Improvement of the Johns/Goldsborough Groundwater Model from Steady-State to Transient: Incorporating Variable Recharge

DRAFT

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Table of Contents

A. Introduction, purpose, and scope

The purpose of the study described in this report is to convert an existing, steady-state groundwater flow model for the Johns/Goldsborough watershed into a transient (i.e., time-varying) model. The steady-state model, which was developed in a previous phase of this study and is described in Keta Waters (2015), simulates average groundwater conditions while the transient model describes seasonal fluctuations in these conditions.

The area included in the study is shown in Figure A.1. The study area covers approximately 160 mi^2 in southeastern Mason County, Washington, and includes the Goldsborough Creek subbasin, which drains an area of approximately 60 mi^2, and the Johns Creek subbasin, which drains an area of approximately 11 mi^2. This is the same area that was included in the steady-state model for the Goldsborough and Johns Creek watersheds (Keta Waters, 2015).

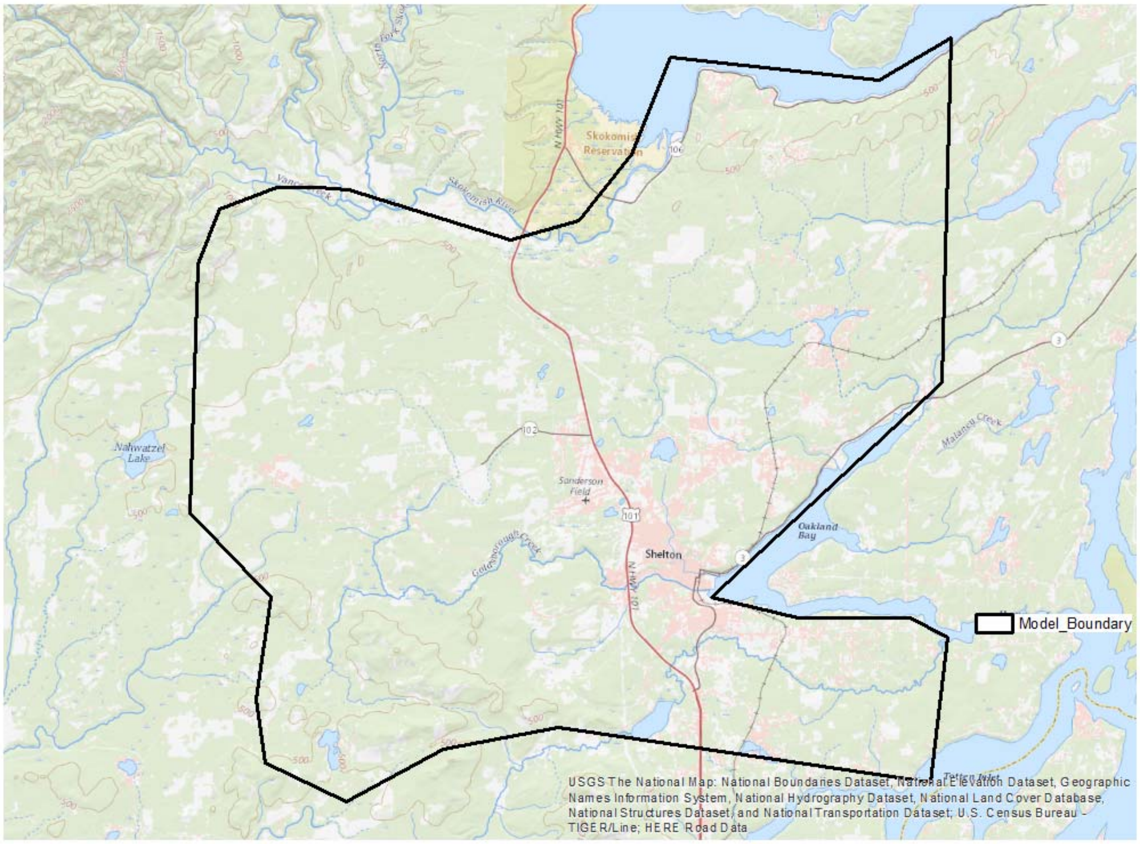
The transient model incorporates monthly groundwater recharge rates that were derived using the USGS Soil Water Balance (SWB) Model. The monthly variation in recharge rates is the primary driver for the transient groundwater model. The SWB model developed for the Johns/Goldsborough watershed, which is described in Keta Waters (2018), estimates groundwater recharge rates .

Tasks that were completed as part of the current study include the following. Additional detail regarding these tasks is provided in subsequent sections.

1. Downloaded and compiled an updated SWB model.
2. Ran updated the SWB model for all months between (and including) January of 1999 and December of 2019.
3. Compared the SWB results between 1999 and 2017 to evaluate effects of the SWB model update.
4. Incorporated monthly recharge rates from the SWB model into the MODFLOW groundwater flow model.
5. Compiled data on storage parameters required as input to the transient model. This compilation included values used in similar models developed by USGS for watersheds in the Puget Sound area as well as site-specific values from pumping tests completed in the Johns/Goldsborough model area.
6. Incorporated transient groundwater level data collected by USGS at 20 wells located in the model area. The data were incorporated in the groundwater model as monthly averages.
7. Derived baseflow estimates using transient streamflow data measured at four locations in the model area. The baseflow was derived from the streamflow using

the SWAT Software. Baseflow data were incorporated into the model as monthly averages.

8. Calculated groundwater discharge along stream sections based on seepage-run data collected in Goldsborough and Johns Creeks during the summer of 2019.
9. Compared the 2019 seepage run data with data from seepage runs conducted in 2011 (Goldsborough Creek), 2012 (Johns Creek), and 2015 (Johns Creek).
10. Calibrated the model by adjusting storage parameters and comparing calculated and observed baseflows and groundwater levels.



USGS The National Map: National Boundaries Dataset, National Elevation Dataset, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; U.S. Census Bureau - TIGER/Line; HERE Road Data

Figure A.1. Area included in the study

B. Groundwater recharge rates

The strongest driver of transient effects in groundwater systems in western Washington is typically seasonal variations in groundwater recharge rates. A monthly time series of ground water recharge in the Goldsborough and Johns Creek watersheds was developed as part of a previous study (Keta Waters, 2018). The groundwater recharge was calculated using the Soil-Water-Balance (SWB) code developed by the U.S. Geological Survey (Westenbroek et al., 2010). This code was developed explicitly for calculating spatially- and temporally-varying ground water recharge. Input to the model includes land-use type, soil type, surface-water flow direction , temperature, and precipitation. The model employs a water-balance approach to calculate recharge. The approach used in the SWB model is summarized in Keta Waters (2018).

The recharge rates described in Keta Waters (2018) were developed for all months in-between (and including) January of 1999 and December of 2017. In the period since this earlier work was completed, an updated version of the SWB model was published.[1] This updated model was used to develop monthly recharge rates for all months in-between (and including) January of 1999 and December of 2019 as part of the current study. Meteorological input data to the model include daily maximum and minimum temperature and daily precipitation values. Data from the Global Historical Climatology Network (Menne et al., 2012) were downloaded for the Sanderson Field site (KSHN) in Shelton.

Table B.1 compares the average annual recharge rates for the updated model and the previous version used in Keta Waters (2018). On average, the annual recharge from the updated SWB model is 6% less than the previous SWB version.

The average annual recharge rate for the period January 1999 through December 2019 from the updated SWB model is 38.5 inches. As a point of comparison, the average recharge rate used in the steady state model (Keta Waters, 2015) was 29.6 inches year. This value was based on regression equations developed by Bidlake and Payne (2001).

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[1] The updated SWB model was downloaded from https://github.com/smwesten-usgs/swb.
The commit hash (or version id) is 518ad3502da691f0f743cf643fe7cf11121ed579.

Table B.1 Average annual recharge rates for the updated and previous SWB versions (full model domain, including inactive cells)

	Updated SWB model	**Previous SWB version**	**Difference**
	in/yr	**in/yr**	
1999	47.09	50.29	6.4%
2000	29.64	30.02	1.2%
2001	22.55	23.58	4.4%
2002	43.71	46.02	5.0%
2003	35.20	37.94	7.2%
2004	31.70	33.43	5.2%
2005	31.59	32.82	3.7%
2006	43.64	46.67	6.5%
2007	46.43	50.43	7.9%
2008	33.09	36.00	8.1%
2009	31.26	32.97	5.2%
2010	45.04	48.29	6.7%
2011	50.65	53.59	5.5%
2012	40.07	42.60	6.0%
2013	42.41	44.74	5.2%
2014	33.13	35.54	6.8%
2015	44.65	46.88	4.8%
2016	44.52	47.41	6.1%
2017	46.85	50.82	7.8%
2018	49.76	53.41	6.8%
Average, 1999-2018	**39.65**	**42.17**	**6.0%**
2019	27.99	n.a.	n.a.

Table B.2 Monthly average groundwater recharge rates for 2018 and 2019 (only active portion of model)

	Monthly recharge (cfs)	
	2019	**2018**
Jan	960	1556
Feb	469	460
Mar	42	69
Apr	64	327
May	0	0
Jun	0	0
Jul	0	0
Aug	0	0
Sep	1	0
Oct	160	61
Nov	138	688
Dec	942	1436
Average (cfs)	**231**	**383**

C. Overview of model layers and stratigraphy

The stratigraphy and model layering used in the transient model is the same as what was used in the steady-state model described in Keta Waters (2015). A summary and overview of this stratigraphy is provided below.

- Alluvial Aquifer (AA) – Holocene gravel, sand, and silt; clay and peat.
- Upper Aquifer (UA) – Pleistocene sand and gravel; lenses of clay, silt, and fine sand. Vashon glacial deposits – recessional outwash. The AA and UA units were combined in the NWLW model as well as in this study.
- Upper Confining Unit (UC) – Pleistocene unsorted and compacted clay, silt, sand, and gravel; lenses of sand and gravel. Vashon glacial deposits – glacial till and lacustrine deposits.
- Middle Aquifer (MA) – Pleistocene sand, gravel, and silt; occasional lenses of clay. Vashon glacial deposits – advance outwash.
- Lower Confining Unit (LC) – Pleistocene clay and silt; some till; occasional peat and wood. Pre-Vashon, non-glacial deposits; often classified as the Kitsap formation.
- Lower Aquifer (LA) – Pleistocene sand and gravel, silt and clay; some till. Pre-Vashon deposits
- Undifferentiated Deposits (UD) – Pleistocene alternating layers of clay and silt, sand, and gravel. Pre-Vashon deposits.
- Bedrock (BR) – Eocene volcanic and sedimentary rock.

Model Layer	Hydrogeologic Unit
1	UA
2	UC
3	MA
4	LC
5	LA
6	UD
7	BR

D. Specific storage parameters

Transient groundwater models require estimates of specific storage values for the various hydrogeologic units included in the model. The specific storage is a measure of the compressibility and porosity of the hydrogeologic unit. In general, hydrogeologic units with lower specific storage values are "stiffer" and contain less water than units with higher specific storage values. The specific storage values control how quickly hydraulic changes propagate through the groundwater system. Hydrogeologic units with lower specific storage values tend to respond more quickly to changes in pumping rates or groundwater recharge rates.

The specific storage parameters are typically adjusted as part of model calibration. Table C.1 lists calibrated specific storage values for models developed by the USGS for watersheds in the Puget Sound region. These models were selected because they contain hydrogeologic units that are similar to the units used in the JOHNS/GOLDSBOROUGH model. The last three rows in Table C.1 give the minimum, median, and maximum values of the calibrated estimates in the three studies. The median values in these last three rows were used as the starting values in the Johns/Goldsborough transient model.

Table C.1. Specific storage values in ft^{-1} used in USGS Puget Sound modeling studies.

	Kitsap Peninsula (Frans and Olsen, 2016)			
Unit ID	**Low**	**Median**	**High**	**Layer type[1]**
Qvt	2.52E-06	7.16E-06	1.64E-05	C
Qva	3.05E-07	8.01E-07	2.60E-06	A
QC1	2.94E-06	1.02E-05	1.84E-04	C
QC1pi	4.37E-07	6.36E-07	2.64E-06	A
QA1	3.41E-07	7.32E-07	1.91E-06	A
QC2	1.00E-06	5.99E-06	2.42E-04	C
QA2	3.87E-07	9.51E-07	2.41E-06	A
QC3	1.97E-06	7.71E-06	2.23E-05	C
QA3	1.00E-07	9.94E-07	1.95E-06	A
QC4	2.66E-06	8.70E-06	2.64E-05	C
BR1	2.26E-06	9.99E-06	3.14E-05	B
BR2	4.47E-06	8.21E-06	2.59E-05	B
	Chambers-Clover Creek (Johnson et al., 2011)			
AL	1.00E-03	1.90E-03	1.00E-01	A
A1	1.00E-03	5.53E-03	1.00E-01	A
A2	1.00E-06	1.40E-05	1.00E-04	C
A3	1.00E-07	2.48E-06	1.00E-05	A
B	1.00E-06	2.74E-05	1.00E-04	C
C	1.00E-07	1.74E-06	1.00E-05	A
D	1.00E-06	6.09E-06	1.00E-04	C
E	1.00E-07	1.44E-06	1.00E-05	A
F	1.00E-06	5.52E-06	1.00E-04	C
G	3.00E-07	3.00E-07	3.00E-05	U
	Bainbridge Island (Frans et al., 2011			
Qva	2.50E-07	4.80E-07	6.50E-07	A
QC1	2.55E-07	1.40E-06	2.50E-06	C
QC1pi	1.40E-07	2.00E-07	2.40E-07	A
QA1	1.00E-07	1.75E-07	2.85E-07	A
QC2	5.50E-08	9.50E-07	2.50E-06	C
QA2	5.50E-08	1.70E-07	1.95E-06	A
QC3	4.75E-08	1.35E-06	2.50E-06	C
QA3	3.70E-08	1.45E-07	6.00E-07	A
QC4	2.10E-07	1.45E-06	2.50E-06	C
BR	7.50E-07	1.55E-06	2.50E-06	B
All aquifer	**3.70E-08**	**1.95E-07**	**2.64E-06**	A
All confining	**4.75E-08**	**5.99E-06**	**2.42E-04**	C
All bedrock	**7.50E-07**	**8.21E-06**	**3.14E-05**	B

[1] A=aquifer, C=confining unit, B=bedrock

E. Estimating baseflow from continuous streamflow data

Estimates of baseflow were derived directly from continuous streamflow measurements collected at four gauges in the Goldsborough and Johns Creek basins. The locations of the gages are shown in Figure E.1 and listed in Table E.1.

The SWAT software package was used separate baseflow from stream flow (Arnold et al., 1995; Arnold and Allen, 1999)[1]. The SWAT software uses an algorithm with multiple passes. The user's manual indicates that "In general, the fraction of water yield contributed by baseflow should fall somewhere between the value for the first and second pass." The first-pass values, which assign a larger fraction of the streamflow to baseflow, were used in the current study. Monthly average values for the baseflow were calculated and were used as input to the groundwater flow model.

Addendum E.1 includes graphs showing the streamflow and baseflow values. The monthly average values shown in the addendum were input to the groundwater flow model.

Table E.1. Locations of continuous streamflow gages and periods of record used to calculate base flows

Gauge ID	Latitude	Longitude	Start date	End date
12076800	47.2119	-123.1117	10/1/2004	12/31/2019
GOLDS_7TH	47.2114	-123.1079	10/1/2004	9/30/2018
JOHN1	47.2478	-123.0457	10/1/2005	9/30/2018
JOHN2	47.2520	-123.0864	10/1/2004	9/30/2018

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[1] The SWAT software was accessed at the following website during February 2020: http://www.envsys.co.kr/~swatbflow/USGS_GOOGLE/swatbflow_help.cgi

Figure E.1. Locations of the gauges used to derive continuous baseflow estimates.

F. Seepage run data

Data from synoptic stream flow measurements collected at 10 locations on Johns Creek and 10 locations on Goldsborough Creek are available to further constrain the groundwater model. These data provide information related to inflows to the stream over specific stream segments.

The locations for the synoptic flow measurements are shown on Figure F.1 for Johns Creek and on Figure F.2 for Goldsborough Creek. Eight sets of data were collected on Johns Creek between August 2012 and September 2019. These data are included in Table F.1 Three sets of data were collected on Goldsborough Creek between August 2011 and September 2019. These data are included in Table F.2

Table F.1. Summary of data collected during seepage runs on Johns Creek. All values in cfs.

Approximate Location	Map ID	8/16/12	8/23/12	9/5/12	9/14/12	3/4/13	7/14/15	8/20/19	9/4/19
Highway 3	JOH1	12.85	10.80	10.47	9.59	48.30	9.865	6.36	5.61
Upstream of rock pit surface water intake	URP						10.02		
Coldwater Tributary	CWT		2.39	2.12	1.73		2.12	1.29	1.18
Upstream of Coldwater Tributary	UCWT						8.43	4.77	3.83
Downstream of Coldwater Tributary	DCWT		13.08	10.83	10.78	41.50	10.11		
Railroad	RRD	9.00		8.12	7.31			4.03	3.48
Johns Creek Road	JOH2	9.34		7.39	6.78			3.52	2.8
Oak Park	OAK	5.60		4.43	4.10			2.3	1.51
Jenson Road	JER							2.02	1.56
Brockdale Road	BDR		4.27	4.08	3.68			2.41	1.82

Table F.2. Summary of data collected during seepage runs on Goldsborough Creek. All values in cfs.

Approximate location	Map ID	8/26/2011	8/20/2019	9/4/2019
North Fork	GOLNF	8.25	3.41	2.29
South Fork	GOLSF	2.52	1.90	1.65
Confluence	GOLCON	22.48	15.97	14.33
Shelton Matlock Road	GOLSM	25.32	16.32	15.52
Railroad	GOLRR	30.6	20.35	19.71
Above Coffee Creek	GOLUC	32.2	23.61	23.29
Below Coffee Creek	GOLDC	37.8	26.97	27.25
Coffee Creek	GOLCC		3.50	3.93
USGS Gage	GOLUSGS	43	31.97	31.19
Highway 3	GOLHWY3	50.05	33.00	33.29

Figure F.1. Locations used for seepage runs on Johns Creek.

Figure F.2. Locations used for seepage runs on Goldsborough Creek.

G. Groundwater wells used for transient model calibration

Data describing transient groundwater levels were collected by the USGS from twenty wells located within the model area.[1] The locations for these wells are shown in Figure F.1 and are listed in Table F.1. Figure F.1 also includes an outline of the model area. Well logs are included in Addendum F.1 and observed water levels are included in Addendum F.2. Water levels were measured by the USGS on approximately one-month intervals at these wells. The period of observations was between June of 2016 and November of 2019. Methods used in collecting the data are described in Tecca and Frans (2019). Statistics describing the water level measurements are included in Table F.2.

The groundwater wells were incorporated into the model as calibration targets. Table F.2 lists the model layers in which the wells were placed. There are 435 water level targets for these 17 wells.

Table F.1. Locations and depths for wells used in transient model calibration.

USGS name	Name used in model	Latitude	Longitude	Well depth (ft)	Number of measurements
470916123103701	TR_well01	47.15439	123.17703	97	26
470937123144101	TR_well02	47.16019	123.24461	55	25
470956123115801	TR_well03	47.16561	123.19939	340	26
471002123090301	TR_well04	47.16725	123.15078	90	26
471043123060301	TR_well05	47.17869	123.10094	119.6	26
471148123081801	TR_well06	47.19681	123.13833	65	26
471154123095901	TR_well07	47.19828	123.16633	100	25
471155123145201	TR_well08	47.19872	123.24778	80	26
471219123042701	TR_well09	47.20525	123.07419	59	26
471443123035601	TR_well10	47.24517	123.06558	70	26
471445123034201	TR_well11	47.24592	123.06175	341	26
471504123113701	TR_well12	47.25106	123.19369	115	26
471514123152401	TR_well13	47.25385	123.25653	50	26
471620122595201	TR_well14	47.27236	122.99769	160	26
471636123060901	TR_well15	47.27661	123.10261	188	26
471643123073401	TR_well16	47.27622	123.12225	171	11
471718123074801	TR_well17	47.28833	123.13014	300	26
471749123145101	TR_well18	47.29683	123.24747	218	26
471755123010001	TR_well19	47.29864	123.01661	118	26
472052123063001	TR_well20	47.34775	123.10833	133	26

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[1] Three of the 20 wells shown in Figure F.1 are located outside of the active portion of the model. These wells are TR1, TR4, and TR14. These wells could not be used in model calibration.

Table F.2. Summary of depth to water measurements. All values are in feet.

Well	Max	Min	Range	Stand. Dev.	Average	Model layer
TR_well01	8.53	2.11	6.42	2.08	5.11	7
TR_well02	54.67	17.24	37.43	11.24	30.79	5
TR_well03	19.35	6.30	13.05	3.93	13.68	7
TR_well04	34.16	3.73	30.43	7.01	14.26	7
TR_well05	28.02	19.59	8.43	2.21	24.80	4
TR_well06	9.32	0.80	8.52	2.56	5.20	4
TR_well07	80.17	65.71	14.46	3.68	72.52	2
TR_well08	7.27	2.38	4.89	1.79	5.10	2
TR_well09	0.92	0.35	0.57	0.16	0.79	4
TR_well10	32.58	17.49	15.09	3.08	20.33	3
TR_well11	116.30	110.91	5.39	1.52	113.59	6
TR_well12	46.69	22.47	24.22	7.28	34.81	3
TR_well13	37.21	15.11	22.10	6.95	24.22	2
TR_well14	113.12	108.74	4.38	1.24	110.94	4
TR_well15	105.36	96.83	8.53	2.32	102.05	4
TR_well16	134.17	130.36	3.81	1.40	131.77	5
TR_well17	220.47	212.68	7.79	1.91	217.02	6
TR_well18	204.68	150.32	54.36	13.23	181.89	3
TR_well19	65.72	48.35	17.37	4.70	58.64	3
TR_well20	8.61	3.91	4.70	1.28	5.97	6

Figure F.1. Locations of monitoring wells used in transient model calibration. Solid line shows outline of model area.

H. City of Shelton transient groundwater withdrawals

Data describing transient withdrawal rates for the City of Shelton groundwater wells for the time period 1/1/2002 through 3/12/2018 was provided by the City of Shelton.[1] These data consist of approximately weekly readings from water meters on the City's deep wells 1, 2, and 3. The annual average pumping rates in gallons and in gallons per day are listed in Table G.1 and are shown in Figure G.1. Monthly average pumping rates were calculated for the period 1/1/2002 through 12/31/2017. These monthly values are listed in Table G.2.

The average pumping rate for each month during the period 1/1/2002 through 12/31/2017 were directly input into the model. The monthly average pumping rates listed in Table G.2 were used in the model for the periods 1/1/1999 through 12/31/2001 and 1/1/2018 through 12/31/2019 as pumping data were not available for these times. The annual average value listed in the last row of Table G.1 was used for the steady-state simulation.

Table G.1. Annual average pumping rates for City of Shelton

	Gallons	Gals/day
2002	551,988,000	1,512,296
2003	511,487,000	1,401,334
2004	507,895,000	1,391,493
2005	486,669,000	1,333,340
2006	440,064,000	1,205,655
2007	345,885,000	947,630
2008	383,492,000	1,050,663
2009	391,884,000	1,073,655
2010	363,361,000	995,510
2011	372,524,000	1,020,614
2012	371,358,000	1,017,419
2013	348,121,000	953,756
2014	375,962,000	1,030,033
2015	404,112,000	1,107,156
2016	380,131,789	1,041,457
2017	406,325,409	1,113,220
Average	**418,569,481**	**1,146,766**

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[1] Personal communication. Email from Mike Albaugh (mike.albaugh@sheltonwa.gov), Public Works Superintendent, City of Shelton. With attachment file "Pump Reads.XLS." Described as "Source and Booster Pump Reading History from 2002-2018." Forwarded to Keta Waters by Erica Marbet (Squaxin Island Tribe) on March 22, 2018.

Table G.2 Monthly average pumping rates for the period 1/1/2002 through 12/31/2017.

Month	Total gallons
Jan	930,483
Feb	898,838
Mar	917,559
Apr	1,058,241
May	1,122,977
Jun	1,417,599
Jul	1,758,249
Aug	1,686,954
Sep	1,252,741
Oct	948,009
Nov	882,140
Dec	835,172

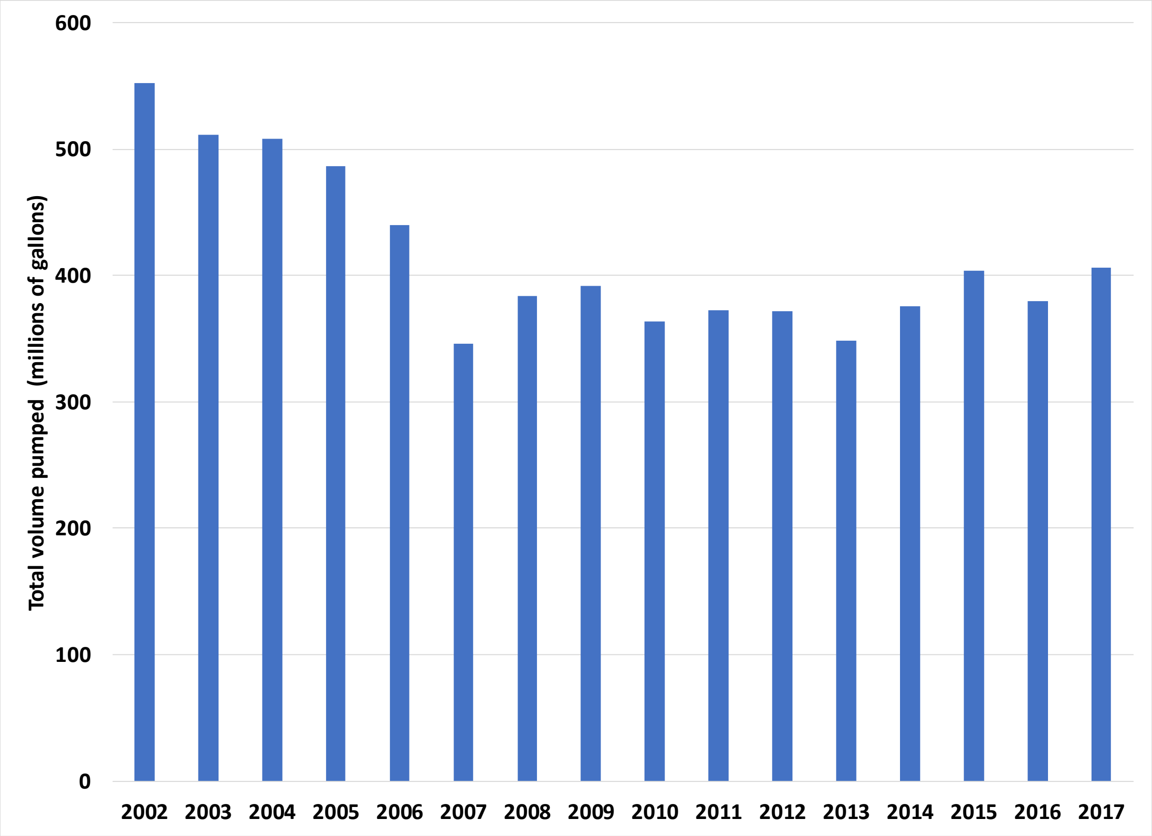

Figure G.1. Annual pumping rate for City of Shelton wells in millions of gallons.

I. Model simulation

The transient MODFLOW groundwater model was used to simulate monthly groundwater flow conditions for the 21-year period between January 1, 1999 and December 31, 2019. A total of 253 stress periods were used in the model.[1] The first stress period was used to simulate average or steady conditions within the model. Annual average groundwater recharge rates and annual average pumping rates were assigned in this steady-state portion of the simulation. The results from this initial stress period were then used as initial conditions for the transient portion of the model, which was comprised of 252 stress periods (1 stress period for each month for 21 years). Each 21-year simulation requires approximately 90 minutes of computer time.

The model was calibrated using a trial-and-error approach in which storage parameters were adjusted to improve the match between calculated and observed baseflows and calculated and observed groundwater levels. Approximately 15 different simulations were conducted as part of this calibration.

J. Comparison of observed and calculated baseflows and groundwater levels

Figures J.1 through J.4 compare observed and calculated baseflows between January 2017 and December 2019. Figures J.4 through J.10 compare observed and calculated groundwater levels between June 2016 and November 2019.

These results were derived using a specific storage value of 2x10-6 ft^{-1} for the aquifers and 6x10-5 ft^{-1} for the confining units. These values are higher than the median values for the USGS studies ($1.95x10^{-7}$ and 5.99x10-6 ft^{-1}) described in Section C but are within the ranges of values listed in Table C.1.

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[1] Stress periods are used in MODFLOW to incorporate time-varying conditions. All input variables (such as recharge, pumping rates, etc.) are assumed constant within each stress period.

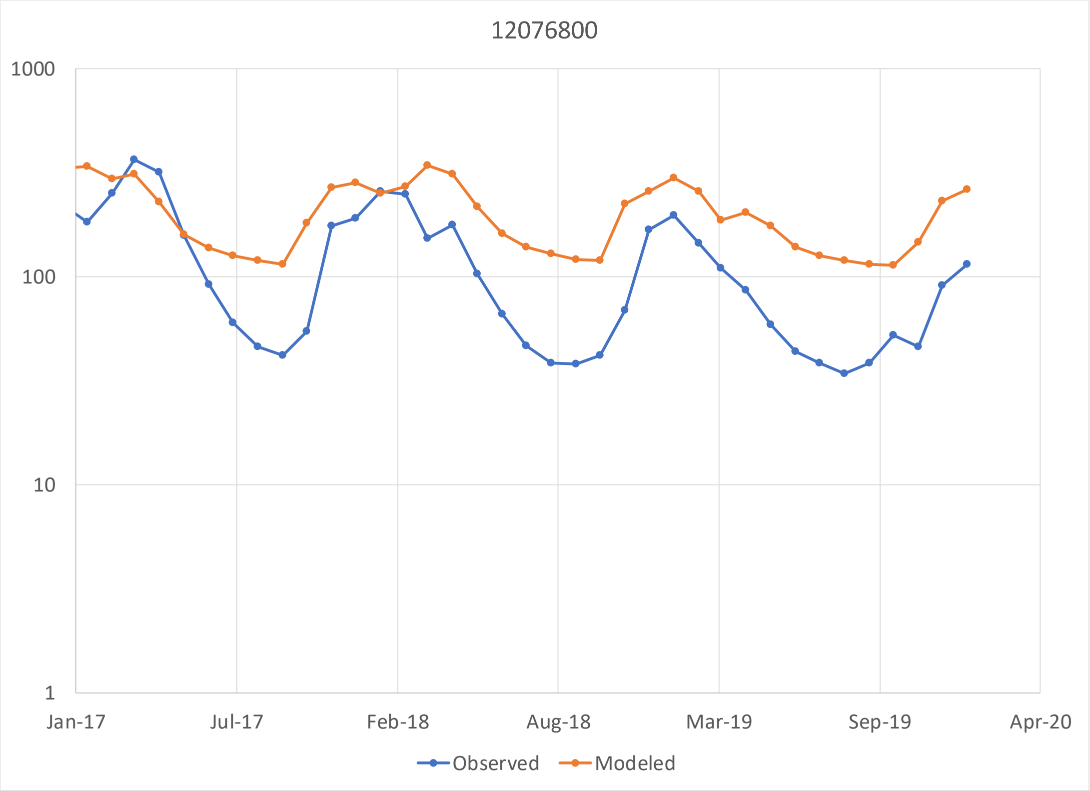

Figure J.1. Comparison of observed and calculated baseflow for Station 12076800.

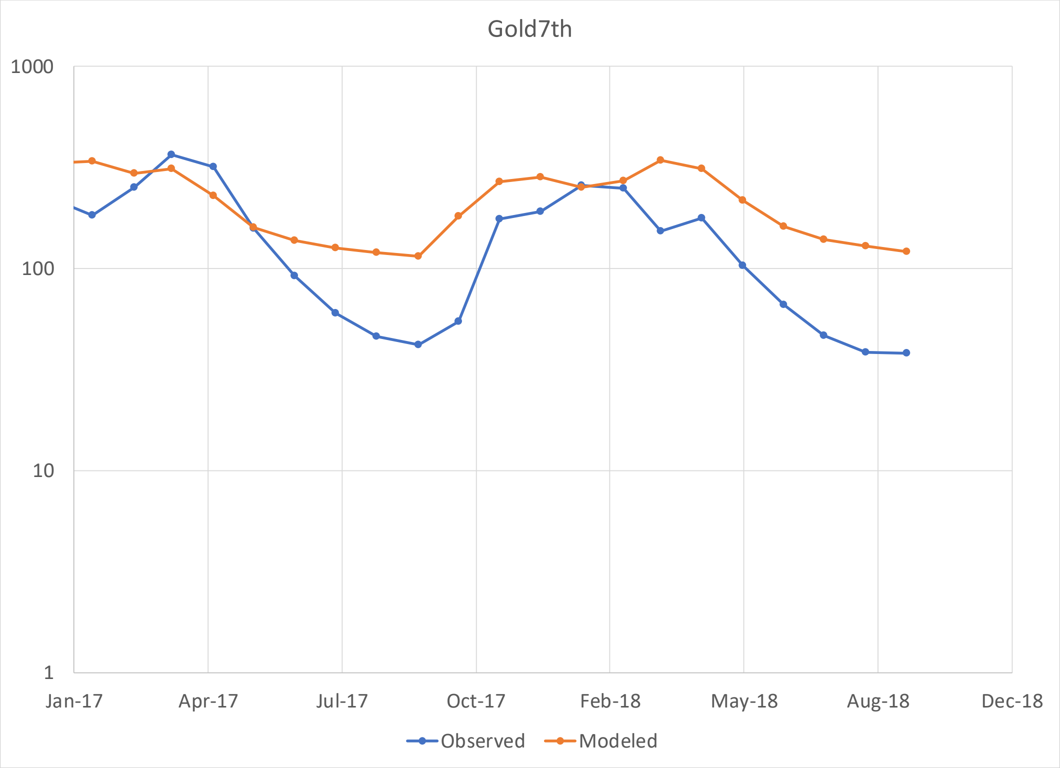

Figure J.2. Comparison of observed and calculated baseflow for Station Gold7th.

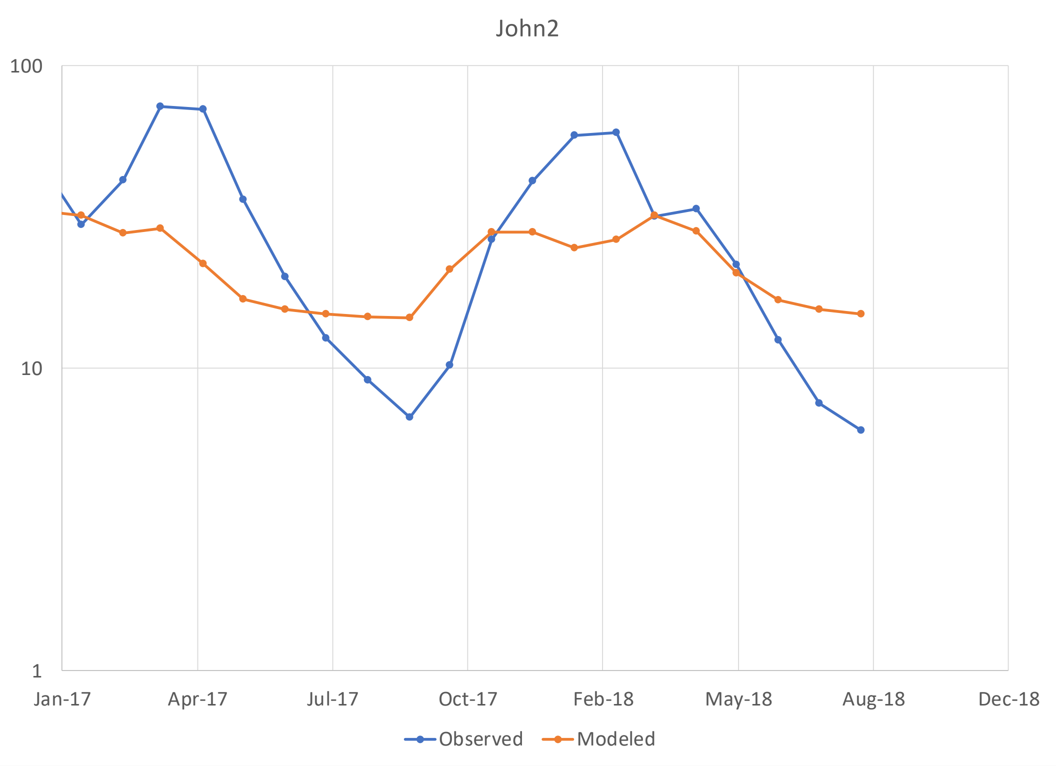

Figure J.3. Comparison of observed and calculated baseflow for Station John 2.

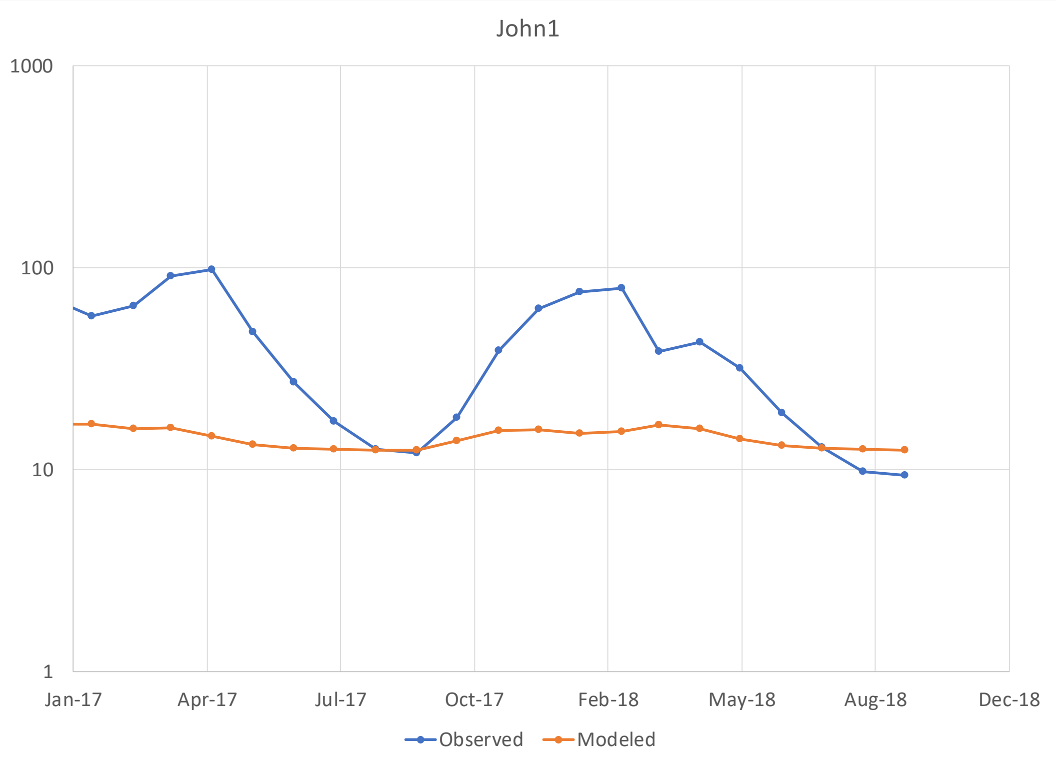

Figure J.4. Comparison of observed and calculated baseflow for Station John 1.

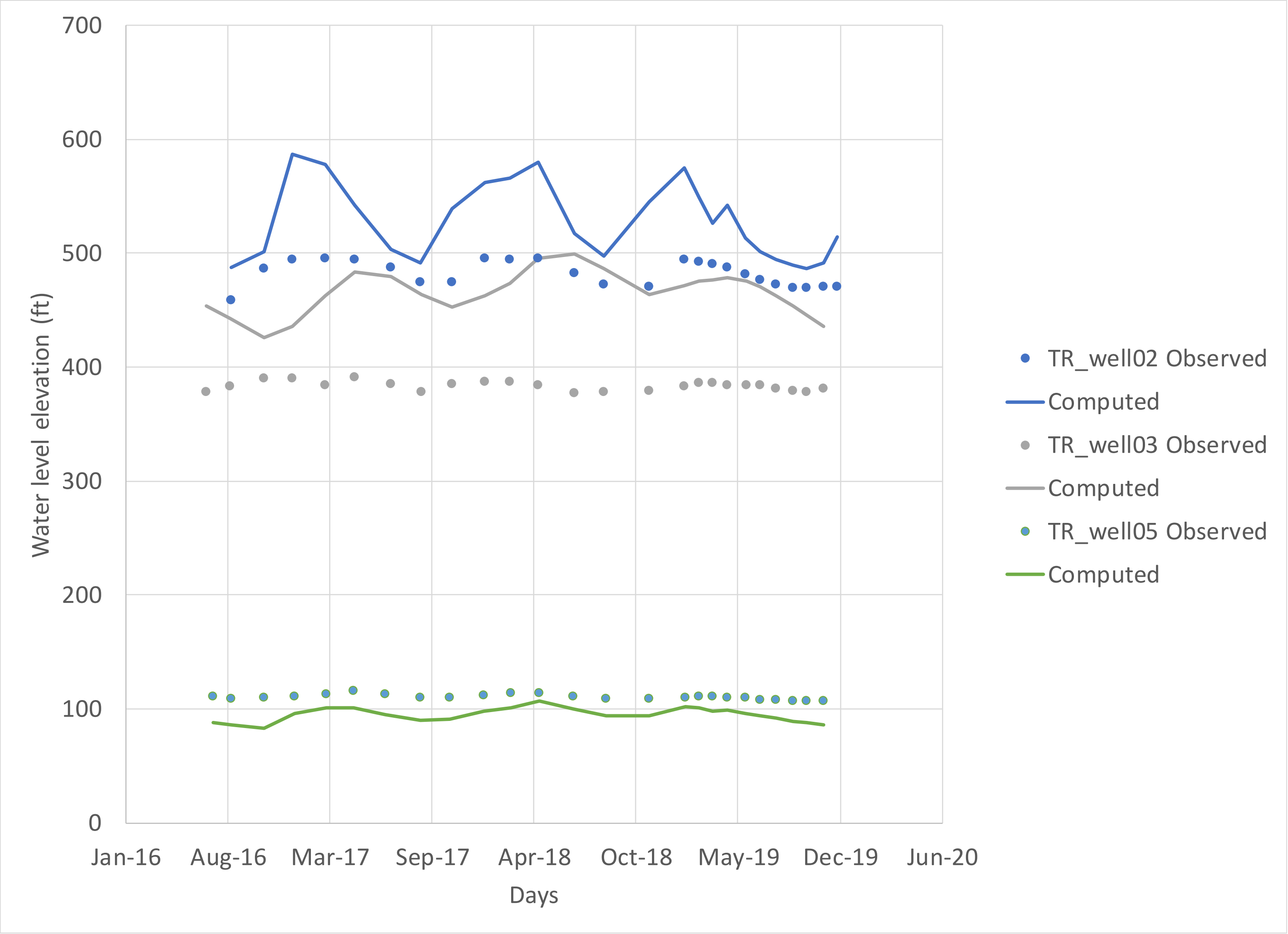

Figure J.5. Comparison of observed and calculated water levels for wells 2, 3, and 5.

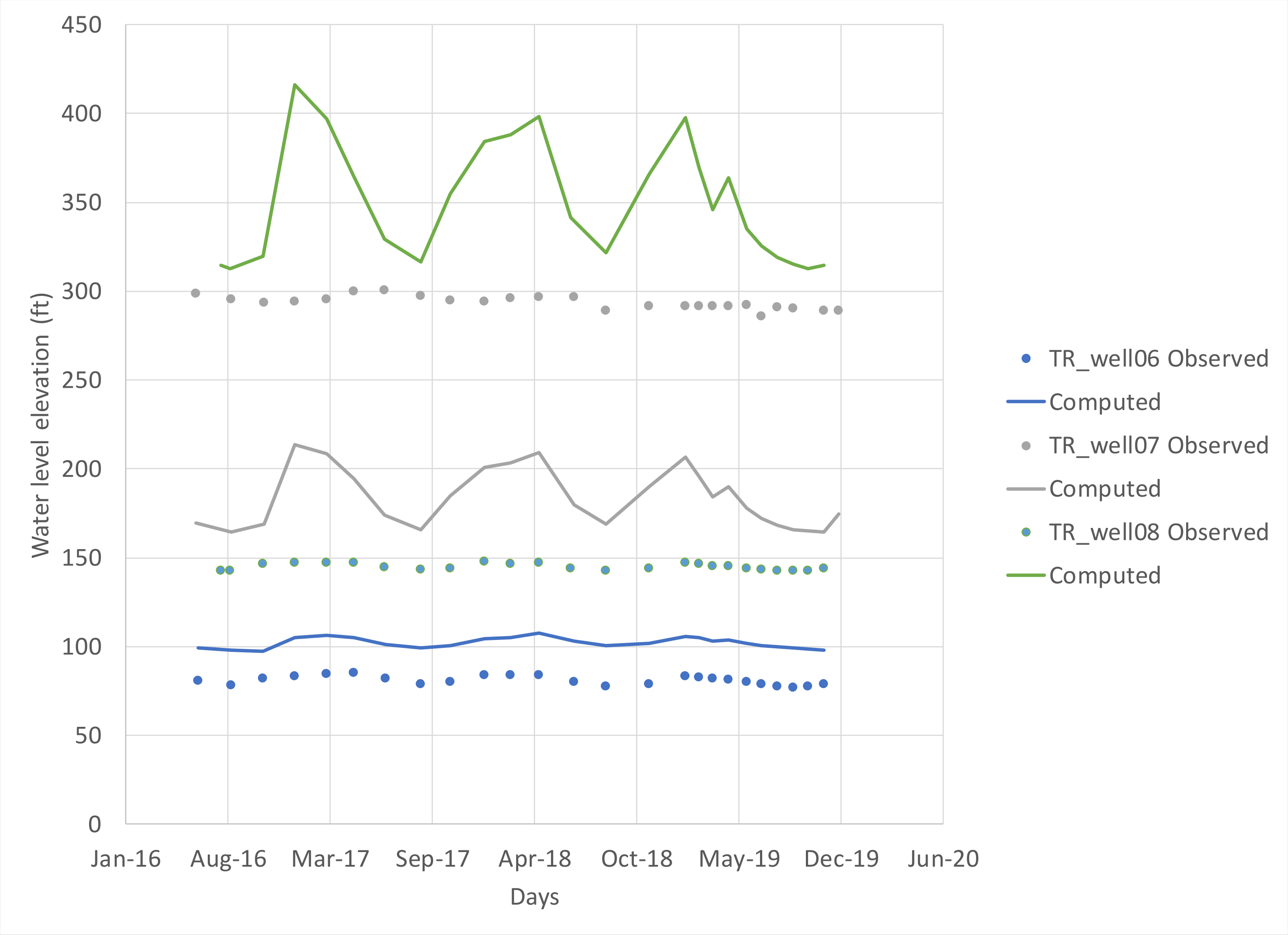

Figure J.6. Comparison of observed and calculated water levels for wells 6,7, and 8.

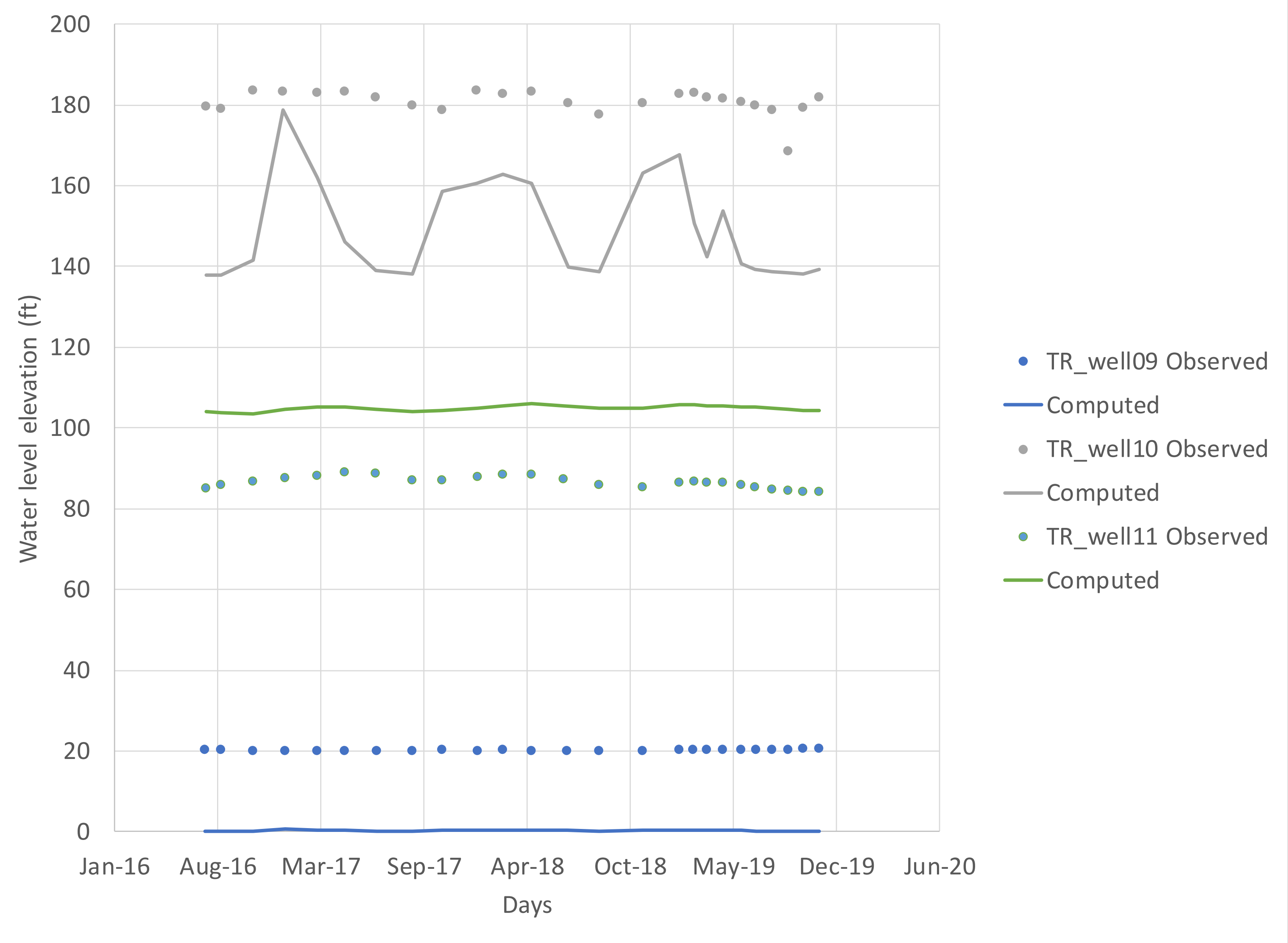

Figure J.7. Comparison of observed and calculated water levels for wells 9,10, and 11.

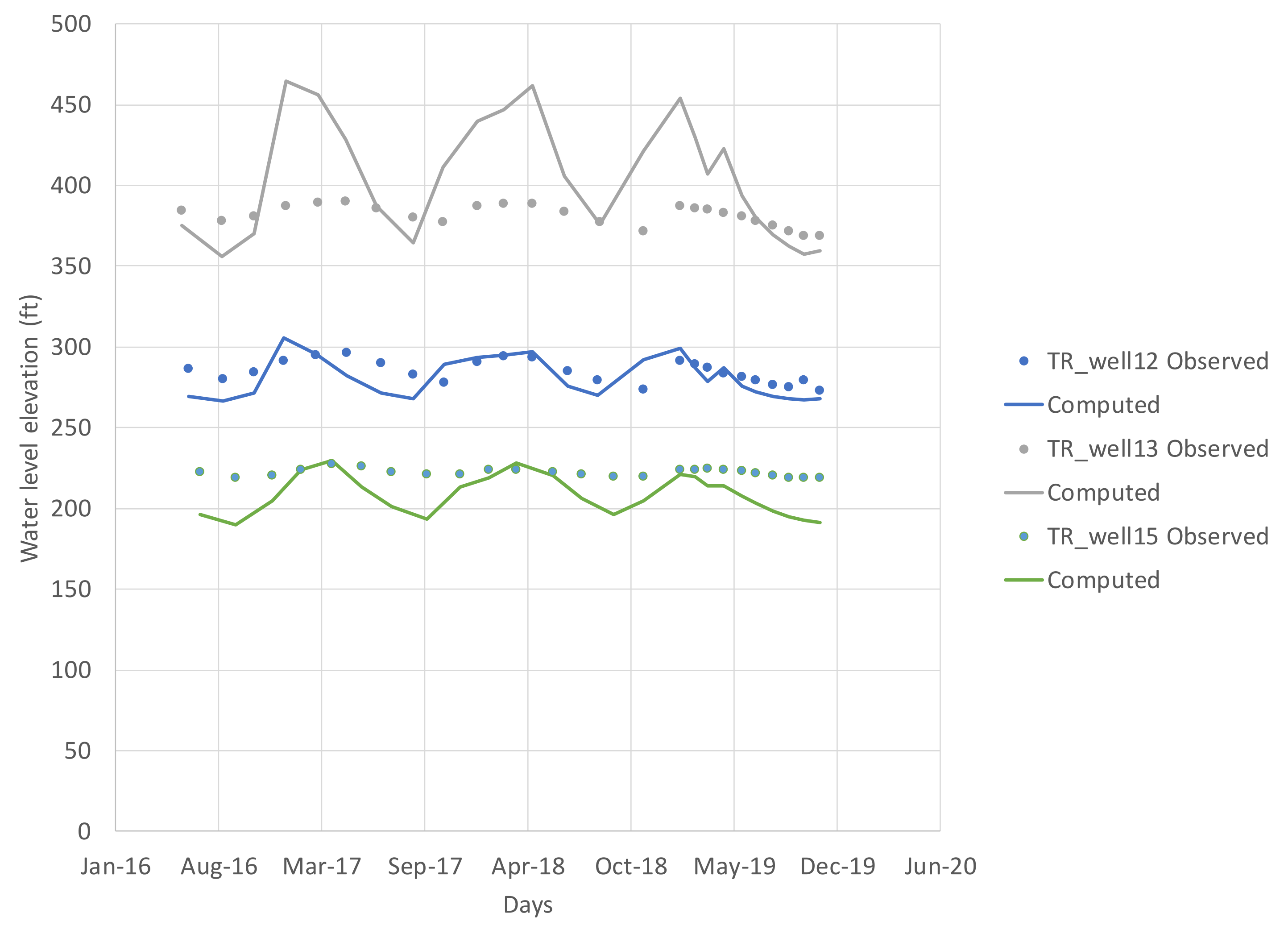

Figure J.8. Comparison of observed and calculated water levels for wells 12, 13, and 15.

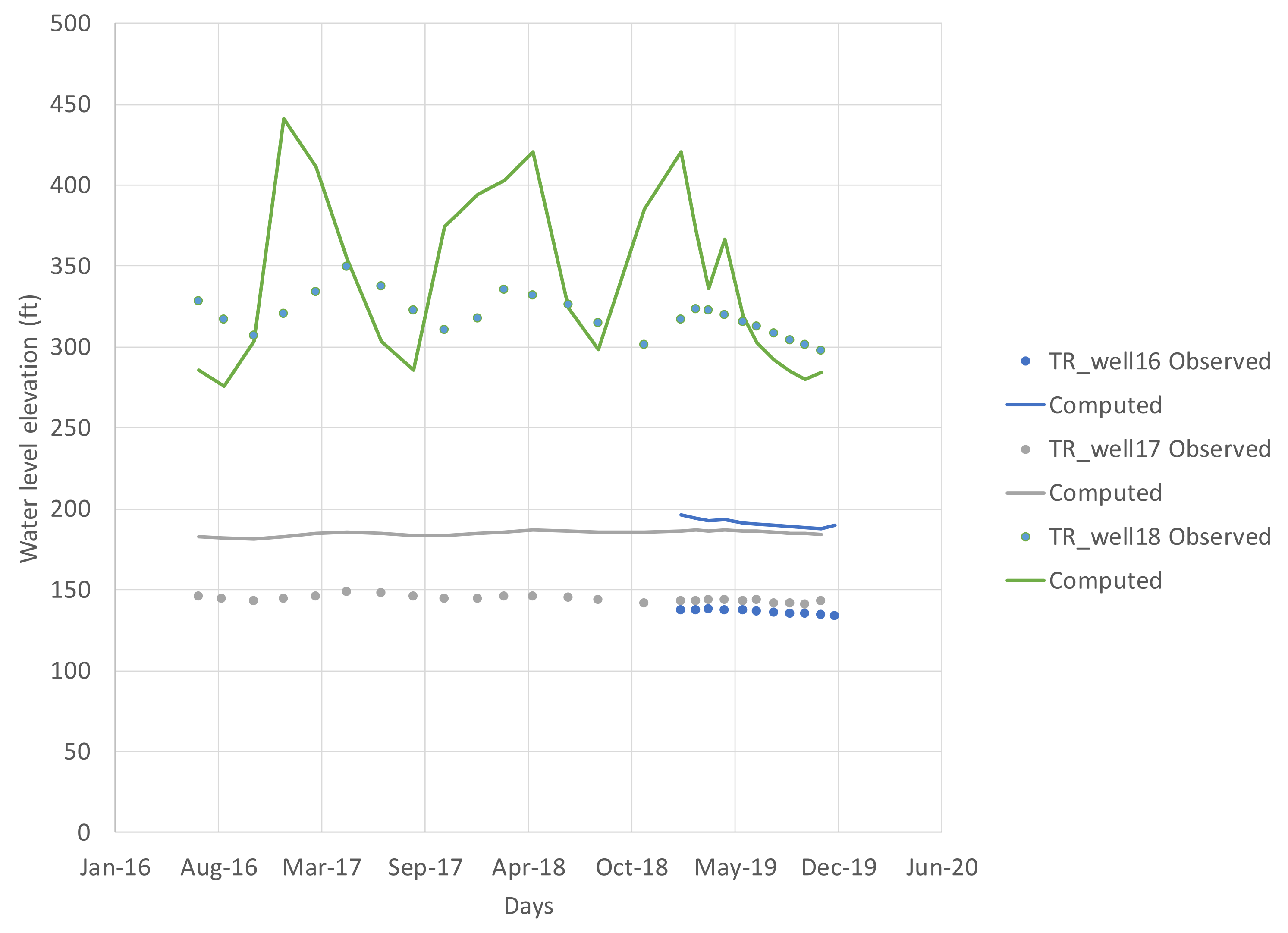

Figure J.9. Comparison of observed and calculated water levels for wells 16, 17 and 18.

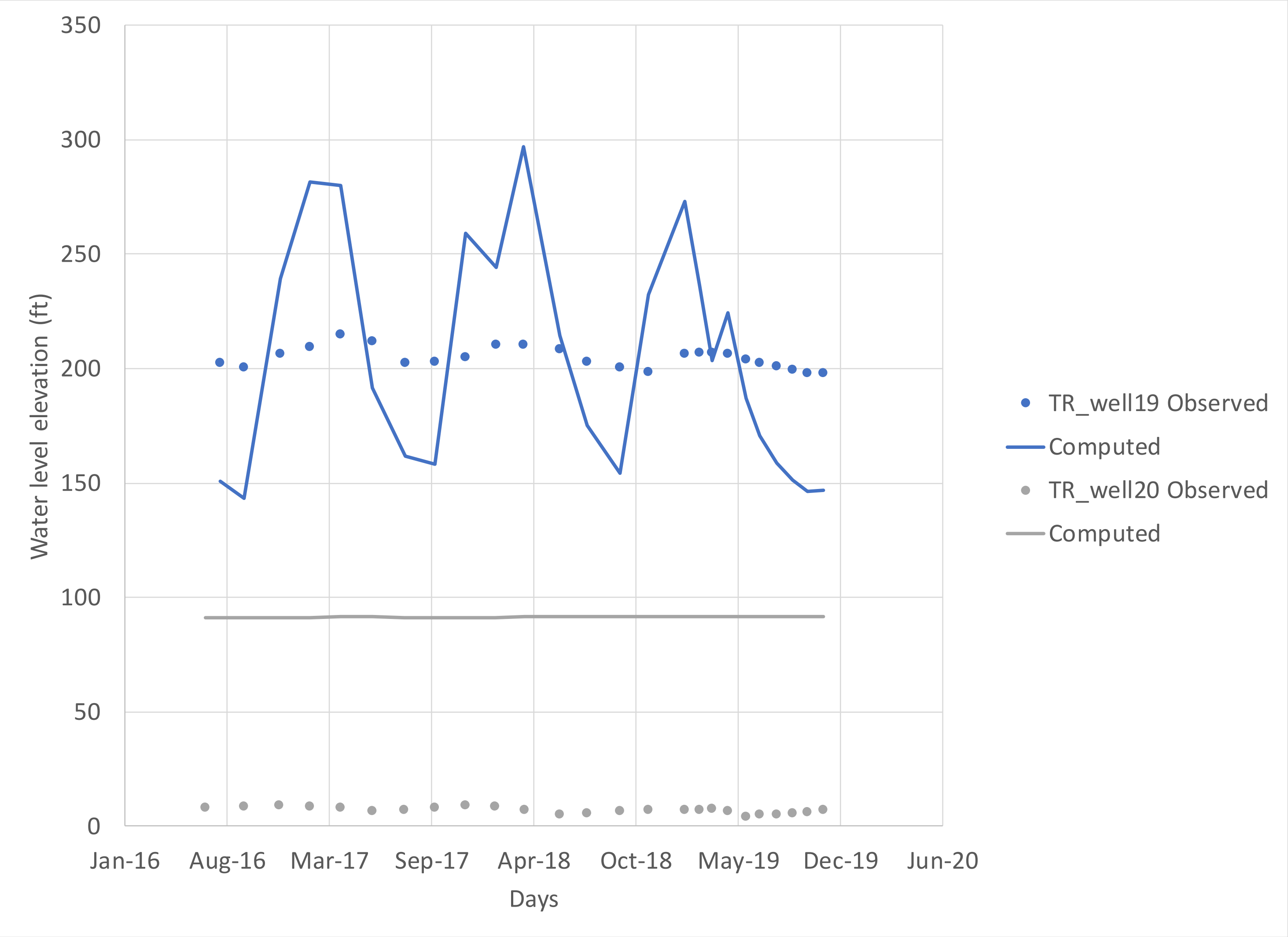

Figure J.10. Comparison of observed and calculated water levels for wells 19 and 20.

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Addendum E.1
Graphs showing streamflow and baseflow values

Addendum F.1
Well logs

Addendum F.2
Observed groundwater levels