APPENDIX G

CALCULATION OF IN-WELL LOSSES

CALCULATION OF IN-WELL LOSSES

As explained in Section 4.1, drawdown due to in-well losses was considered for each of the wells within the Tier Three Assessment. These in-well losses were calculated using the methodology described below.

The two components of observed drawdown in a given pumping well are shown in the following equation (Bierschenk 1963; Hantush 1964; Jacob 1947):

$$\Delta S_{in-well} = BQ + CQ^2$$

Where s is drawdown, Q is the pumping rate, B is the aquifer loss coefficient, which increases with time (Theis 1935), and C is the well loss coefficient, which is constant for a given pumping rate. The first term of the equation (BQ) describes the linear component of the drawdown (i.e., doubling the pumping rate leads to a doubling of the drawdown). This term accounts for the head losses in the formation in the vicinity of the well. The second term of the equation (CQ^2) describes the non-linear, well-loss component of drawdown (Jacob 1947) in the well itself. This is the additional component that was quantified in this assessment.

Non-linear in-well losses can be estimated using step test results. Step tests are hydraulic tests where a pumping well is pumped at a series of pumping rates and the drawdown throughout the test is recorded. The loss coefficient, *C*, was calculated directly from step test data following the technique developed by Kasenow (1998):

$$C = \frac{s_2Q_1 - s_1Q_2}{Q_1Q_2^2 - Q_2Q_1^2}$$

Where: s1 is the total stabilized drawdown at the end of pumping step 1
Q1 is the pumping rate for step 1
s2 is the total stabilized drawdown at the end of pumping step 2
Q2 is the pumping rate for step 2

For each step test, these coefficients were calculated for consecutive steps and then averaged, to determine the loss coefficient for the well at the time of the step test. The coefficients were conducted across the Region and compiled by Region staff, as shown in Table 7.

The well loss coefficients were used in the following equation (Jacob 1947) to calculate the additional drawdown due to in-well losses for the increased pumping from existing conditions (2008) to the 2031 Allocated Rates:

$$\Delta S_{in-well} = C[(Q_{2008} + \Delta Q)^2 - Q_{2008}^2]$$

Where Q2008 is the existing (2008) pumping rate and ΔQ represents the increase in pumping from 2008 to the 2031 Allocated Rates. The results are shown in Table G1.

Table G1: Well Loss Coefficients and In-Well Losses Statistics

Well	Well Field	Well Loss Coeff. C (m/[m^3/day]^2)	Date of Most Recent Step Test	2008 Pumping Rate (m^3/day)	2031 Allocated Rate (m^3/day)	ΔQ (m^3/day)	Drawdown from In-Well Losses (m)
G4	BLAIR ROAD	7.56E-07	1-May-01	945	1,728	783	1.6
G4A	BLAIR ROAD	0.00E+00		0	1,728	1,728	0.0
G16	CLEMENS MILL	4.07E-07	25-Mar-11	1,666	2,938	1,272	2.4
G17	CLEMENS MILL	1.37E-07	17-Mar-05	1,997	2,160	163	0.1
G18	CLEMENS MILL	3.03E-07	26-Jul-10	1,041	1,296	255	0.2
G6	CLEMENS MILL	2.38E-07	28-Sep-07	1,347	864	-483	-0.3
C3	CONESTOGO PLAINS	0.00E+00	18-Jan-11	70	214	144	0.0
C4	CONESTOGO PLAINS	1.64E-06	23-Oct-07	9	38	29	0.0
P6	DUNBAR ROAD	7.90E-07	20-May-04	884	0	-884	-0.6
G9	ELGIN	8.14E-07	27-Oct-09	1,000	0	-1,000	-0.8
E10	ELMIRA	2.95E-08	3-Sep-03	0	0	0	0.0
W6A	ERB STREET	1.33E-07	21-Apr-11	1,614	1,296	-318	-0.1
W6B	ERB STREET	1.18E-07	18-Mar-11	0	1,296	1,296	0.2
W7	ERB STREET	5.36E-09	9-Feb-00	6,042	6,048	6	0.0
W8	ERB STREET	4.55E-08	12-Dec-10	3,672	2,592	-1,080	-0.3
K70	FORWELL/POMPEII	2.95E-08	15-Jun-06	0	0	0	0.0
K71	FORWELL/POMPEII	0.00E+00	18-Jul-06	0	0	0	0.0
K72	FORWELL/POMPEII	9.83E-07	15-Jun-06	0	0	0	0.0
K73	FORWELL/POMPEII	1.95E-06	15-Jun-06	0	0	0	0.0
K74	FORWELL/POMPEII	1.97E-06	21-Dec-05	0	0	0	0.0
K75	FORWELL/POMPEII	1.42E-06	4-Jan-06	0	0	0	0.0
P16	FOUNTAIN STREET	0.00E+00	3-Nov-05	0	0	0	0.0
K1	GREENBROOK	1.92E-07	21-Oct-94	0	0	0	0.0
K1A	GREENBROOK	2.68E-08	12-Apr-10	372	1,728	1,356	0.1
K2	GREENBROOK	5.76E-08	26-Sep-94	0	0	0	0.0
K2A	GREENBROOK	6.43E-08	6-Jun-08	1,874	1,728	-146	0.0
K4B	GREENBROOK	9.78E-08	13-May-58	3,413	1,728	-1,685	-0.8
K5A	GREENBROOK	0.00E+00	6-Feb-09	957	1,728	771	0.0
K8	GREENBROOK	8.98E-08	18-Oct-02	126	864	738	0.1
H3	HESPELER	8.09E-06	17-Nov-04	561	864	303	3.5
H4	HESPELER	2.77E-06	9-Dec-03	0	1,296	1,296	4.7
H5	HESPELER	6.26E-07	10-Dec-03	383	864	481	0.4
K41	LANCASTER	3.17E-07	14-Jun-07	0	0	0	0.0

Well	Well Field	Well Loss Coeff. C (m/[m^3/day]^2)	Date of Most Recent Step Test	2008 Pumping Rate (m^3/day)	2031 Allocated Rate (m^3/day)	ΔQ (m^3/day)	Drawdown from In-Well Losses (m)
K42A	LANCASTER	2.05E-07	16-Jun-07	0	0	0	0.0
K21	MANNHEIM EAST	0.00E+00	16-Feb-11	2,303	2,592	290	0.0
K25	MANNHEIM EAST	9.38E-09	5-Jun-08	3,813	3,456	-357	0.0
K29	MANNHEIM EAST	6.43E-08	6-Jun-08	2,503	2,592	89	0.0
K91	MANNHEIM PEAKING	0.00E+00	21-Feb-90	674	2,160	1,486	0.0
K92	MANNHEIM PEAKING	0.00E+00	19-Feb-90	813	2,160	1,347	0.0
K93	MANNHEIM PEAKING	0.00E+00	1-Mar-90	813	2,592	1,779	0.0
K94	MANNHEIM PEAKING	0.00E+00	24-Jan-90	843	2,592	1,749	0.0
K22A	MANNHEIM WEST	5.09E-08	29-Apr-08	1,252	0	-1,252	-0.1
K23	MANNHEIM WEST	1.06E-07	24-May-11	2,256	432	-1,824	-0.5
K24	MANNHEIM WEST	3.40E-07	5-Oct-05	2,562	2,592	30	0.1
K26	MANNHEIM WEST	1.34E-09	5-Jun-10	6,841	6,048	-793	0.0
G1	MIDDLETON	4.29E-08	13-Nov-02	3,475	5,184	1,709	0.6
G14	MIDDLETON	1.00E-07	11-Mar-97	3,206	2,160	-1,046	-0.6
G1A	MIDDLETON	1.42E-07	20-Apr-10	3,996	1,728	-2,268	-1.8
G2	MIDDLETON	1.34E-08	27-Feb-96	5,375	6,912	1,537	0.3
G3	MIDDLETON	5.22E-08	11-Mar-97	3,407	4,752	1,345	0.6
G15	WILLARD	8.98E-08	4-Sep-91	2,143	2,592	449	0.2
ND2	NEW DUNDEE	0.00E+00	4-Oct-77	0	0	0	0.0
ND3	NEW DUNDEE	0.00E+00	23-Apr-78	0	0	0	0.0
ND4	NEW DUNDEE	1.43E-06	23-Feb-99	2	2	0	0.0
ND5	NEW DUNDEE	1.22E-07	19-Nov-03	222	222	0	0.0
K31	PARKWAY	8.04E-09	4-Oct-10	2,567	2,160	-407	0.0
K32	PARKWAY	5.09E-08	6-Oct-10	2,270	2,592	322	0.1
K33	PARKWAY	0.00E+00	15-Jan-04	2,894	3,024	130	0.0
G5	PINEBUSH	0.00E+00	28-Sep-07	1,638	1,296	-342	0.0
P10	PINEBUSH	1.93E-07	16-Dec-99	2,943	3,110	167	0.2
P11	PINEBUSH	6.55E-07	13-Oct-09	1,131	1,728	597	1.1
P15	PINEBUSH	3.43E-07	10-Jun-08	962	1,296	334	0.3
P17	PINEBUSH	4.35E-07	15-Jan-04	741	0	-741	-0.2
P9	PINEBUSH	5.89E-07	15-May-03	1,474	1,296	-178	-0.3
G38	SHADES MILL	5.37E-07	15-Jan-04	0	1,296	1,296	0.9
G39	SHADES MILL	1.13E-07	11-Mar-05	0	2,592	2,592	1.0
G7	SHADES MILL	4.15E-08	24-Mar-06	2,306	1,728	-578	-0.1
G8	SHADES MILL	3.11E-07	27-Oct-09	1,206	864	-342	-0.2
SA3	ST. AGATHA	0.00E+00	25-Jun-86	8	0	-8	0.0

Well	Well Field	Well Loss Coeff. C (m/[m³/day]²)	Date of Most Recent Step Test	2008 Pumping Rate (m³/day)	2031 Allocated Rate (m³/day)	ΔQ (m³/day)	Drawdown from In-Well Losses (m)
SA4	ST. AGATHA	0.00E+00	20-Jan-88	12	0	-12	0.0
SA5	ST. AGATHA	2.56E-07	15-May-85	52	0	-52	0.0
SA6	ST. AGATHA	8.16E-07	2-Oct-85	37	0	-37	0.0
K10A	STRANGE STREET	5.34E-07	18-Jan-11	327	432	105	0.0
K11	STRANGE STREET	8.81E-07	16-Oct-02	0	0	0	0.0
K11A	STRANGE STREET	0.00E+00	2-Mar-10	199	1,728	1,529	0.0
K13	STRANGE STREET	0.00E+00	10-Nov-09	526	1,296	770	0.0
K18	STRANGE STREET	1.23E-07	29-Mar-10	2,160	1,296	-864	-0.4
K19	STRANGE STREET	1.49E-07	12-Apr-10	216	1,296	1,080	0.2
K34	STRASBURG	1.47E-07	7-Oct-10	3,184	2,764	-420	-0.4
K36	STRASBURG	1.65E-06	7-Oct-10	0	0	0	0.0
W10	WATERLOO NORTH	3.09E-07	10-Nov-06	0	1,296	1,296	0.5
W5A	WATERLOO NORTH	0.00E+00	4-Jun-08	1,614	0	-1,614	0.0
WM1	WEST MONTROSE	0.00E+00	12-Dec-10	69	0	-69	0.0
WM2	WEST MONTROSE	0.00E+00	12-Dec-10	0	0	0	0.0
WM3	WEST MONTROSE	0.00E+00	12-Dec-10	0	0	0	0.0
WM4	WEST MONTROSE	5.03E-06	12-Dec-10	0	0	0	0.0
W1B	WILLIAM STREET	1.00E-07	7-Nov-12	818	432	-386	0.0
W1C	WILLIAM STREET	0.00E+00	14-Mar-12	14	2,160	2,146	0.0
W2	WILLIAM STREET	4.55E-07	22-Apr-09	2,384	1,728	-656	-1.2
W3	WILLIAM STREET	3.20E-06	16-Jun-98	0	0	0	0.0
K80	WOOLNER	1.33E-07	12-Jan-06	0	0	0	0.0
K81	WOOLNER	1.39E-07	11-Jan-06	220	0	-220	0.0
K82	WOOLNER	2.68E-08	19-Jan-06	1,072	0	-1,072	0.0

As outlined in Table G1, drawdown due to non-linear, in-well losses is minimal for the majority of the municipal wells within the Region. The only well field that appears to possess reasonably high in-well losses is Hespeler; with losses of 3.5 and 4.7 m at H3 and H4, respectively. The majority of wells have minor (< 0.25 m) in-well losses, or show gains within the in-well water level elevation as the Allocated Rates demands are expected to be lower than the 2008 demands.

REFERENCES

Bierschenk W.H. 1963. *Determining Well Efficiency by Multiple Step-Drawdown Tests*. International Assocociation of Scientific Hydrology Bulletin. Publ. 64; 493-507.Hantush M.S. 1964. *Hydraulics of Wells, Advances in Hydroscience*. Volume 1. Academic Press. New York and London.

Jacob C.E. 1947. “Drawdown test to determine effective radius of artesian well.” *Transactions of the American Society of Civil Engineers 112(1)*: 1047-1064.

Kasenow, M.C. 1998. Analysis and Design of Step-Drawdown Tests. Water Resources Publications, LLC, Highlands Ranch, Colorado. Theis C.V. 1935. “The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage.” *Transactions, American Geophysical Union 16 (2)*: 519-524.

APPENDIX H

DERIVATION OF SAFE ADDITIONAL AVAILABLE DRAWDOWN VALUES

Derivation of Safe Additional Available Drawdown Values

The Safe Additional Available Drawdown value used in the Risk Assessment is the difference between the existing conditions (2008) water level elevation, and the safe water level elevation reported by the region (which may be coincident with the top of screen, open hole, etc.). Some wells in the Risk Assessment were missing groundwater elevations in 2008 or had erroneous groundwater elevations and alternative methods were used to estimate reliable pumped water level elevations within those wells; these alternative methods are outlined below.

Several municipal wells in the Region record the depth to water level within the well using an air-line technique. The air-line method is less reliable than wetted tape methods, but groundwater elevations can be collected in wells where turbulence in the well may preclude the use of a more precise method. The air-line method is convenient, non-intrusive and once installed can be left in the well for future measurements. The disadvantage of using an air-line method is the quality of the water level measurements is dependent on the accuracy and range of the pressure gauge, and the precision to which the length of the air-line is known.

Given the uncertainty with the air-line data, the erroneous groundwater elevations recorded in some wells in the region were disregarded and the groundwater elevations in nearby monitoring wells were used to estimate the pumped water level elevations from within the production wells in 2008. Details regarding the wells and the methodologies used to derive 2008 pumped water level elevations (used in the Safe Additional Available Drawdown calculation) are outlined in detail below. (Note: municipal well hydrographs, illustrating the observed pumped groundwater elevations within the wells, are illustrated in Appendix F).

Strange Street

K11/K11A – Well K11A replaced Well K11 in 2008. The pumped water level data for 2008 represents Well K11 performance, as Well K11A performance was not available for use. Aquifer groundwater elevations for Well K11A were determined from adjacent monitoring wells as an average of the data for 2008. The average 2008 pumped water level for Well K11A was estimated from the aquifer groundwater elevations based on the average 2008 pumping rate and the measured specific capacity of Well K11A following well construction.

K13 – Well K13 was replaced by Well K13A in 2013 due to poor performance of Well K13. Pumped water level data for 2008 represents performance in Well K13 as performance data for Well K13A was not available. Aquifer groundwater elevations were determined from adjacent monitoring wells as an average of the data for 2008. The average 2008 pumped water level for Well K13A was estimated from the aquifer groundwater elevations based on the average 2008 pumping rate and the measured original specific capacity of Well K13 following well construction. This assumes that the new Well K13A will be of similar specific capacity as Well K13 when it was first constructed.

K18/K19 - Well K19 was offline for all of 2008 and water level data were unavailable for this well. No nearby monitoring wells were available to estimate aquifer groundwater elevations in 2008. To further complicate the situation, Well K18 (situated adjacent to Well K19) was operated only part of the year and so there is limited data collected in that well in 2008 to reflect the average 2008 pumped groundwater elevations for Well K18. As a result, historical pumping rate data were reviewed to identify a time period where the average pumping rate was similar to the 2008 rate, and where there were sufficient data to estimate an average pumped water level. For this analysis, available data for the first 8 months of 2005 were selected and an average of these pumped groundwater elevations was used. This value was assumed representative of the average 2008 pumped water level in Well K18. To estimate a representative water level in the aquifer outside the well at the average 2008 pumping rate, the specific capacity of the K18 was used (i.e., the estimated drawdown was added to the average pumped water level in Well K18 as determined above). As Well K19 was not pumping in 2008, and other water level data were unavailable, the estimated average 2008 aquifer water level was assumed to represent the water level in Well K19. This may underestimate the extent of well interference of Well K18 on Well K19; however, the estimated aquifer water level is very similar to that of other nearby wells in the well field, which suggests this is a reasonable estimation.

William Street

W1C – Well W1C was offline in 2008. As a result, no representative water level data were collected in this well for this time period. Aquifer groundwater elevations were determined from adjacent monitoring wells as an average of the water level data for 2008. As Well W1C was not pumping in 2008, the estimated average 2008 aquifer water level was assumed to be coincident with the water level in the well.

W2 – It was determined that 2008 pumped water level data for Well W2 were unreliable due to air-line measurement issues. To estimate the average 2008 pumped water level in Well W2, the specific capacity of the well and the average 2008 pumping rate were used to estimate the average drawdown that would be expected in the well. This estimated drawdown was subtracted from the average aquifer groundwater elevations reported in nearby monitoring wells.

Strasburg

K36 – Well K36 was offline in 2008 and no water level data were collected over this period. In addition, there were no adjacent monitoring wells available in 2008. A nearby monitoring well provided an indication of the non-pumping groundwater elevations in the aquifer during 2003, and a representative 2008 aquifer water level was determined using the observed 2003 data. As Well K36 was not pumping in 2008, the estimated average 2008 (2003) aquifer water level was assumed to represent the water level in the well.

Waterloo North

W10 – Well W10 was not pumping in 2008 and as such, water level data were unavailable. The aquifer groundwater elevations were estimated using observed groundwater elevations from 2008 collected in an adjacent monitoring well. As Well W10 was not pumping in 2008, the estimated average 2008 aquifer water level was assumed to represent the water level in the well.

Hespeler

H4 – Well H4 was offline in 2008 and there were limited water level data obtained. In addition, there were no adjacent monitoring wells available in 2008. The typical aquifer water level under non-pumping conditions was estimated using available data for Well H4 from previous years. This water level was assumed to represent the water level in Well H4 in 2008.

H5 – Well H5 was only operated during the summer months in 2008 and as such, very limited pumped groundwater elevations exist for this well in 2008. As a result, there were no representative water level data for this well that reflect this condition. No adjacent monitoring wells available for 2008, so the representative pumped water level in Well H5 for 2008 was estimated using historical pumping rate data to identify a time period where the average pumping rate was similar to the 2008 rate and where there were sufficient data to estimate an average pumped water level. For this analysis, the available data for 2006 were selected and an average of these pumped groundwater elevations was determined. This value was assumed to be representative of the average 2008 pumped groundwater elevations in Well H5.

Middleton

G1A - Well G1A has limited available pumped water level data that could be used to estimate an average pumped water level for 2008. Aquifer groundwater elevations were determined using adjacent monitoring wells as an average of the available data for 2008. The average 2008 pumped water level for Well G1A was estimated from the aquifer groundwater elevations based on the average 2008 pumping rate and the measured specific capacity of Well G1A.

Pinebush

G5 – Pumping water water level data from 2008 was unavailable for this well. There were also no nearby monitoring wells that could be used to estimate average 2008 aquifer groundwater elevations. To estimate a representative pumped water level in Well G5 for 2008, the historical pumping rate data were reviewed to identify a time period where the average pumping rate was similar to the 2008 rate and where there were sufficient data to estimate an average pumped water level. For this analysis, the available data for 2005 were selected and an average of these pumping groundwater elevations was determined. This value was assumed to be representative of the average 2008 pumped water level in Well G5. This value was conservatively also applied to represent the 2008 pumped water level in Well G5A, which was not drilled until 2011.

P9/P15 – These wells are located at the same site. Pumped water level data were not collected in 2008 for Well P15, and limited 2008 pumped water level data were available for Well P9. In addition, there were no adjacent monitoring wells within the production aquifer available in 2008. The average pumped water level for Well P9 was estimated from the available monitoring data, and the average 2008 pumped water level for Well P15 was assumed to be similar to Well P9, as the wells were pumping at similar rates, have similar specific capacities and are in close proximity to each other.