APPENDIX F

Water Balance Calculations

APPENDIX F

SUPPORTING DATA AND CALCULATIONS
WATER BALANCE FOR PAPA

This appendix details equations and values used in calculating water balance components for the entire hydrologic system and the groundwater system at the PAPA study area (see **Figure 30** in the FIGURES section of this report to view the specified water balance region) as described previously in this hydrogeologic data gaps investigation report. The water balance below assumes steady-state conditions where inflow equals outflow, and there is no change in storage. Each water balance is addressed individually (hydrologic system and groundwater system), and both are generally represented by the following equation:

Inflow = Outflow ± Change in Storage

HYDROLOGIC SYSTEM WATER BALANCE

The entire hydrologic system water balance is described by the following equation:

$$P + R_{on} + U_{in} = R_{off} + U_{out} + G_{pump} + ET \pm S$$

Where:
- P = precipitation
- R_{on} = surface water run-on
- U_{in} = groundwater underflow into region
- R_{off} = surface water run-off
- U_{out} = groundwater underflow out of region
- G_{pump} = groundwater pumped for consumptive use
- ET = evapotranspiration
- S = any positive or negative change in storage.

Because no large lakes exist within the water balance region, meaningful changes in storage occur only within the groundwater system. The steady-state water balance is represented by the following equation:

$$P + R_{on} + U_{in} = R_{off} + U_{out} + G_{pump} + ET$$

Precipitation

Parameter-elevation Regressions on Independent Slopes Model (PRISM) data were used to calculate average annual precipitation for the water balance region. PRISM uses point data and a digital elevation model to generate climatic data. Based on PRISM precipitation data for years 1971-2000, approximately 375,000 acre-feet per year (ac-ft/yr) of precipitation falls within the water balance region.

Surface Water Run-On

Surface water run-on is summarized in **Table A** and calculated using the following method:

1. Difference in Annual Average Stream Flow (ft^3) = Downgradient Flow – Upgradient Flow

2. Area of Catchment in Water Balance Region was calculated using a USGS level 6 watershed map (http://nhd.usgs.gov/data.html).

3. $\text{Average Annual Flow per ft}^2 \left(\frac{\text{ft}^3}{\text{ft}^2}\right) = \frac{\text{Difference in Annual Average Stream Flow (ft}^3)}{\text{Area of Catchment in Water Balance Region (ft}^2)}$

4. $\text{Annual Flow Above Water Balance Region} \left(\frac{\text{ft}^3}{\text{yr}}\right) =$
   $\text{Catchment Above Water Balance Region} * \text{Annual Flow per ft}^2 \left(\frac{\text{ft}^3}{\text{ft}^2}\right)$

The resulting flow is assumed to be the amount of surface water run-on entering the water balance region. For streams that are boundaries to the water balance region, the run-on value was reduced by 50 percent because it was assumed half of the flow in the stream comes from outside of the water balance region. The average annual run-on volume into the water balance region is approximately 227,400 ac-ft/yr.

Groundwater Underflow into Region

Groundwater underflow into the water balance region was calculated using Darcy's Law:

Q = KIA

Where:
Q = groundwater flux
K = hydraulic conductivity (**Table B**)
I = hydraulic gradient (**Table C**)
A = cross-sectional area

Average hydraulic gradients were estimated for each boundary based on the potentiometric surface for the Regional Wasatch Formation.

A = wt

Where:
w = width of the water balance region boundary
t = saturated thickness (water table – base of Wasatch Formation)

Using minimum and maximum hydraulic conductivity values, underflow into the water balance region ranges from 95,040 to 345,690 ac-ft/yr, with an average of approximately 220,400 ac-ft/yr.

Table A. Summary of Surface Water Run-On Calculations

River	Up-Gradient Gauge Station	Down-Gradient Gauge Station	Difference in Annual Average Stream Flow (ft^3)	Area of Catchment in Water Balance Region (ft^2)	Annual Flow per ft^2 (ft^3/ft^2)	Catchment Above Water Balance Region	Annual Flow Above Water Balance Region (ft^3/yr)	Annual Flow Above Water Balance Region (ac-ft/yr)	50% of Water Flowing into Water Balance Region for Boundary Rivers (ac-ft/yr)
Green	Green River Near Daniel, WY	Green River at LaBarge	33,431,048,963	95,957,452,800	0.3484	13,013,471,200	4,533,821,816	104,082	52,041
New Fork	Near Pinedale	Near Big Piney	20,384,812,276	27,571,737,600	0.7393	9,852,445,400	7,284,279,753	167,224	167,224
East Fork	East Fork Near Big Sandy / Silver Creek	East Fork at New Fork	860,645,057	6,764,536,063	0.1272	2,760,515,856	351,217,630	8,063	8,063
Big Sandy	at Leckie Ranch	Near Farson	34,133,593	6,536,073,510	0.0052	1,675,782,651	8,751,506	201	100
								Total =	**227,428 ac-ft/yr**

Note: ft^3 = cubic feet; ft^2 = square feet; yr = year; ac-ft = acre-feet.

Table B. Hydraulic Conductivity Values Measured in December 2010 within PAPA

Pumping Well	Saturated Thickness	Hydrostratigraphic Unit (HSU)	Recovery Analysis			Drawdown Analysis		
			T (ft^2/day)	K (ft/day)	Method	T (ft^2/day)	K (ft/day)	Method
T-1-RW	23	Wasatch	19.07	0.83	Theis	0.07	0.003	Theis
T-1-SW	20	Wasatch	43.08	2.15	Theis	0.23	0.012	Theis
X-2-SW	40	Wasatch	262.2	6.56	Theis	0.26	0.007	Hantush
X-2-A	25	Alluvium	11,144	445.8	Theis	1,982	79.3	Neuman

Note: T = transmissivity; K = hydraulic conductivity; ft = feet; ft^2 = square feet.

Table C. Average Hydraulic Gradient

Hydrostratigraphic Unit (HSU)	Average Hydraulic Gradient (ft/ft)
Alluvial	0.0079
Wasatch	0.0094
Glacial Outwash	0.0093

Note: HSU = hydrostratigraphic unit

Surface Water Run-off

Surface water run-off was calculated using the same method as described for surface water run-on plus gain from groundwater discharging to the rivers (**Table D**). Average annual run-off within the water balance region is 454,200 ac-ft/yr.

Table D. Summary of Surface Water Run-Off Calculations

River	Catchment Above and Within Water Balance Region (ft^2)	Surface Water Run-On (ac-ft/yr)	Estimated Annual Flow Below Water Balance Region (ft^3/yr)	Surface Water Run-Off (ac-ft/yr)
Green	16,334,924,481	52,041	5,690,997,877	130,647
New Fork	17,870,054,400	167,224	13,211,996,632	303,306
East Fork	6,764,536,063	8,063	860,645,057	19,758
Big Sandy	4,257,853,660	100	22,235,956	510
			Total =	**454,221 ac-ft/yr**

Groundwater Underflow out of Region

Underflow was calculated using Darcy's Law as described previously for the calculation of underflow into the water balance region. Using minimum and maximum hydraulic conductivity values for each HSU, groundwater underflow out of the water balance region ranges from 4,400 to 34,400 ac-ft/yr, with an average of approximately 19,400 ac-ft/yr.

Groundwater Pumped for Consumptive Use

Table E summarizes data used to calculate groundwater pumped for consumptive use. Based on values from literature and the Wyoming State Engineer's Office (2010) groundwater well database, groundwater pumped for consumptive use was calculated using the equation:

$$\text{Total Consumed} = \text{Number of Wells} * \text{Withdrawal Rate} - \text{Total Groundwater Return} \left(\frac{\text{ac} - \text{ft}}{\text{yr}}\right)$$

Withdrawal rates for irrigation, stock and domestic wells are from Clarey et al. (2010) and withdrawal rates for industrial water supply wells are from Operator data for 2010. Withdrawal rates were calculated as follows using irrigation wells as an example:

From Clarey et al. (2010):

There are 115 irrigation wells in the Green River Basin which consume 7,600 ac-ft/yr

7,600 ac-ft/yr / 115 wells = 66.08 ac-ft/yr/well

From SEO well database:

There are 9 irrigation wells in the water balance region

Total consumed = 9 wells * 66.08 ac-ft/yr/well = 595 ac-ft/yr

Total estimated consumptive groundwater volume from irrigation, stock, domestic/other, and industrial water supply wells in the PAPA water balance regions is approximately 1,300 ac-ft/yr.

Table E. Summary of Values for Groundwater Pumped for Consumptive Use Calculations

Type	Number of Wells	Withdrawal Rate (ac-ft/yr)	Total Groundwater Withdrawal (ac-ft/yr)	Total Groundwater Return (ac-ft/yr)	Total Consumed (ac-ft/yr)
Domestic/Other	1,076	0.08	222	200	22
Industrial Water Supply Well*	366	7	590	0	590
Irrigation	9	66	595	0	595
Stock	145	0.6	88	0	88
				Total =	**1,294 ac-ft/yr**

* Based on available well data, an average of 20 percent of the industrial supply wells are actively in use.
Note: ac-ft/yr = acre-feet per year.

Evapotranspiration (ET)

Long-term average water loss via ET can be estimated by using ET to balance the water balance equation:

$$ET = P + R_{on} + U_{in} - R_{off} - U_{out} - G_{pump}$$

$$ET = 375{,}000 + 227{,}400 + 220{,}400 - 454{,}200 - 19{,}400 - 1{,}300 \text{ ac-ft/yr}$$

Thus, average annual loss due to ET in the PAPA water balance region is approximately 347,900 ac-ft/yr. This is slightly less than the amount of precipitation that falls within the water balance region (375,000 ac-ft/yr) as previously described.

STEADY STATE GROUNDWATER BALANCE

The groundwater balance is described by the following equation:

$$R_N + R_I + R_D + U_{in} = BF + U_{out} + G_{pump} + ET_G$$

Where:

R_N = natural recharge
R_I = irrigation application recharge
R_D = irrigation ditch loss recharge
U_{in} = groundwater underflow into region
BF = groundwater discharge to rivers and streams (base flow)
U_{out} = groundwater underflow out of region
G_{pump} = groundwater pumped for consumptive use
ET = evapotranspiration directly from saturated zone.

Recharge

Total groundwater recharge is described by the following equation:

Total Recharge = Natural Recharge + Irrigation Recharge

Natural recharge was calculated by multiplying the area of the water balance region (647 mi^2) by recharge values estimated by Martin (1996) and Hammerlick and Arneson (1998). Natural recharge values range from 7,600 to 12,600 ac-ft/yr, with an average of about 10,000 ac-ft/yr.

Irrigation recharge was calculated by multiplying the area of irrigated lands in the PAPA (35,172 acres) by a range of recharge rates estimated by Martin (1996) (2 to 2.5 in/yr). Irrigation recharge values range from 5,900 to 7,300 ac-ft/yr, with an average of approximately 6,600 ac-ft/yr. Total recharge values (natural + irrigation) range from 13,500 to 19,900 ac-ft/yr, with an average of about 16,600 ac-ft/yr.

Groundwater Underflow into Region

Groundwater underflow into the water balance region was estimated as described in the entire water balance section above. Groundwater underflow into the PAPA region ranges from 95,090 to 345,690 ac-ft/yr, with an average of approximately 220,400 ac-ft/yr.

Ditch Loss

Table F summarizes ditches in the water balance region, and minimum and maximum loss estimates based on literature values. Ditch loss estimates range from approximately 1,300 to 43,100 ac-ft/yr, with an average estimate of 16,100 ac-ft/yr.

Groundwater Discharge to Rivers and Streams (Base Flow)

For each stream, discharge data from the upstream location, along with any tributary flow, was subtracted from the downstream location. The difference in discharge was then divided by the catchment area between gaging stations minus any tributary catchment area, resulting in a base flow per catchment area ratio for each stream. This ratio was then multiplied by the catchment area within the water balance region for each stream to obtain the estimated base flow. **Table G** summarizes flow data, catchment areas, and estimated groundwater flux for the major streams in the water balance region. Some of the flow data are from a synoptic measurement event completed by Geomatrix in early November 2009. The estimated base flow contribution to streams and rivers within the model domain ranges from 160,981 to 241,472 ac-ft/yr, with an average of approximately 201,200 ac-ft/yr.

Groundwater Underflow out of Region

Groundwater underflow out of the water balance region was estimated as described in the entire water balance section above. Groundwater underflow out of the PAPA region ranges from 4,400 to 34,400 ac-ft/yr, with an average of approximately 19,400 ac-ft/yr.

Evapotranspiration from Groundwater

Evapotranspiration from groundwater was calculated by multiplying the area of mapped wetlands by the potential ET rate for Sublette County (**Table H**).

Table F. Summary of Values Used for Ditch Loss Calculations

Ditches in AECOM (2009) Model Reach	Length in Water Balance Region (feet)	Total Flow (ac-ft/yr)	Estimated Loss (ac-ft/yr)		
			Min	Max	Average
Sill	30,031	490	20	1,422	416
Hanna	15,765	4,819	33	746	360
Pole Creek No 2	35,198	2,794	74	1,667	649
Fayette	58,743	1,891	39	2,781	954
Unnamed 17	12,301	748	8	582	177
Unnamed 19	5,032	540	3	238	71
Unnamed 1	4,266	1,300	3	202	67
Metz	6,893	2,101	5	326	119
Paradise	132,252	2,511	277	6,262	2,213
Last Chance	23,553	447	16	1,115	325
Taylor	490	48	0	23	6
Lovatt	4,860	475	3	230	68
Jaycox No 1	6,205	606	4	294	88
Unnamed 18	16,158	62	5	765	210
Unnamed 21	4,962	11	0	235	64
Griffin No 2	6,354	119	4	301	84
Bertram	36,095	678	76	1,709	521
Butler	14,091	265	9	667	189
Hanna No 2	15,561	292	10	737	210
Wardell	17,505	329	12	829	237
Ada	24,942	897	17	1,181	366
Luman	23,666	851	16	1,121	345
Hill	43,637	1,569	29	2,066	689
Harman	43,557	1,567	29	2,062	688
Howard Routh Main; Howard Routh L1	12,319	493	8	583	171
Unnamed 7	5,688	228	4	269	76
Boulder Canal; Unnamed 8; Naylor; Unnamed 20; Ball; Oliver; White; Burkhalter	192,684	7,716	404	9,123	4,338
Highland Main; Highland L1; Highland L2	36,865	9,908	77	2,348	1,173
Unnamed 10	13,685	812	9	648	199
Unnamed 11	11,520	684	8	545	165
Unnamed 12	14,694	872	10	696	215
Unnamed 13	7,475	444	5	354	103
Unnamed 14	34,098	2,024	23	1,614	571
	Total =	**48,591**	**1,239**	**43,744**	**16,128**

Note: ac-ft/yr = acre-feet per year.

Table G. Summary of Values Used for Base Flow Calculations

Location of Stream Flow Measurement	Stream Flow (ft^3/sec)	Date of Steam Flow Measure-ment	Stream Gain (ft^3/sec)	Area of Catchment* (ft^2)	Stream Gain (per ft^2)	Catchment* Area in Water Balance Region (ft^2)	Estimated Gain in Model Domain (ft^3/sec)
Pine Creek							
Pine Creek below Fremont Lake	31	Average on 11/5	---	---	---	---	---
Pine Creek above New Fork River (Synoptic Flow)	41	11/5/2009	+10	403,995,941	2.475E-08	134,884,799	**3.3**
Pole Creek							
Pole Creek Below Little Half Moon Lake	22.5	Average on 11/5	---	---	---	---	---
Fall Creek Near Pinedale	4.2	Average on 11/5	---	---	---	---	---
Pole Creek above New Fork River (Synoptic Flow)	42.1	11/5/2009	+15.4	855,364,055	1.800E-08	445,194,856	**8.0**
Boulder Creek							
Boulder Creek Below Boulder Dam	25	Average for Nov. 1938-72	---	---	---	---	---
Boulder Creek above New Fork River (Synoptic Flow)	18.9	11/5/2009	-6.1	136,020,684	-4.485E-08	136,020,684	**-6.1**
New Fork River & Tributaries (all flows from synoptic event)							
New Fork River NFA-100	21.8	11/5/2009	---	---	---	---	---
Duck Ck DCA-1	12.9	11/5/2009	---	---	---	---	---
New Fork River NF-04	37	11/5/2009	+2.3	---	---	---	---
Pine Creek PCA-1	41	11/5/2009	---	---	---	---	---
Pole Creek POCA-1	42.1	11/5/2009	---	---	---	---	---
New Fork River NF-70	172.8	11/5/2009	+52.7	---	---	---	---
New Fork River NFA-300	173.5	11/5/2009	+0.7	---	---	---	---
Boulder Creek BCA-1	18.9	11/5/2009	---	---	---	---	---
New Fork River NF-60	211.8	11/5/2009	+19.4	---	---	---	---
East Fork River EFA-1	77.6	11/5/2009	---	---	---	---	---
New Fork River NF-50	289.8	11/5/2009	+0.4	---	---	---	---
New Fork River NF-50	282.1	11/6/2009	---	---	139.7	---	---
New Fork River NF-40	298	11/6/2009	+15.9	---	---	---	---
New Fork River	355.8	11/6/2009	+57.8	---	143.7	---	---

Location of Stream Flow Measurement	Stream Flow (ft^3/sec)	Date of Steam Flow Measure-ment	Stream Gain (ft^3/sec)	Area of Catchment* (ft^2)	Stream Gain (per ft^2)	Catchment* Area in Water Balance Region (ft^2)	Estimated Gain in Model Domain (ft^3/sec)
NF-30							
New Fork River NFA-400	324.1	11/6/2009	-31.7	---	---	---	---
New Fork River NFA-500 – USGS Station	354	11/6/2009	+29.9	---	---	---	---
New Fork River from NFA-100 to NFA-500	---	---	+147.4	7,575,641,566	1.946E-08	7,004,210,992	**136.3**
Green River							
Green River Near Daniel WY	131	11/6/2009	---	---	---	---	---
Green River above New Fork River at GRA-1	239.3	11/6/2009	93.3	2,503,248,447	3.727E-08	2,759,744,812	**102.9**
Cottonwood Creek mouth near Big Piney WY	15	Average on 11/6	---	---	---	1,390,430,400	---
East Fork River							
East Fork River Near Big Sandy WY	17	Average on 11/6	---	---	---	---	---
East Fork River at New Fork on 11/5/2009	77.6	Average on 11/6	---	---	---	---	---
Silver Creek near Big Sandy River	4.5	Average on 11/6	56.1	6,764,536,063	8.293E-09	4,004,020,207	**33.2**
Big Sandy River							
Big Sandy River near Leckie WY	18.3	---	---	---	---	---	---
Big Sandy River near Farson WY	18.7	Average for Nov.	0.4	6,536,073,510	6.120E-11	2,582,071,009	**0.16**
						Total Base Flow Leaving Model =	**277.76 ft^3/sec**

* Catchment areas were calculated using a USGS level 6 watershed map (http://nhd.usgs.gov/data.html).

Note: ft^3/sec = cubic feet per second; ft^2 = square feet. The "synoptic" flow measurements were conducted by Geomatrix on November 5-6, 2009.

Table H. Summary of Values Used for Evapotranspiration Calculations

Area Included in Calculation	Area (acres)	Rate (in/yr)		Evapotranspiration (ac-ft/yr)	
		Minimum	Maximum	Minimum	Maximum
All Mapped Wetlands minus Rivers and Ponds	33,089	15	20	41,361	55,148
All Mapped Wetlands	35,425	15	20	44,281	59,042

Note: in/yr = inches per year; ac-ft/yr = acre-feet per year.

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