\frac{2\pi T_1(h_1 - h_w)}{ln(\frac{r_0}{r_w})} + \frac{2\pi T_2(h_2 - h_w)}{ln(\frac{r_0}{r_w})} + \cdots + \frac{2\pi T_n(h_n - h_w)}{\ln\left(\frac{r_0}{r_w}\right)} = 0 \tag{4}$$

Which reduces to:

$$T_1(h_1 - h_w) + T_2(h_2 - h_w) + \cdots + T_n(h_n - h_w) = 0 \tag{5}$$

Solving for h_w:

$$h_w = \frac{T_1 h_1 + T_2 h_2 + \cdots + T_n h_n}{T_1 + T_2 + \cdots + T_n} \tag{6}$$

If we now impose a water level change (Δh_w) on the head in the well *(h_w)* due to a change in head in one of the aquifer layers in the system (Δh_1) this can be expressed as:

$$h_w + \Delta h_w = \frac{T_1(h_1 + \Delta h_1) + T_2 h_2 + \cdots + T_n h_n}{T_1 + T_2 + \cdots + T_n} \tag{7}$$

Substituting the expression for (h_w) in equation (6) and reducing terms gives:

$$\Delta h_w = \frac{T_1 \Delta h_1}{T_1 + T_2 + \cdots + T_n} \tag{8}$$

Thus the change in head measured in a well screened across more than one aquifer layer (Δh_w) is proportional to the ratio of T_1 (the T of the layer in which the head change occurred) to the total T of all the aquifer layers in the system.

From the foregoing discussion, it is evident that how closely the measured head in the well matches the true head in any screened aquifer layer will depend on the T contrast between the layer in question and the composite T of all of the aquifer layers screened in the well.

Hypothetical Example 1: Multi-completed well, full penetration in two aquifer layers

As a simple illustrative example, typical SLV confined aquifer layer characteristics may be represented by the values in Table 1. This example is not intended to represent any particular well in the SLV.

Table 1

Example: typical aquifer layers characteristics			
Layer	**Kh (ft/d)**	**b (ft)**	**T (ft^2/day)**
L2	10	200	2,000
L3	30	300	9,000
L4	20	800	16,000
Total		1,300	27,000

If a confined-aquifer well is 1,300 feet deep and is screened in the interval from 200 to 1,300 feet (i.e. across none of L2 and across 100% of L3 and L4) then from equation (8) a **10-foot** change in head in L4 (with no head changes in L2 or L3) would result in a measured head change (Δh_w) of **6.40** feet in the multi-completed well:

$$\Delta h_w = \frac{(16{,}000 \times 10)}{25{,}000} \tag{9}$$

This suggests that a measured head change assigned to the deepest screened layer in a well that is also screened and has substantial transmissivity in other layers, may benefit from a correction based on the foregoing. This method implicitly assumes, however, that there is no vertical communication between the aquifer layers except in the multi-completed well. If there is substantial vertical leakance between aquifers, or if the T in the layer to which the measurement is assigned is substantially larger than T in the other screened layers, then the difference between measured head and true head is likely to be much smaller than this example indicates. Leakance and vertical movement of ground water between layers does exist in many areas of the SLV, as shown by head differences in nearby wells screened at different depths, and by downhole flow logging[3] and aquifer test results[4]. Large contrast in T between screened layers is more site-specific, but also exists in some areas.

Effect of Partial Penetration on T

A relatively common situation is depicted in Figure 2, where one aquifer layer – often the deepest layer – is partially penetrated and screened. According to the present RGDSS protocol, if less than 6 feet of the deepest aquifer layer is screened, then the next shallower layer is assigned the head measurements from that well. Conversely, if the deepest layer is screened with 6 feet or more, irrespective of the thickness or T of the layer, the well measurements are assigned to the deepest aquifer layer.

[3] Brendle, D., 2002, Geophysical Logging to Determine Construction, Contributing Zones, and Appropriate Use of Water Levels Measured in Confined-Aquifer Network Wells, San Luis Valley, Colorado, 1998–2000. U.S. Geological Water-Resources Investigations Report 02–4058, 58p.
[4] HRS Water Consultants, Inc., 2001, RGDSS Ground Water, Task 28 – Confined Aquifer Preliminary Summary Report. 14p.

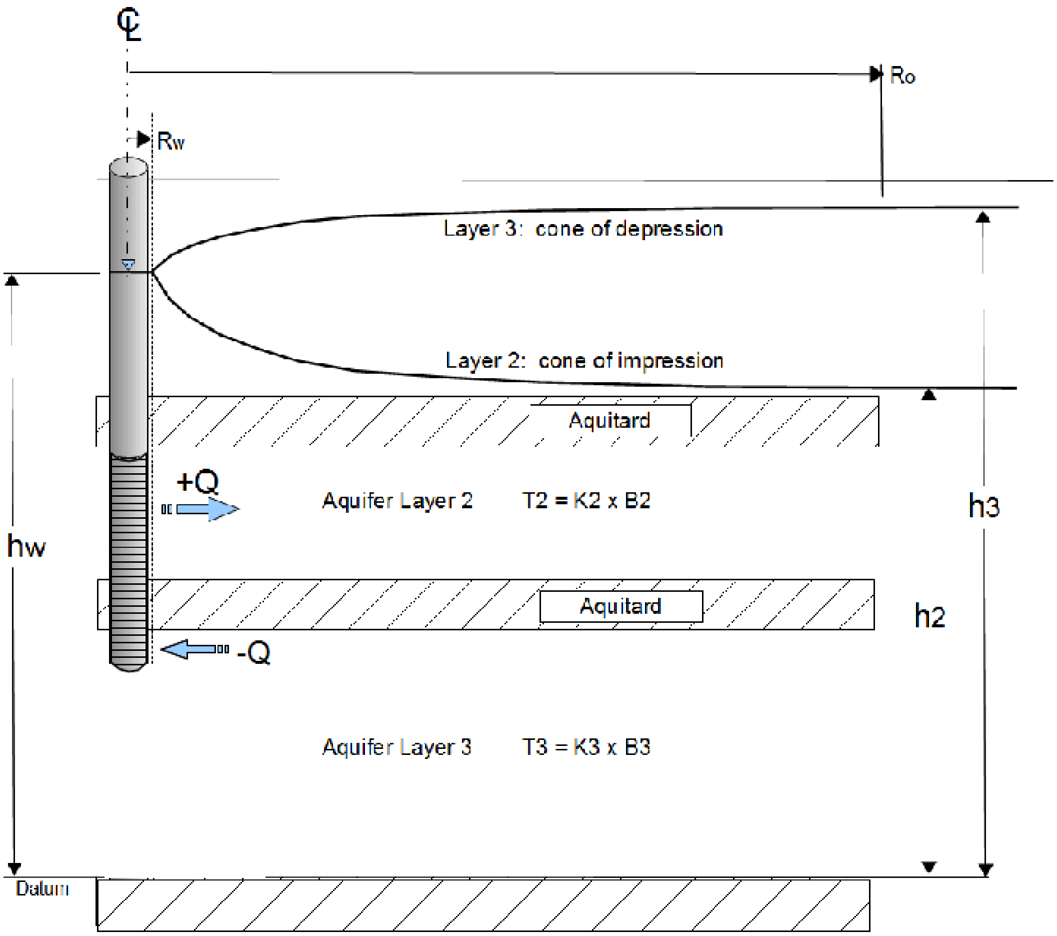

Figure 2: multi-completion with partial penetration in the deepest aquifer layer. B2 ande B2 are the thicknesses of Layer 2 and Layer 3, respectively.

The analysis discussed above using the T ratio from the Thiem equation should still apply although the partially-penetrated aquifer may require T adjustment. It is worth considering whether a well that penetrates a small percentage of the aquifer layer should be assigned the measured head in the well, because the portion of the layer transmissivity that affects the head change in a multi-completion well, or that one would calculate from test data analysis, in a partially-penetrating well with a small percentage of penetration, may not represent the T of the entire aquifer layer.

A correction to T for a partially-penetrating well based on specific capacity (unit production per unit of drawdown; e.g. gpm/ft) has been developed by various researchers including Turcan, [1963][5] Walton [1970][6] and Bradbury & Rothschild [1985][7].

[5] Turcan, A.M., 1963, Estimating the Specific Capacity of a Well. U.S. Geological Survey Professional Paper 450-E, pp. E-145 – E148.

[6] Walton, W.B., 1970, Groundwater Resource Evaluation. McGraw-Hill, NY. Pp. 310-321.

Jacob's linearization of the Theis equation, which describes drawdown in a pumped well under non-equilibrium conditions, given an aquifer T, S, pumping rate (Q gpm), effective well radius (r_w in ft) and pumping time (t days), can be expressed in terms of specific capacity (Q/s) as[8]:

$$\frac{Q}{s} = \frac{T}{264 \ln \frac{0.3Tt}{r_w{}^2 S}} \tag{10}$$

This equation would pertain for the T of an entire aquifer layer, if fully penetrated by a well. For partial penetration, a correction based on empirical evidence is proposed by Turcan[9] and Walton[10], where Q/s_p is the corrected specific capacity for partial penetration, and P is the ratio of the screened thickness to the aquifer layer thickness (B).

$$\frac{Q}{s_p} = \frac{Q}{s}\left[P\left(1 + 7\sqrt{\frac{r_w}{2PB}}\cos\frac{\pi P}{2}\right)\right] \tag{11}$$

This relationship is independent of T and S. The relationship was developed for another region – central Wisconsin - [11] not the SLV. Increased accuracy is expected to result if a similar empirical relationship were developed for the confined aquifer system of the San Luis Valley.

As an example, at a well completed in SLV confined aquifer Layer 4 with a T = 16,000 ft^2/day (119,700 gpd/ft); S = 5 x 10^{-4}, and r_w of 0.5 ft, the calculated Q/s for the entire aquifer layer after 1 day pumping calculates to 7.99 gpm per foot of drawdown. If the well is screened only in the upper 10% of the aquifer layer thickness, the estimated corrected specific capacity (Q/s_p) is approximately 1.67 gpm per foot of drawdown.

Using the specific capacity to transmissivity relationship (equation 10), the estimated T of the partially-penetrated portion of the aquifer that contributes to the well is approximately 3,350 ft^2/day, or about 21% of the full layer T. Figure 3 shows the relationship between the partial penetration as a fraction of the full aquifer layer thickness versus the ratio of effective T for partial penetration to T for the full aquifer layer thickness.

[7] Bradbury, K.R., Rothschild, E.R., 1985, A Computerized Technique for Estimating the Hydraulic Conductivity of Aquifers from Specific Capacity Data. Groundwater Journal, Vol. 23, no. 2, pp. 240 – 246.
[8] Driscoll, F., 1986, Groundwater and Wells. P. 1021
[9] Turcan, 1963.
[10] Walton, 1970.
[11] Turcan, 1963.

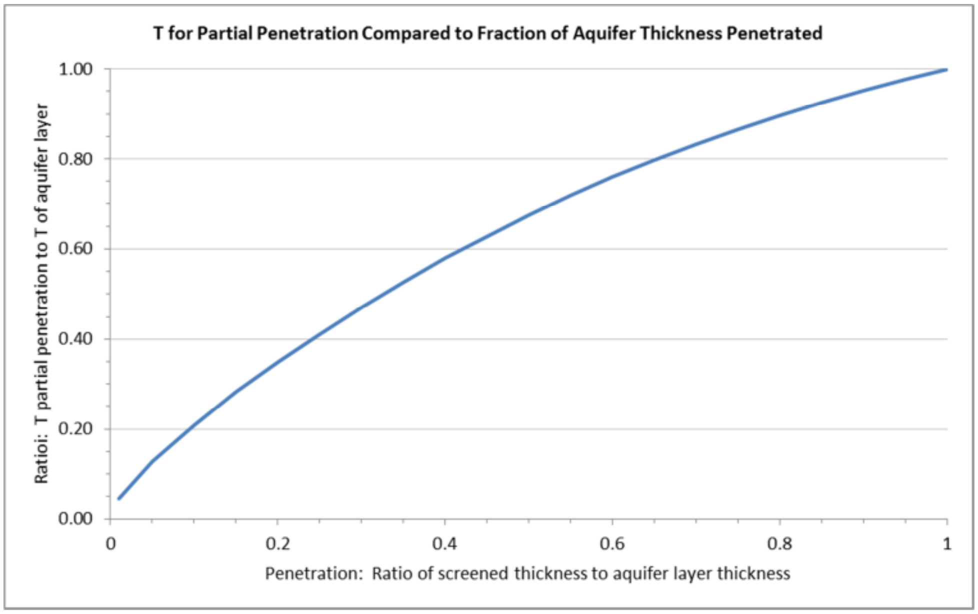

Figure 3: Graph of partial penetration (1 = 100% penetration) versus ratio of T for partial penetration to T for full penetration.

Hypothetical Example 2: Multi-completed well with partial-penetration in deepest layer

When the well has a relatively small percentage of penetration into the deepest aquifer layer, the effect on whether the measured head in the well represents the deepest layer is relatively pronounced. Table 2 shows an example.

Table 2

Example: typical aquifer layers characteristics with partial penetration in L4					
Layer	**Kh (ft/d)**	**b (ft)**	**Partial Penetration**	**Layer T (ft^2/day)**	**Partial T (ft^2/day)**
L2	10	200	1.00	2,000	2,000
L3	30	300	1.00	9,000	9,000
L4	20	800	0.10	16,000	3,344
Total		1,300		27,000	14,344

This is a partial-penetration variation on Example 1 discussed previously. In this example, the confined-aquifer well is 880 feet deep; L4 is 800 feet thick (as in example 1) and the well is screened in the interval from 200 to 880 feet (i.e. across none of L2; across 100% of L3, and only the upper 10% of L4). From equation (8) a **10-foot** change in head in L4 (with no head changes in L2 or L3) would result in a measured head change (Δh_w) of **2.33** feet in the multi-completed well (see equation 12).

$$\Delta h_w = \frac{(3{,}344 \times 10)}{14{,}344} \tag{12}$$

As in the first example, if there is substantial vertical leakance between aquifers, or if the T in the layer to which the measurement is assigned is substantially larger than T in the other screened layers, then the difference between measured head and true head in a partially penetrating well will be smaller than this example indicates.

This relationship can be generalized to explore how the observed head change in a multi-completed well (h_w) relates to actual head change (h_i), if the head change is only due to the deepest layer if the well penetrates that layer in different percentages. This is shown in Figure 4.

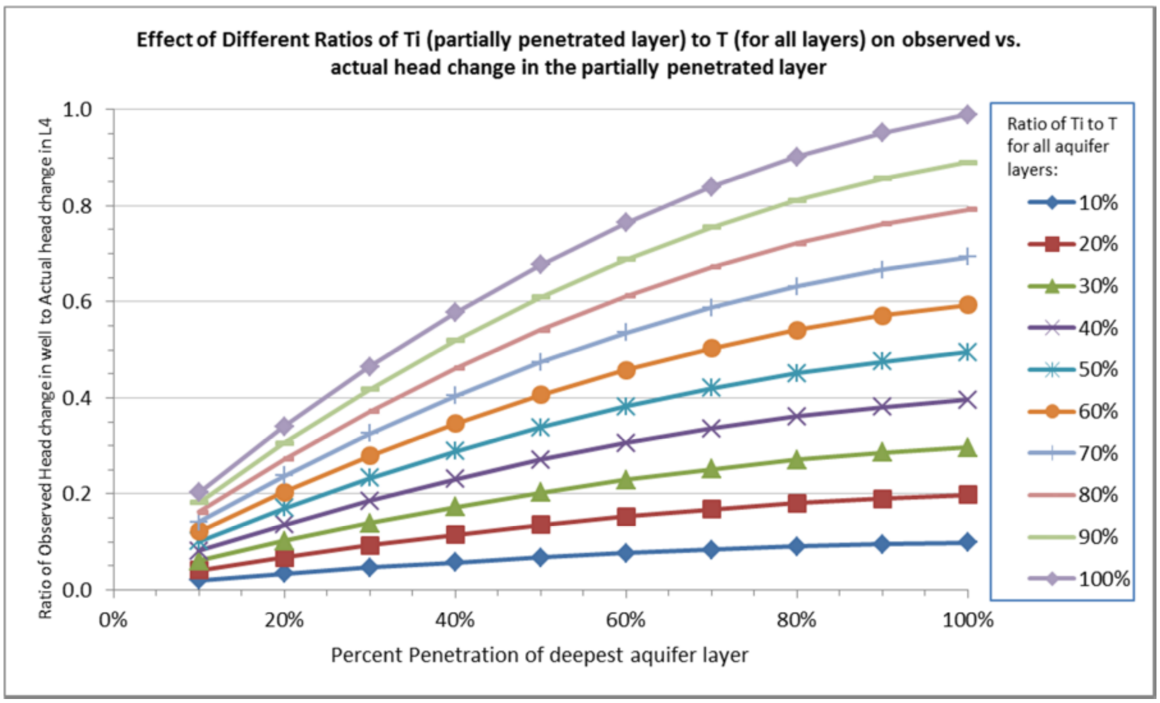

Figure 4

Figure 4 shows that when penetration is only 10% for the deepest aquifer layer, about 5% of an observed head change in the well is attributable to the partially-penetrated layer when the T of the partial penetration is about 30% of the total T of all layers. By contrast, if the T of the partially penetrated layer accounts for only 50% of the total T of all the layers, then penetration approaching 100% of the deepest layer is needed for 50% of the observed head change to be attributable to the actual head change in that layer.

Measured Example: RGWCD Confined Aquifer Well SAG-11

Well SAG-11 is one well of the RGWCD network of confined aquifer monitoring wells, and has a head measurement record from April, 1998, through the present. This well was logged by the U.S. Geological Survey as part of its cased-well flow logging program in 1998 – 2000.[12]

Although not so identified by Brendle or RGWCD, HRS has identified this well as permit no. R-11666. This well was one of the wells tested by HRS during the RGDSS confined aquifer testing phase in 1999 – 2001. RGDSS piezometer P-13 is located approximately 500 feet north of SAG-11. Based on the records of R-11666, the USGS logging, and the lithologic log of P-13, this well has two zones of perforations: 540' to 670' (all in layer 3) and 834' to 1,320 feet (all in Layer 4). The total depth of the well was reported as 1,320 feet (USGS) and 1,347 feet (Well registration of R-11666). The well registration shows perforations continuously from 730' to total depth, 1,347'. Based on the flowmeter logging of the USGS, we believe the ground water inflow depth intervals identified by Brendle from stationary flowmeter measurements (850 to 900 ft, 1,065 to 1,090 ft, 1,170 to 1,250 ft, and greater than 1,274 ft are more accurate.

From RGDSS[13], as compared to the RGWCD well database, at this well location aquifer layer 2 is from 108' – 325'; layer 3 is from 325' to 780', and layer 4 is from 870' – 2,436'. Based on the perforated intervals, the well has zero penetration (slotting) in layer 2; is 28.6% penetrating in layer 3 and 29.3% penetrating in layer 4 (see Table 3).

Table 3

SAG-11 / R-11666: aquifer layer characteristics with partial penetration in L3 & L4					
Layer	**Kh (ft/d)**	**b (ft)**	**Partial Penetration**	**Layer T (ft^2/day)**	**Partial T (ft^2/day)**
L2	--	217	0.0%	1,413	--
L3		455	28.6%	3,900	1,747
L4		1,656	29.3%	15,989	7,296
Total		2,328		21,302	9,043

A T value of approximately 9,000 was interpreted from the RGDSS pumping test of R-11666, with P-13 used as an observation well. The "Layer T" values shown in Table 3 were calculated using the total thickness of each aquifer layer and the thickness of productive material (generally sand or gravel) reported. For layer 3, we used the geologist's description of P-13, located about 500 feet north. For layer 4, we extrapolated to the estimated bottom of layer 4 (2,436') using the driller's description to TD (1,347'). This resulted in an estimated 30% productive material in the

[12] Brendle, D., 2002, Geophysical Logging to Determine Construction, Contributing Zones, and Appropriate Use of Water Levels Measured in Confined-Aquifer Network Wells, San Luis Valley, Colorado, 1998–2000. U.S. Geological Water-Resources Investigations Report 02–4058, pp. 42-44.

[13] HRS Water Consultants, Inc., 2001, RGDSS Ground Water, Task 28 – Confined Aquifer Preliminary Summary Report. 14p.

entire thickness of layer 3, and 60% productive material in layer 4. The Turcan and Walton correction discussed above for estimation of layer T in partially-penetrating wells then was used to estimate the partially-penetrating T of layer 3 and layer 4. The sum of these partially-penetrating T values is 9,043 ft^2/day (see Table 3), which agrees well with 9,000 ft^2/day from the RGDSS pumping test.

The USGS flowmeter log of well R-11666, in its shut-in condition, showed only about 0.8 gallons per minute (0.0018 cfs) flowing upward between layer 4 and layer 3 at the time of their measurements. USGS (Brendle, 2000) measured the inside diameter of the well casing at 10.6 inches. From these data, we have calculated an average uphole velocity of flow of only 0.0029 feet per second. Due to these very small values, in our judgment no correction for head loss due to pipe friction is needed. Also, we have estimated that the drawdown (cone of depression; see Figure 1) in layer 4 due to this discharge from that aquifer layer is negligible.

Using the relationship developed in Equation 8 (copied below) we have estimated the actual head in aquifer layer 4 (to which SAG-11 head measurements are assigned for purposes of model calibration) based on the partial penetration and the ratio of T in layer 4 to T at the L3 / L4 partially penetrating well.

$$\Delta h_w = \frac{T_1 \Delta h_1}{T_1 + T_2 + \cdots + T_n} \tag{8}$$

The estimated head values in aquifer layer 4 are shown below, (see Figure 5).

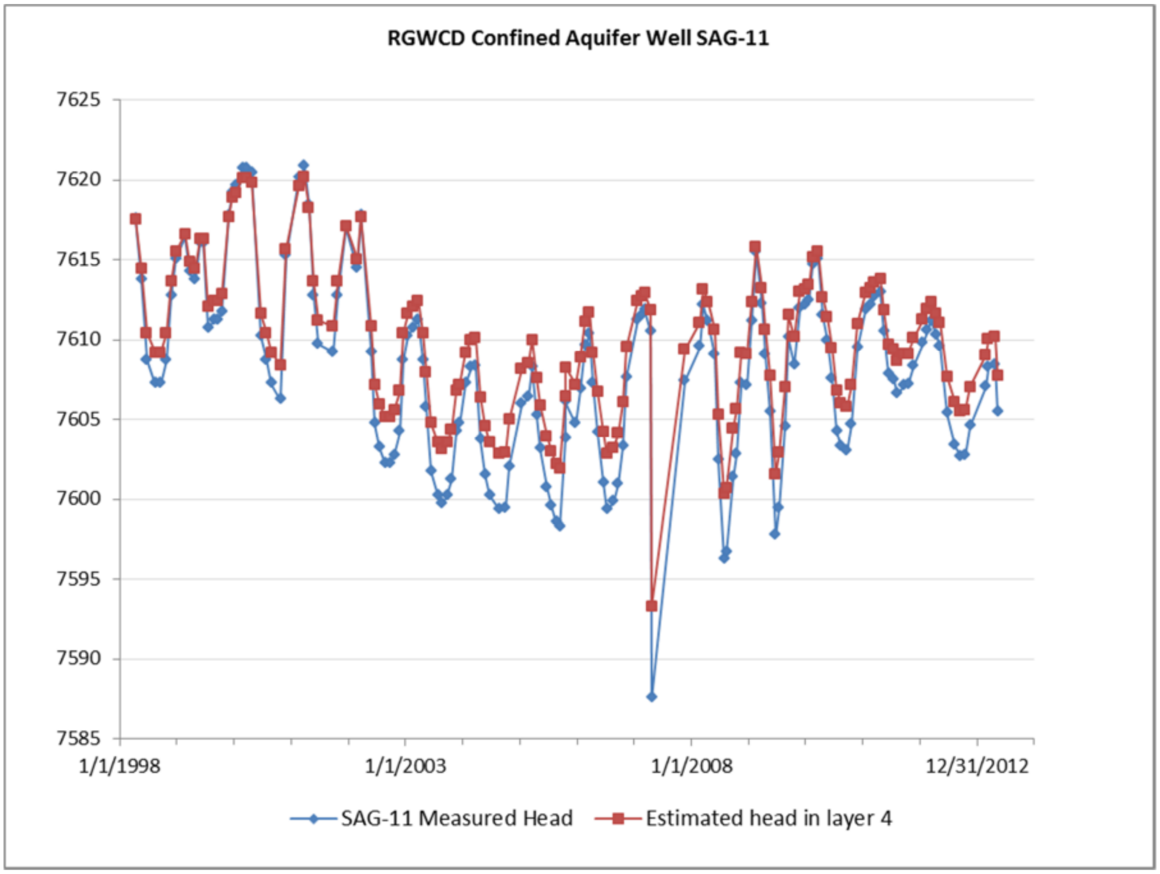

Figure 5: Head in Confined Aquifer Well SAG-11.

Conclusions

From this analysis, we conclude the following:

1. Current protocol, including assignment of observed head change to one confined-aquifer layer, may be attributing too much head change to that layer. The magnitude of any error will be well-specific, and will be most evident where substantial percentages of the total screened interval and the total transmissivity are attributable to shallower confined aquifer layers.

2. For monitoring wells that have only a small percentage of penetration into the deepest layer, the current assignment protocol may be attributing too much of the head change to that layer. A well-specific head correction may be appropriate. This would need to be judged on an individual well basis.

3. Calculations based solely on horizontal ground water movement and nonleaky conditions may overstate the correction needed. It is recommended that several example wells be checked to see whether there is sufficient data in the SLV to establish a SLV-specific

correction factor between full-penetration specific capacity (*Q/s*) and specific capacity for partial penetration (Q/s_p).

Recommendations

The applicability of equation 12 below should be checked against several example wells in the SLV to determine its usefulness.

From Equation 6 above:

$$h_w = \frac{T_1 h_1 + T_2 h_2 + \cdots + T_n h_n}{T_1 + T_2 + \cdots + T_n} \tag{6}$$

A general linear equation that describes the relative weight of each layer of the 4-layer confined system (Layers 2 through 5) measured in a well (h_w) can be written as:

$$h_w = \frac{T_2}{\sum T_i} h_2 + \frac{T_3}{\sum T_i} h_3 + \frac{T_4}{\sum T_i} h_4 + \frac{T_5}{\sum T_i} h_5 \tag{12}$$

In this equation T of a particular layer is zero if there is no contribution from that layer, either through no slotted / screened interval, or because the well is not deep enough to reach, for example, Layer 5. Each layer transmissivity (T_i) in this equation is the T for that layer corrected for partial penetration.

Recommended modifications to the layer assignment protocol, based on Equation 12, are as follows, shown in bold (additions) and strikethrough:

1) If the aquifer layer assigned to a particular well used for water level monitoring has been selected by others (e.g. RGWCD, RGDSS Piezometers, designated in the GRSA Dunes model, or provided by Davis Engineering) the head measurements are assigned to that layer. ***(no change recommended).***

2) If a perforated interval is defined, the bottom of the well is defined as the bottom of the perforations, otherwise total depth (TD) is used as the bottom of the screened or perforated interval. ***(no change recommended).***

3) If the bottom of the screened interval is known, it is used to determine the layer as follows:

   a) If the bottom is in layer 1 ~~or layer 5,~~ no adjustment is made, and the measurements are assigned to that layer.

   b) ~~If the bottom of the screened interval is less than 6 feet below the top of a layer, the head measurements are assigned to represent the next shallower layer.~~

   b) If the well is screened or slotted in more than one confined aquifer layer, Equation 12 shall be used to compare confined aquifer head in a particular layer to the observed head in the well. The T values used should be the best estimates of T that pertain to the location of the well.

4) If the bottom of the screened interval is unknown:

   a) Head measurements for wells labeled "Unconfined wells" are assigned to layer 1.

   b) Head measurements for wells labeled "Confined wells" are assigned to layer 2.

   (no change recommended).

5) If no information can be found as to total depth or screened interval, the well is not used. ***(no change recommended).***