APPENDICES

Appendix A

Technical Memorandum

To: Peter Schwartzman

From: Randy Asplund, P.E. and Dick Erickson, P.E.

Subject: Study Area Water Use – Current Practices & Conservation Potential

Date: October 13, 2010
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Introduction

Three irrigated areas in eastern Washington were selected for evaluation. Background and criteria for selecting these study areas were discussed at an organizational meeting on March 10, 2010. Participating in that meeting were representatives of the Washington State Department of Ecology (Ecology), Franklin Conservation District (FCD), Washington State Conservation Commission (WSCC), Columbia Basin Ground Water Management Area (GWMA), Pacific Groundwater Group (PGG) and RH2 Engineering, Inc., (RH2). In preparation for the meeting, FCD, Ecology and GWMA compiled information about nine irrigated areas of the State of Washington. At the meeting, all nine areas were discussed and evaluated relative to the study objectives. At the conclusion of the meeting, three areas were tentatively agreed upon as the sites to be studied. Those areas are:

- Southern Franklin County (largely within the South Columbia Basin Irrigation District of the Columbia Basin Project with relatively small areas supplied by Franklin County Irrigation District and by private wells);
- Horse Heaven Hills (the Benton County portion supplied by pumping from the John Day Pool of the Columbia River); and
- Walla Walla Valley (supplied by a variety of sources diverting from the Walla Walla River, its tributaries and associated groundwater).

Subsequent to the March 10, 2010, meeting, further communications between the parties confirmed that these three irrigated areas would be the general sites to be evaluated. More specific sites within some or all of these general areas were to be identified for more detailed study in future tasks. To date, specific sites for pilot projects or further study have not been identified. For the Southern Franklin County and Horse Heaven Hills areas this inability to identify such sites is largely due to the scarcity and/or scattered locations of grossly inefficient irrigation methods. For the Walla Walla area the incidence of partial season irrigation and/or combined use of surface and groundwater irrigation sources complicate pilot site selection.

Approach

FCD undertook gathering and organizing the necessary crop and irrigation data for each of the three areas. This effort concluded on June 24, 2010, when FCD released the data to RH2. For each area, the information included:

- 2009 crop types based on Washington State Department of Agriculture (WSDA) data.
- 2009 acres for each crop based on WSDA data.
- Net irrigation requirements for each crop based on the appropriate climatic station for the area.
- 2009 on-farm irrigation equipment by type.
- 2009 acres for each type of irrigation equipment.
- Irrigation method efficiencies as outlined in "Irrigation Efficiency" by Terry Howell (2003).

For the Franklin County area, FCD also provided the above crop and irrigation system data based on its own GIS database and other records. This information compared very closely with the WSDA information and it was decided that the WSDA data would be utilized so the information sources would be consistent for all three study areas.

FCD also provided 1991 – 2009 average irrigation water delivery information from the South Columbia Basin Irrigation District (SCBID) for farms in the Franklin County study area. This value (3.57 acre-feet per acre) provided a method to check the validity of calculated farm water needs. While some of the study area is not within the SCBID service area, the vast majority is, making this a valid value for comparison purposes. This check is important because actual water use information for the Benton and Walla Walla areas is not easily available.

Crop data and irrigation system data from WSDA are presented area-wide and are not cross referenced to specific parcels. Therefore, it was not possible to determine which type of irrigation equipment is being used to irrigate specific crops.

RH2 utilized the information provided by FCD to calculate the existing area-wide irrigation efficiencies for each of the three study areas. The crop data were then utilized to estimate the crop irrigation requirements for each area. The previously calculated existing area-wide irrigation efficiencies were then utilized to estimate the total irrigation water needs for each area. Because all crop and irrigation system information is of an on-farm nature and does not involve conveyance of irrigation water to the farm, the differences between the crop irrigation requirement and the total irrigation needs are losses. Initially FCD advised that for the purpose of this initial assessment, these losses should be assumed as deep percolation. Subsequently, PGG determined that an estimate of the distribution of these losses between surface runoff and deep percolation would be desirable. In response to this, RH2 developed an estimate distributing losses among deep percolation, surface runoff and evaporation (See **Appendix B**). This resulted in estimates being based on other estimates, which are useful and appropriate for this assessment area-wide. These estimates should be used only for making area-wide conclusions and should not be used for individual farm or sub-area basins without further review.

Calculations were then made to determine possible irrigation water savings for an array of actions including upgrading on-farm irrigation equipment, implementing irrigation water management (IWM) and a combination of both.

For each area, this information, along with calculations and results, is presented in Tables 1, 2 and 3. For each area, a graphic is also provided, illustrating selected water conservation opportunities.

Explanation of Tables

Three separate tables for each study area were generated to describe current irrigation practices and plausible upgrades to increase irrigation efficiency. The first table generated for a study area summarizes current water use efficiency, using data provided by FCD. This table also segregates losses into evaporation, runoff and deep percolation categories with deep percolation further classified into pre-IWM and post-IWM. (It should be noted for clarity that tables/figures for Franklin County are suffixed with the letter "a," tables for Benton County are suffixed with the letter "b" and tables for Walla Walla County are suffixed with the letter "c.") The information was organized and calculated in the tables to obtain weighted average irrigation efficiency (WAIE). The WAIE was used in Table 2, along with crop data provided by FCD to calculate current water use volumes in each district. The purpose of Table 2 is to illustrate differences between the volume of water needed by a study area to support current crop irrigation and the current amount of water being applied to the area. The difference between water applied and water needed is the maximum volume of water that can be recovered, which leads to Table 3. Additionally, Table 2 illustrates the quantity of water that can be recovered by area-wide adaptation of IWM practices. Table 3 describes incremental amounts of water that can be recovered through different irrigation structure and irrigation management upgrades. In reality, each upgrade lessens the amount of water applied to a crop while maintaining the crop irrigation requirement. Values shown in Table 3 are also depicted in Figure 1. Referencing the figures quickly demonstrates which upgrades will recover large increments of water. Savings in evaporation reduce a consumptive loss. Savings in runoff and deep percolation reduce non-consumptive losses.

Explanation of Methods and Sources

The current average efficiencies for each study area were calculated using irrigation efficiencies reported by Terry A. Howell, USDA-ARS, *Irrigation Efficiency,* Encyclopedia of Water Science (2003) and the percentage of land area for a particular irrigation system. The product of these two percentages yields a weighted average irrigation efficiency per irrigation method (see Table 1 (a),(b),(c)). Summing the weighted average irrigation efficiency per irrigation method yields the WAIE for the study area. The WAIE describes how well the study area is currently utilizing irrigation water.

The WAIE was used to calculate the irrigation field-based water use for each of the three different study areas in Tables 2(a, b and c). The total current field application volume was estimated by dividing the total volume of water needed per crop (acre-feet, from WIG) by the WAIE, which yielded the field application per crop. Summing the field application per crop netted the total current field application volume. More specific calculations, where water use was calculated based on efficiencies specific to unique combinations of irrigation method efficiency and crop type, were not supported by the available data.

The method described here for estimating current water use for a study area, shown in Table 1((a),(b), (c)), was supported by water use records for Franklin County. SCBID data between 1991 and 2009, reports that the average water use in Franklin County was 3.57 acre-feet per acre. Summing estimated application volumes on Table 2(a) and dividing by the total study area (129,343 acres) yields an average water use for Franklin County of 3.46 acre-feet per acre. This value differs

from SCBID actual data by 3.1 percent, indicating that the method used to estimate total application volume is reasonable.

IWM Assumptions

RH2 based calculations for IWM on 2005 research by the Columbia Basin Groundwater Management Area (GWMA). This research indicates that the weighted average savings coming from IWM is 17.31 percent. For these estimates, the 17.31 percent improvement is applied to crop need based on the statement from the GWMA report that, "GWMA supports the Washington Irrigation Guide (WIG) as a realistic guide to micro-climate irrigation water consumption prior to the adoption and use of IWM concepts."

The crop water needs presented in the WIG were developed empirically based on historical water use with the intention for use in irrigation design. Due to the nature of the development of the WIG values, those numbers are conservative and reflect consumptive use estimates appropriate at the time they were developed and have an intrinsic factor of safety. The GWMA research concludes that IWM can reduce the crop water requirement in WIG by 17.31 percent. (See **Appendix F**)

These tables assume for all three areas that no IWM is presently in use (Pre-IWM). The tables then estimate for all three areas the water savings possible if all acres implement IWM (Post-IWM). Some IWM is presently in use in all three areas but the extent is not known. Also, it is unlikely that all acres in all three areas will implement IWM. Basing the range of the estimates on 0 percent and 100 percent IWM establishes the endpoints for what may be possible.

For each area, the total water savings resulting from going from 0-percent IWM to 100-percent IWM is the difference between the gross application volumes of Column 5 from the gross application volumes of Column 8 on Table 2. The resulting total savings from IWM has two components: 1) The major portion comes from reducing the crop need on 100 percent of the acreage and is the difference between Columns 7 and 4 on each Table 2; and 2) The other portion results from less water being exposed to application inefficiencies and is the difference between Columns 10 and 11.

Center Pivot with LEPA Assumptions

For Southern Franklin County and Walla Walla, we have assumed that 35 percent of present center pivot acreage utilize LEPA and 65 percent use center pivots with end guns without LEPA. For Horse Heaven Hills, we have assumed 50-percent LEPA and 50-percent non-LEPA/end guns. All of these center pivot areal proportions, as well as the definition of LEPA, are based on our discussions at the December 21, 2010, meeting. LEPA can mean different things in different locales; for these study areas, LEPA is defined as a pivot with drop tubes, rotator (spinner) spray heads, and no end gun or corner span. Under these assumptions, a weighted area irrigation efficiency (WAIE) is calculated and then reported on each Table 1. This WAIE is then used to estimate the current gross application volume on each Table 2, both for the present situation with 0-percent IWM (Column 5) and with 100-percent IWM (Column 8).

Cropping Assumptions

For Table 2(b) for Horse Heaven Hills, we have added crop categories for double cropping of bluegrass seed followed by sweet corn, green peas followed by sweet corn, and green beans followed by sweet corn. As we discussed on December 21st, there are no overall, area-wide records for

double cropping. We have used the three example farms, provided by PGG to define the double cropping data and applied these proportions area-wide. For each double cropping calculation, we have assumed the first crop is grown and irrigated during April, May and June, and the second crop (sweet corn) is grown and irrigated during July, August and September.

Pathway Assumptions

To evaluate the timing of surface runoff and deep percolation losses, PGG needed an estimate of the relative quantities of the loss pathways. RH2's estimate for those pathways is included as Appendix B of the PGG draft report. For those estimates the values for evaporation and surface runoff are based on published research as referenced in Appendix B. Deep percolation losses were calculated as the difference between total losses and the sum of evaporation and surface runoff. Deep percolation losses are broken into two components. The first component is the result of the difference between Pre-IWM and Post-IWM. This assumes that the additional water applied before implementing IWM is lost to deep percolation. (See Appendix F) The second component of deep percolation loss is the result of application inefficiency. That loss is less after IWM because less water is exposed to loss but there is still a loss to deep percolation even after implementing IWM. For each Table 1, a table of loss pathways for the Pre-IWM situation and a table of the Post-IWM situation is presented.

Conservation potential

Each Table 3 estimates conservation potential from irrigation equipment upgrades, and estimate the IWM conservation potential by reducing the crop water application volume 17.31 percent. These tables reflect that IWM conservation potential is estimated first and then the conservation potential of equipment upgrades is estimated. For the stacked bar graphs illustrating potential savings, we have only displayed those equipment upgrades that are most likely, e.g., upgrading center pivots with end gun to center pivots with LEPA, or upgrading rill or wheel line to center pivot with LEPA. We anticipate that most irrigators making improvements will upgrade to center pivots with LEPA and not to some intermediate technology.

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Horse Heaven Hills Study Area

Table 1(b): Area wide irrigation efficiency based on present irrigation methods and method efficiency.

	1	*1/Total Acres = 2*	*3*	*2 * 3 = 4*						
Estimated Irrigation Usage with Current Irrigation Methods					Estimated Pre-IWM Irrigation Losses					
Irrigation method	Acres	Percent of Area	Method Efficiency[2]	Weighted Efficiency per Method		Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total	
Center Pivot[1]	124168	89.27%	87.50%	78.11%		33154	1658	6631	49825	91267	
Center Pivot/Sprinkler	146	0.11%	80.00%	0.08%		59	4	16	59	137	
Sprinkler (Handline/Solid set)	4660	3.35%	75.00%	2.51%		1244	373	1493	1870	4980	
Drip	8217	5.91%	85.00%	5.02%		1097	0	2194	3297	6588	
Drip/Sprinkler	1191	0.86%	80.00%	0.68%		318	0	318	478	1114	
Rill	0	0.00%	65.00%	0.00%		0	0	0	0	0	
Wheel line	46	0.03%	75.00%	0.02%		12	4	15	18	49	
Other[3]	667	0.48%	79.50%	0.38%		178	53	134	268	633	
Total Acres	139095	100.00%	Weighted Average Irrigation Efficiency (WAIE)	**86.82%**	**Total**	**36062 Ac-ft[5]**	**2092 Ac-ft[5]**	**10800 Ac-ft[5]**	**55815 Ac-ft**	**104768 Ac-ft**	**(Ac-ft)**
	Estimated Current Water Use[4]		2.69 Ac-ft/ac								

Estimated Post-IWM Irrigation Losses						
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total	
	27415	1371	5483	0	34269	
	48	3	13	0	65	
	1029	309	1235	0	2572	
	907	0	1814	0	2721	
	263	0	263	0	526	
	0	0	0	0	0	
	10	3	12	0	25	
	147	44	110	0	302	
Total	**29820 Ac-ft**	**1730 Ac-ft**	**8930 Ac-ft**	**0 Ac-ft**	**40480 Ac-ft**	**(Ac-ft)**

Reductions in Totals from Pre to Post IWM				
6242 Ac-ft	**362 Ac-ft**	**1869 Ac-ft**	**55815 Ac-ft**	**64288 Ac-ft**

[1]Value is a weighted average of 50% center pivot with LEPA and 50% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[3] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[4] See Table 2(b)

[5] Total of 48,958 compares to 49,250 in columns 6, Table 2(b). Variance is due to multiple roundings.

[6] Total of 40,480 compares to 40,724 in columns 7, Table 2(b). Variance is due to multiple roundings.

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Horse Heaven Hills Study Area

Table 2(b): Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area.

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)[9]	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[8]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[9]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[8]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Potato	29137	20.9%	2.19 [2]	63859	73555	9695	52805	60822	8017	12732	11054	1678
Sweet Corn	20974	15.1%	1.98 [2]	41423	47712	6289	34253	39453	5200	8259	7170	1089
Wheat	13611	9.8%	2.53 [3]	34368	39586	5218	28419	32734	4315	6852	5949	903
Field Corn	12185	8.8%	2.48 [2]	30260	34855	4594	25022	28821	3799	6033	5238	795
Onion	10964	7.9%	2.71	29721	34234	4512	24576	28308	3731	5926	5145	781
Bluegrass Seed	7538	5.4%	1.39 [2]	10491	12083	1593	8675	9992	1317	2092	1816	276
Bluegrass Seed/Sweet Corn[11]	1932[12]	1.4%	2.28 [2,14]	4397	5064	668	3636	4188	552	877	761	116
Alfalfa Hay	6632	4.8%	3.53 [2]	23376	26925	3549	19330	22265	2935	4661	4046	614
Wine Grape	5804	4.2%	2.08	12054	13884	1830	9967	11480	1513	2403	2086	317
Green Pea	5629	4.0%	1.97 [4]	11069	12750	1681	9153	10543	1390	2207	1916	291
Green Pea/Sweet Corn[11]	1442[12]	1.0%	2.36 [2]	3399	3916	516	2811	3238	427	678	588	89
Apple	3309	2.4%	2.95	9764	11246	1482	8074	9300	1226	1947	1690	257
Mint	3189	2.3%	2.82	8990	10355	1365	7434	8562	1129	1792	1556	236
Hybrid Poplar	2743	2.0%	3.17 [5]	8686	10005	1319	7182	8273	1090	1732	1504	228
Carrot	2671	1.9%	1.89	5046	5812	766	4173	4806	634	1006	874	133
Sugar Beet	2142	1.5%	2.73	5842	6728	887	4830	5564	733	1165	1011	154
Green Bean	1305	0.9%	1.91 [2]	2490	2868	378	2059	2371	313	496	431	65
Green Bean/Sweet Corn[11]	334[12]	0.2%	1.83 [2,13]	611	703	93	505	582	77	122	106	16
Timothy	1127	0.8%	2.78 [6]	3136	3612	476	2593	2987	394	625	543	82
Other	6427	4.6%	2.40 [7]	15407	17747	2339	12740	14675	1934	3072	2667	405
Total	**139095**	**100%**		**324390**	**373640**	**49250**	**268238**	**308963**	**40724**	**64677**	**56152**	**8525**

[1] WA Irr. Guide, McNary, WA station (WIG)

[2] 1988-1994 average from USBR-Agrimet Hermiston station.

[3] Average of winter and spring wheat values

[4] Includes green pea and pea seed acreage

[5] Estimate based on Agrimet crop curves

[6] Used pasture/turf values

[7] Average of above crops

[8] Estimated application volume is based on a 84.59% weighted average irrigation efficiency (WAIE), see Table 1

[9] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).

[10] Estimated current water use is the total current crop need divided by the total acres.

[11] First crop is grown and irrigated from April to June. Second crop (Sweet corn) is grown and irrigated from July to September.

[12] Double Crop acreage was determined by taking 20.4% of the original crop acres. E.g. Total acres growing blue grass seed is 9470. Acres double cropped is 9470*20.4% = 1932. Actual acres in blue grass seed is 7538 (9470-1932).

[13] Irrigation requirement for the months of April, May, and June for Green Bean was taken from WA Irr. Guide, Richland, WA station.

[14] Irrigation requirement for the months of April, May, and June for Bue Grass seed is 50% of the total annual irrigation requirment as determined by 1988-1994 average from USBR-Agrimet Hermiston station.

Current Average Crop Need	2.33 Ac-ft/Ac
Estimated Current Water Use[10]	2.69 Ac-ft/Ac
IWM Average Crop Need	1.93 Ac-ft/Ac
Estimated Water use With IWM	2.22 Ac-ft/Ac

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Horse Heaven Hills Study Area

Table 3(b): Horse Heaven Hills Study Area upgrades matrix. Different upgrades options were evaluated. Structural irrigation upgrades were kept separate from IWM upgrades. IWM upgrades represent the entire study area adopting IWM practices. Mechanical upgrade values represent incremental recoverable water values. Calculations that are not possible are represented with a dash (-).

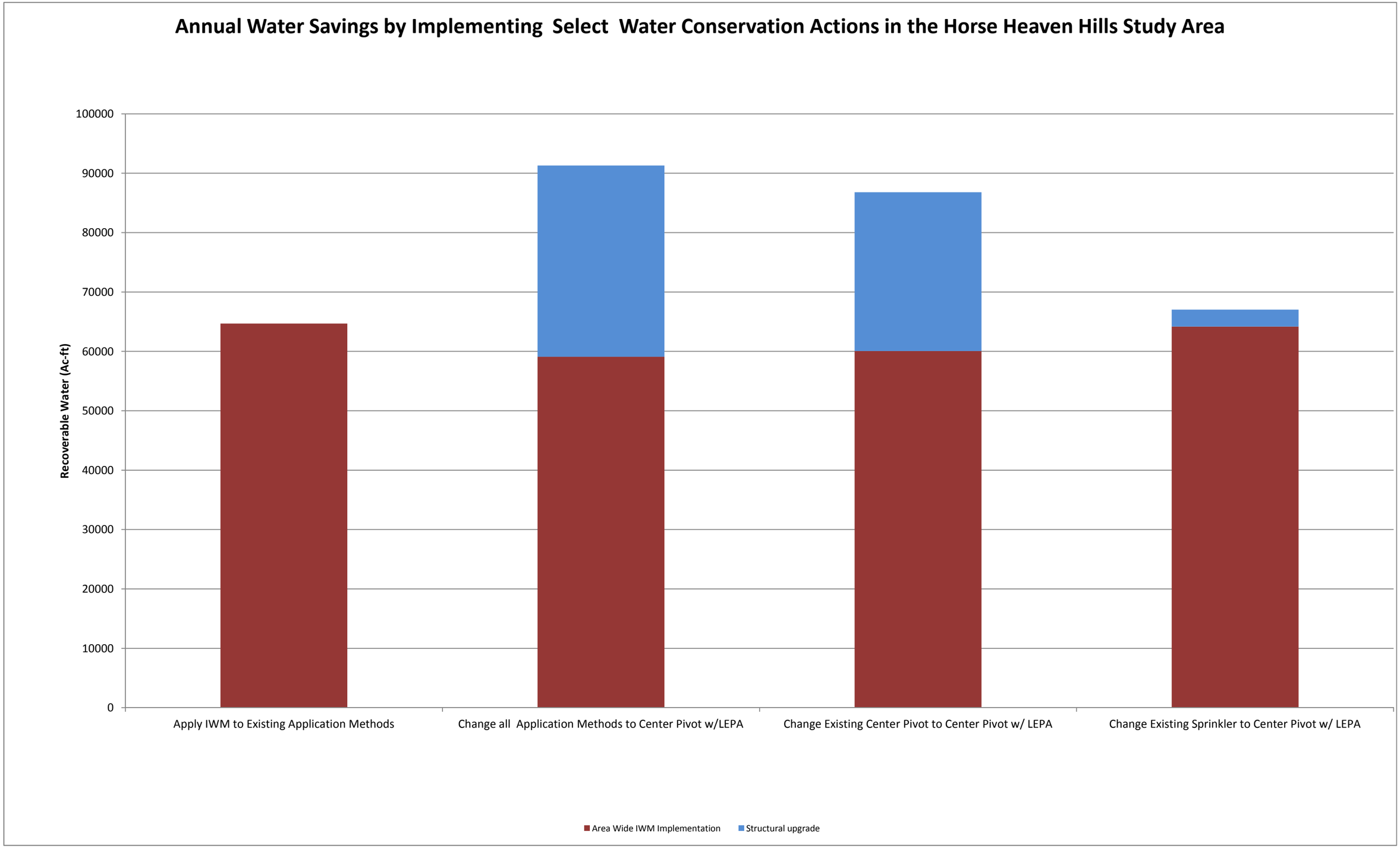
	Structural Irrigation Upgrades			**Area Wide IWM[1] Irrigation Upgrade**	**Combined Water Recovered**		
Change in irrigation method	Increase In Area Wide Efficiency	Water Recovered (Ac-ft)	Percent of Water Recovered[3]	Additional Water Recovered (Ac-ft)	Maximum Water Recoverable. Sum of IWM and Structural Upgrade (Ac-ft)	Percent of water Recovered	Unrecovered Water
Apply IWM to Existing Application Methods	-	-	-	64680	64680	17.31%	40,722
Change all Application Methods to Center Pivot w/LEPA	8.18%	32176	8.61%	59110	91280	24.43%	14,122
Change Existing Center Pivot to Center Pivot w/ LEPA	6.70%	26751	7.16%	60050	86800	23.23%	18,602
Change Existing Rill to Sprinkler	-	-	-	64680	64680	17.31%	40,722
Change Existing Rill to Center Pivot[2]	-	-	-	64680	64680	17.31%	40,722
Change Existing Rill to Center Pivot w/ LEPA	-	-	-	64680	64680	17.31%	40,722
Change Existing Sprinkler to Center Pivot[2]	0.42%	1794	0.48%	64370	66160	17.71%	39,242
Change Existing Sprinkler to Center Pivot w/ LEPA	0.67%	2861	0.77%	64180	67040	17.94%	38,362
Change Existing Sprinkler to Drip Only	0.34%	1436	0.38%	64430	65860	17.63%	39,542
Change Existing Wheel Line to Center pivot[2]	0.00%	18	0.00%	64670	64690	17.31%	40,712
Change Existing Wheel Line to Center Pivot w/LEPA	0.01%	28	0.01%	64670	64700	17.32%	40,702
Change Existing 'Other' to Center pivot[2]	0.04%	165	0.04%	64650	64810	17.35%	40,592
Change Existing 'Other' to Center Pivot w/LEPA	0.07%	320	0.09%	64620	64940	17.38%	40,462

[1] IWM - Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water management Area, 2005).

[2] Center pivot and drip irrigation have equal irrigation efficiencies. Converting a current irrigation structure to a drip system or a center pivot system would yield the same recovery quantities.

[3] Percent of water recovered – is the percentage of water that is no longer needed for irrigation purposes. It is equal to the volume of water recovered because of IWM and/or structural upgrades divided by the volume of current water use.

[4] Structural upgrade efficiency values are reported in Table 1, except center pivot with LEPA, which has an efficiency value of 95%.


Annual Water Savings by Implementing Select Water Conservation Actions in the Horse Heaven Hills Study Area
Recoverable Water (Ac-ft)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Apply IWM to Existing Application Methods
Change all Application Methods to Center Pivot w/LEPA
Change Existing Center Pivot to Center Pivot w/ LEPA
Change Existing Sprinkler to Center Pivot w/ LEPA
Area Wide IWM Implementation
Structural upgrade

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South Franklin County Study Area

Table 1(a): Area wide irrigation efficiency based on present irrigation methods and method efficiency. For this study area, the estimated current water use was within 3.1% of the water use value reported by SCBID

	1	*1/Total Acres = 2*	*3*	*2 * 3 = 4*
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[3]	Weighted Efficiency per Method
Center Pivot[1]	96468	74.58%	85.25%	63.58%
Center Pivot/Sprinkler	4222	3.26%	80.00%	2.61%
Sprinkler (Handline/Solid set)	14841	11.47%	75.00%	8.61%
Drip	514	0.40%	85.00%	0.34%
Drip/Sprinkler	410	0.32%	80.00%	0.25%
Rill	2498	1.93%	65.00%	1.26%
Wheel line	7812	6.04%	75.00%	4.53%
Other[4]	2578	1.99%	79.50%	1.58%
Total Acres	129343	100.0%	Weighted Average Irrigation Efficiency (WAIE)	**82.76%**
	Estimated Current Water Use[5]		3.46 Ac-ft/ac	
		SCBID water use[2]	3.57 Ac-ft/ac	

[1]Value is a weighted average of 35% center pivot with LEPA and 65% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]SCBID Data (1991-2009, Average of Blocks 1,13,14,15,16,17,19,161)

[3]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[4] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[5] See Table 2 (a)

Estimated Pre-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	38431	2172	8689	47875	97167
	2194	146	585	2095	5020
	5141	1542	6170	7365	20219
	89	0	178	255	522
	142	0	142	204	488
	433	865	1731	1240	4269
	2706	812	3248	3877	10643
	893	268	670	1279	3110
Total	**50030**	**5806**	**21412**	**64190**	**141437**

Estimated Post-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	31779	1796	7185	0	40760
	1814	121	484	0	2419
	4251	1275	5102	0	10628
	74	0	147	0	221
	118	0	118	0	235
	358	716	1431	0	2505
	2238	671	2685	0	5595
	738	222	554	0	1514
Total	**41370**	**4801**	**17705**	**0**	**63876**

Reductions in Totals from Pre to Post IWM				
8660 Ac-ft	**1005 Ac-ft**	**3706 Ac-ft**	**64190 Ac-ft**	**77561 Ac-ft**

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South Franklin County Study Area

Table 2(a): Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[11]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[12]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[11]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Alfalfa Hay	46363	35.8%	3.30	152845	184684	31839	126387	152715	26328	31969	26457	5511
Potatoes	20984	16.2%	2.56	53649	64825	11176	44363	53604	9241	11221	9287	1935
Wheat	11688	9.0%	2.17 [2]	25304	30575	5271	20924	25283	4359	5293	4380	912
Timothy Hay	7777	6.0%	3.48 [3]	27059	32696	5637	22375	27036	4661	5660	4684	976
Apples	6879	5.3%	3.48 [4]	23963	28955	4992	19815	23943	4128	5012	4148	864
Field Corn	5270	4.1%	2.61	13731	16592	2860	11355	13720	2365	2872	2377	495
Sweet Corn	4924	3.8%	1.86	9142	11046	1904	7559	9134	1575	1912	1582	330
Asparagus	3010	2.3%	2.93 [5]	8805	10639	1834	7281	8797	1517	1842	1524	317
Cherry	2857	2.2%	3.53 [6]	10096	12200	2103	8349	10088	1739	2112	1748	364
Green Peas	2412	1.9%	1.64	3960	4785	825	3275	3957	682	828	686	143
Grass Hay	1734	1.3%	3.48 [7]	6033	7289	1257	4988	6027	1039	1262	1044	218
Wine Grape	1342	1.0%	2.09 [5]	2808	3392	585	2322	2805	484	587	486	101
Dry Bean	1310	1.0%	2.01	2631	3179	548	2176	2629	453	550	455	95
Buckwheat	1189	0.9%	1.50 [8]	1783	2155	371	1475	1782	307	373	309	64
Bluegrass Seed	1173	0.9%	1.39 [5]	1632	1972	340	1350	1631	281	341	283	59
Seed Corn	1159	0.9%	1.86 [9]	2154	2602	449	1781	2152	371	450	373	78
Pasture	1112	0.9%	3.48	3869	4675	806	3199	3866	666	809	670	140
Onion	1043	0.8%	2.94	3061	3699	638	2531	3059	527	640	530	110
Other	7116	5.5%	2.57 [10]	18300	22112	3812	15132	18284	3152	3828	3168	660
Total	**129343**	**100%**		**370825**	**448073**	**77247**	**306636**	**370511**	**63876**	**77561**	**64190**	**13372**

[1] WA Irr. Guide, Richland, WA station (WIG)

[2] Average of winter and spring wheat values

[3] Used pasture/turf values

[4] Average of apples with cover and apples without cover

[5] 1988-1994 average from USBR-Agrimet Legrow station.

[6] Average of cherries with cover and cherries without cover

[7] Used pasture/turf values

[8] Estimate

[9] Used sweet corn values

[10] Average of above crops

[11] Estimated application volume is based on a 82.6% weighted average irrigation efficiency (WAIE), see Table 1

[12] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).

[13] Estimated current water use is the total current crop need divided by the total acres.

Current Average Crop Need	2.87 Ac-ft/Ac
Estimated Current Water Use[13]	3.46 Ac-ft/Ac
IWM Average Crop Need	2.37 Ac-ft/Ac
Estimated Water use With IWM	2.86 Ac-ft/Ac

Submitted August 19, 2011

South Franklin County Study Area

Table 3(a): South Franklin County Study Area upgrades matrix. Different upgrades options were evaluated. Structural irrigation upgrades were kept separate from IWM upgrades. IWM upgrades represent the entire study area adopting IWM practices. Mechanical upgrade values represent incremental recoverable water values. Calculations that are not possible are represented with a dash (-).

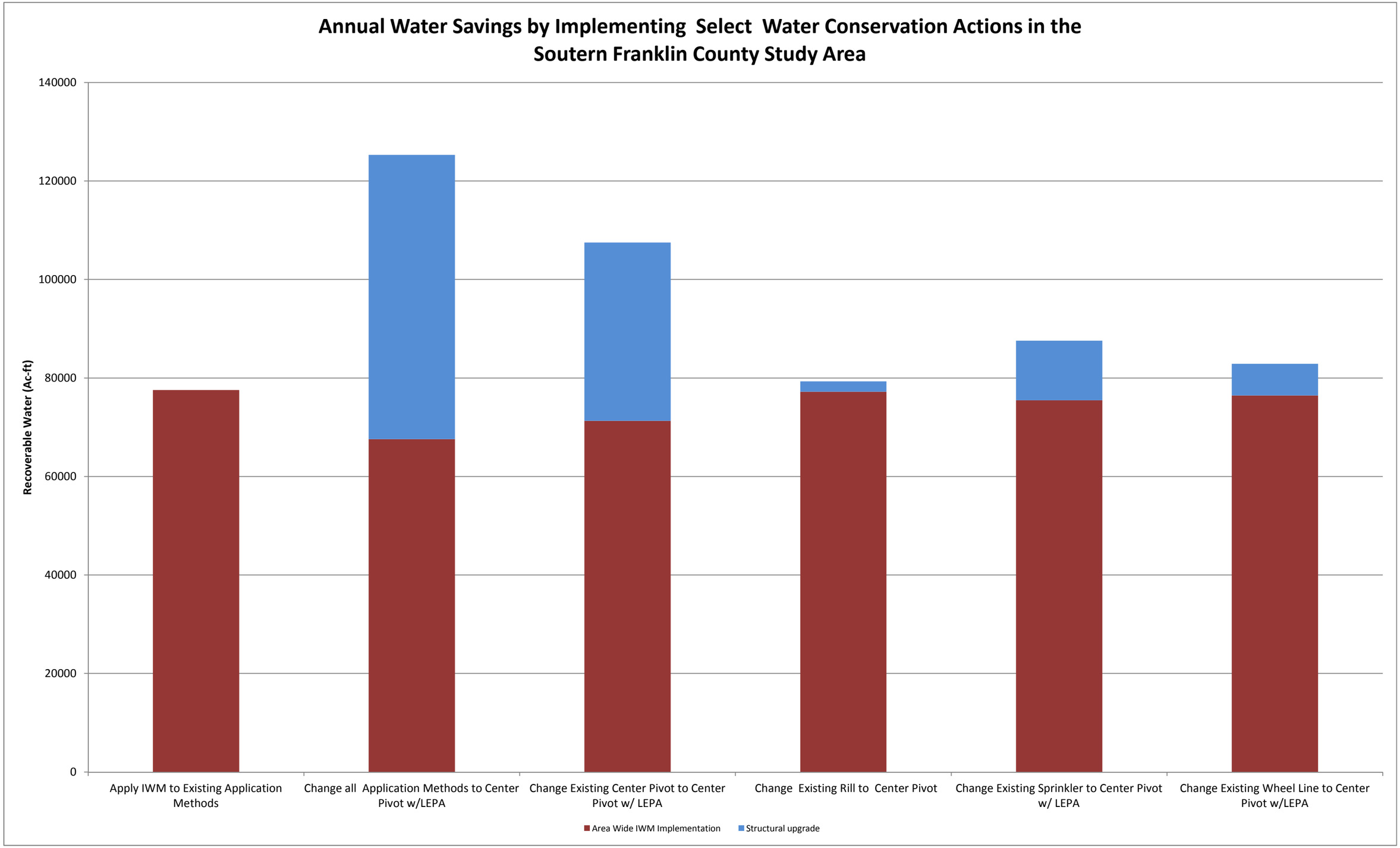
	Structural Irrigation Upgrades			**Area Wide IWM[1] Irrigation Upgrade**	**Combined Water Recovered**		
Change In Irrigation Method	Increase In Area Wide Efficiency	Water Recovered (Ac-ft)	Percent of Water Recovered[3]	Additional Water Recovered (Ac-ft)	Maximum Water Recoverable. Sum of IWM and Structural Upgrade (Ac-ft)	Percent of water Recovered	Unrecovered Water
Apply IWM to Existing Application Methods	-	-	-	77560	77560	17.31%	63,877
Change all Application Methods to Center Pivot w/LEPA	12.24%	57730	12.88%	67570	125300	27.96%	16,137
Change Existing Center Pivot to Center Pivot w/ LEPA	7.27%	36191	8.08%	71300	107490	23.99%	33,947
Change Existing Rill to Sprinkler	0.19%	1043	0.23%	77380	78420	17.50%	63,017
Change Existing Rill to Center Pivot[2]	0.39%	2113	0.47%	77200	79310	17.70%	62,127
Change Existing Rill to Center Pivot w/ LEPA	0.58%	3115	0.70%	77020	80140	17.88%	61,297
Change Existing Sprinkler to Center Pivot [2]	1.18%	6309	1.41%	76470	82780	18.47%	58,657
Change Existing Sprinkler to Center Pivot w/ LEPA	2.29%	12089	2.70%	75470	87560	19.54%	53,877
Change Existing Sprinkler to Drip Only	1.15%	6127	1.37%	76500	82630	18.44%	58,807
Change Existing Wheel Line to Center pivot [2]	0.62%	3343	0.75%	76980	80330	17.93%	61,107
Change Existing Wheel Line to Center Pivot w/LEPA	1.21%	6446	1.44%	76450	82890	18.50%	58,547
Change Existing 'Other' to Center pivot [2]	0.12%	625	0.14%	77450	78080	17.43%	63,357
Change Existing 'Other' to Center Pivot w/LEPA	0.31%	1666	0.37%	77270	78940	17.62%	62,497

[1] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water management Area, 2005).

[2] Center pivot and drip irrigation have equal irrigation efficiencies. Converting a current irrigation structure to a drip system or a center pivot system would yield the same recovery quantities.

[3] Percent of water recovered – is the percentage of water that is no longer needed for irrigation purposes. It is equal to the volume of water recovered because of IWM and/or structural upgrades divided by the volume of current water use.

[4] Structural upgrade efficiency values are reported in Table 1, except center pivot with LEPA, which has an efficiency value of 95%.


Annual Water Savings by Implementing Select Water Conservation Actions in the Soutern Franklin County Study Area
Recoverable Water (Ac-ft)
140000
120000
100000
80000
60000
40000
20000
0
Apply IWM to Existing Application Methods
Change all Application Methods to Center Pivot w/LEPA
Change Existing Center Pivot to Center Pivot w/ LEPA
Change Existing Rill to Center Pivot
Change Existing Sprinkler to Center Pivot w/ LEPA
Change Existing Wheel Line to Center Pivot w/LEPA
Area Wide IWM Implementation
Structural upgrade

Updated August 30, 2011

Walla Walla Study Area

Table 1(c): Area wide irrigation efficiency based on present irrigation methods and method efficiency.

	1	1/Total Acres = 2	3	2 * 3 = 4
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[2]	Weighted Efficiency per Method
Center Pivot[1]	2380	6.49%	83.75%	5.44%
Center Pivot/Sprinkler	45	0.12%	80.00%	0.10%
Sprinkler (Handline/Solid set)	26951	73.52%	75.00%	55.14%
Drip	0	0.00%	85.00%	0.00%
Drip/Sprinkler	767	2.09%	80.00%	1.67%
Rill	369	1.01%	65.00%	0.65%
Wheel line	5177	14.12%	75.00%	10.59%
Other[3]	966	2.64%	79.50%	2.10%
Total Acres	36656	100.00%	Weighted Average Irrigation Efficiency (WAIE)	**75.70%**
	Estimated Current Water Use[4]		3.12 Ac-ft/ac	

Estimated Pre-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	927	56	222	972	2177
	21	1	6	18	46
	8396	2519	10075	11001	31991
	0	0	0	0	0
	239	0	239	313	791
	57	115	230	151	553
	1613	484	1935	2113	6145
	301	90	55	394	840
Total	**11554 Ac-ft5**	**3265 Ac-ft5**	**12762 Ac-ft5**	**14963 Ac-ft**	**42544 Ac-ft**

Estimated Post-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	766	46	184	0	996
	17	1	5	0	23
	6943	2083	8331	0	17356
	0	0	0	0	0
	198	0	198	0	395
	48	95	190	0	333
	1334	400	1600	0	3334
	249	75	187	0	510
Total	**9554 Ac-ft6**	**2700 Ac-ft6**	**10694 Ac-ft6**	**0 Ac-ft**	**22948 Ac-ft**

Reductions in Totals from Pre to Post IWM				
2000 Ac-ft	**565 Ac-ft**	**2068 Ac-ft**	**14963 Ac-ft**	**19596 Ac-ft**

[1]Value is a weighted average of 35% center pivot with LEPA and 65% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[3] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[4] See Table 2(c)

[5] Total of 27,587 compares to 27,752 in columns 6, Table 2(b). Variance is due to multiple roundings.

Submitted August 19, 2011

Walla Walla Study Area

Table 2(c): Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area.

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)[9]	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[8]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)[9]	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[9]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[8]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Barley	236	0.6%	1.65 [2]	388	513	125	321	424	103	89	67	22
Oat	225	0.6%	1.64 [2]	370	489	119	306	404	98	85	64	21
Wheat	10005	27.3%	1.64 [2]	16425	21698	5273	13582	17942	4361	3756	2843	913
Alfalfa Hay	5556	15.2%	2.74 [1]	15209	20092	4883	12576	16614	4038	3478	2633	845
Alfalfa/Grass Hay	610	1.7%	2.74 [1]	1669	2204	536	1380	1823	443	382	289	93
Grass Hay	1070	2.9%	2.90 [3]	3106	4103	997	2568	3393	825	710	538	173
Timothy	817	2.2%	2.90 [3]	2369	3130	761	1959	2588	629	542	410	132
Pasture	2350	6.4%	2.90 [1]	6816	9005	2188	5636	7446	1810	1559	1180	379
Alfalfa Seed	10728	29.3%	2.74 [4]	29414	38858	9444	24322	32131	7809	6726	5092	1635
Golf Course/Lawn	471	1.3%	2.90 [3]	1366	1804	439	1129	1492	363	312	236	76
Onion	499	1.4%	2.58 [1]	1286	1699	413	1063	1405	341	294	223	71
Dry Pea	1452	4.0%	1.35 [5]	1954	2582	627	1616	2135	519	447	338	109
Wine Grape	618	1.7%	2.09 [6]	1293	1708	415	1069	1412	343	296	224	72
Other	2018	5.5%	2.37 [7]	4774	6307	1533	3948	5215	1268	1092	826	265
Total	**36656**	**100%**		**86439**	**114191**	**27752**	**71477**	**94425**	**22948**	**19767**	**14963**	**4804**

[1] WA Irr. Guide, Walla Walla, WA station (WIG)
[2] Average of winter and spring wheat values
[3] Used pasture/turf values
[4] Used alfalfa hay values
[5] Estimate based on Agrimet crop curves
[6] 1988-1994 average from USBR-Agrimet Legrow station.
[7] Average of above crops
[8] Estimated application volume is based on a 75.78% weighted average irrigation efficiency (WAIE), see Table 1
[9] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).
[10] Estimated current water use is the total current crop need divided by the total acres.

Current Average Crop Need	2.36 Ac-ft/Ac
Estimated Current Water Use[10]	3.12 Ac-ft/Ac
IWM Average Crop Need	1.95 Ac-ft/Ac
Estimated Water use With IWM	2.58 Ac-ft/Ac

Submitted August 19, 2011

Walla Walla Study Area

Table 3(c): Walla Walla Study Area upgrades matrix. Different upgrades options were evaluated. Structural irrigation upgrades were kept separate from IWM upgrades. IWM upgrades represent the entire study area adopting IWM practices. Mechanical upgrade values represent incremental recoverable water values. Calculations that are not possible are represented with a dash (-).

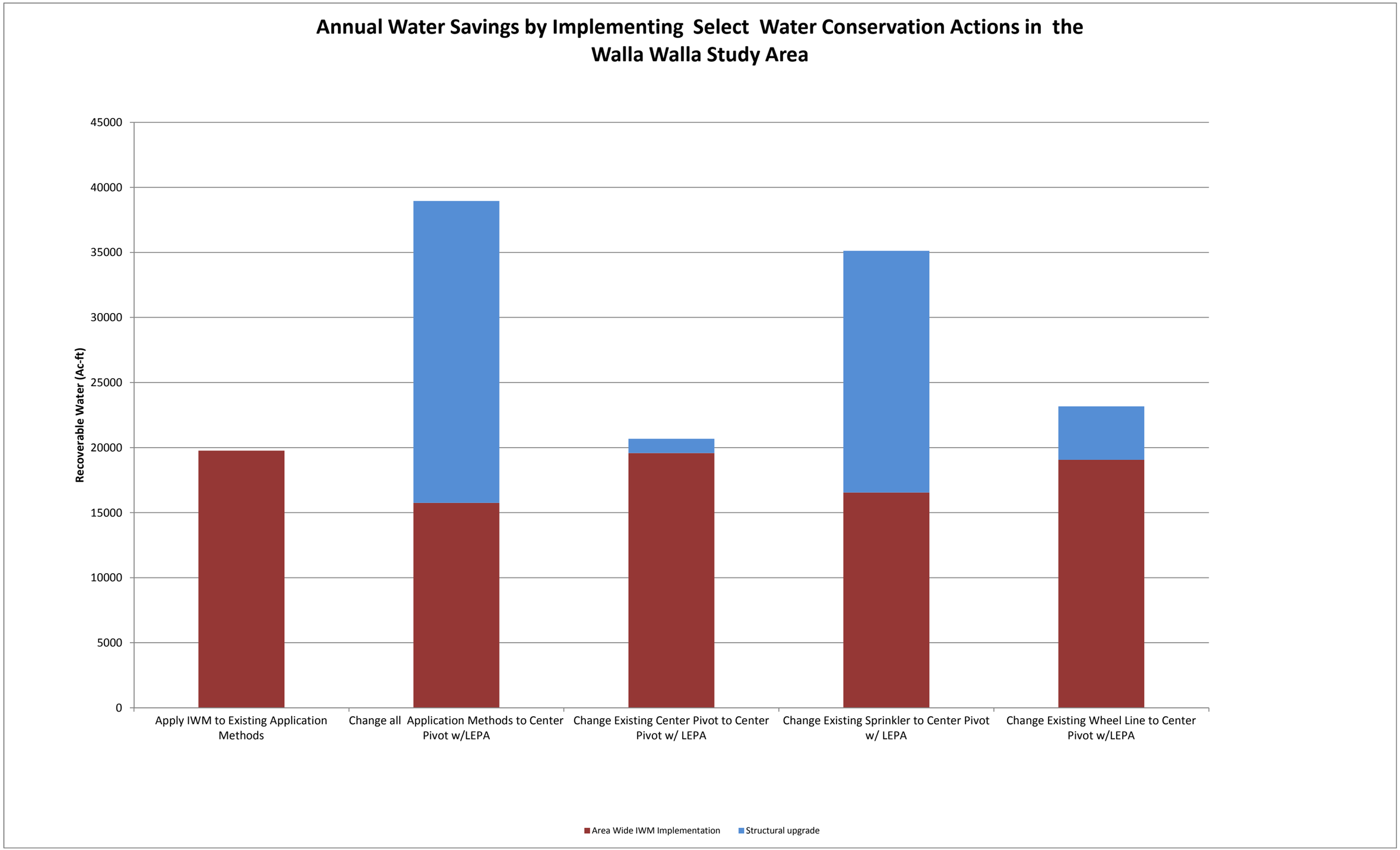
	Structural Irrigation Upgrades			Area Wide IWM[1] Irrigation Upgrade	Combined Water Recovered		
Change in Irrigation Method	Increase In Area Wide Efficiency	Water Recovered (Ac-ft)	Percent of water Recovered[3]	Additional Water Recovered (Ac-ft)	Maximum Water Recoverable. Sum of IWM and Structural Upgrade (Ac-ft)	Percent of water Recovered	Unrecovered Water
Apply IWM to Existing Application Methods	-	-	-	19770	19770	17.31%	22,945
Change all Application Methods to Center Pivot w/LEPA	19.30%	23203	20.32%	15750	38950	34.11%	3,765
Change Existing Center Pivot to Center Pivot w/ LEPA	0.73%	1092	0.96%	19580	20670	18.10%	22,045
Change Existing Rill to Sprinkler	0.10%	152	0.13%	19740	19890	17.42%	22,825
Change Existing Rill to Center Pivot[2]	0.19%	280	0.25%	19720	20000	17.51%	22,715
Change Existing Rill to Center Pivot w/ LEPA	0.30%	454	0.40%	19690	20140	17.64%	22,575
Change Existing Sprinkler to Center Pivot[2]	6.47%	8992	7.87%	18210	27200	23.82%	15,515
Change Existing Sprinkler to Center Pivot w/ LEPA	14.70%	18575	16.27%	16550	35130	30.76%	7,585
Change Existing Sprinkler to Drip Only	7.35%	10109	8.85%	18020	28130	24.63%	14,585
Change Existing Wheel Line to Center pivot[2]	1.24%	1845	1.62%	19450	21290	18.65%	21,425
Change Existing Wheel Line to Center Pivot w/LEPA	2.82%	4108	3.60%	19060	23160	20.28%	19,555
Change Existing 'Other' to Center pivot[2]	0.11%	159	0.14%	19740	19900	17.43%	22,815
Change Existing 'Other' to Center Pivot w/LEPA	0.41%	613	0.54%	19660	20270	17.75%	22,445

[1] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water management Area, 2005).

[2] Center pivot and drip irrigation have equal irrigation efficiencies. Converting a current irrigation structure to a drip system or a center pivot system would yield the same recovery quantities.

[3] Percent of water recovered – is the percentage of water that is no longer needed for irrigation purposes. It is equal to the volume of water recovered because of IWM and/or structural upgrades divided by the volume of current water use.

[4] Structural upgrade efficiency values are reported in Table 1, except center pivot with LEPA, which has an efficiency value of 95%.


Annual Water Savings by Implementing Select Water Conservation Actions in the Walla Walla Study Area
Recoverable Water (Ac-ft)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Apply IWM to Existing Application Methods
Change all Application Methods to Center Pivot w/LEPA
Change Existing Center Pivot to Center Pivot w/ LEPA
Change Existing Sprinkler to Center Pivot w/ LEPA
Change Existing Wheel Line to Center Pivot w/LEPA
Area Wide IWM Implementation
Structural upgrade

Appendix B
Technical Memorandum

To: Peter Schwartzman, Pacific Groundwater Group

From: Randy Asplund, P.E. and Dick Erickson, P.E.

Subject: Estimating Irrigation Losses
Date: October 13, 2010
Revised: August 19, 2011

General Statements

The discussions, quantifications and recommendations of irrigation losses and loss pathways in this Technical Memorandum are based on references A, B and C. Those references are listed at the end of the memorandum.

Spray Evaporative Loss. When water travels through the air during sprinkling, some water evaporates. The magnitude of evaporation depends on drop size (smaller drops evaporate quicker), drop travel time (e.g. sprinkler height off the ground, sprinkler angle and wind), and environmental conditions (temperature, humidity, etc.). For sprinkler systems within low heights and low wind conditions (5 feet or less off the ground and 5 mph or lower average conditions), spray evaporative loss tends to be on the order of 2% or less. For higher elevations and wind conditions, evaporative losses can be greater than 10%. (**Reference A**).

Runoff. When water is applied at a rate greater than the soil can infiltrate, it can lead to runoff. Runoff within a field may still be used by the crop, although areas of low elevation may be areas of deep percolation if runoff typically collects there. Therefore runoff losses from one location in a field can shift to deep percolation losses at another location. If runoff returns to waters of the State, it is considered to be return flow. Runoff is more prevalent in surface irrigation systems (10 – 40%) than in sprinkler systems, although some irrigation systems (e.g. center-pivot LEPA) can have runoff due to high application rates (2 – 20%). (**Reference A**).

Deep Percolation Losses. Water that travels downward beneath the crop's root zone and is lost for the purpose of irrigating the crop at the location where it is applied. Deep percolation losses can migrate downward to shallower depths within a field's subsoil and add to the water table or it can migrate deeper and add to groundwater. Water lost to deep percolation can, depending on topography, soils and geology later daylight back to the surface becoming runoff. Therefore, deep percolation losses from one location can shift to runoff losses at another location. If this water, as either deep percolation or runoff returns to waters of the state, it is considered to be return flow. Deep percolation losses are more difficult to measure directly than evaporation of surface runoff. Therefore, for the purposes of this Technical Memorandum and the larger report it supports, deep percolation is defined as:

deep percolation = total losses – evaporation – runoff.

Surface Irrigation (Reference A, Table 1)

Graded Furrow

Application Efficiency	65%
Evaporation Losses	5%
Runoff and Deep Percolation (Return Flows *)	30%

Graded Furrow with Tailwater Reuse

Application Efficiency	75%
Evaporation Losses	5%
Runoff and Deep Percolation (Return Flows *)	20%

Sprinklers (Reference A, Table 1)

Handline

Application Efficiency	75%
Evaporation Losses	10%
Runoff and Deep Percolation (Return Flows *)	15%

Wheel Line

Application Efficiency	75%
Evaporation Losses	10%
Runoff and Deep Percolation (Return Flows *)	15%

Center Pivots (Reference A, Table 1)

Center Pivot w/o LEPA

Application Efficiency	80%
Evaporation Losses	15%
Runoff and Deep Percolation (Return Flows *)	5%

Center Pivot w/LEPA

Application Efficiency	92%
Evaporation Losses	5%
Runoff and Deep Percolation (Return Flows *)	3%

Drip (Reference A, Table 1)

Application Efficiency	88%
Evaporation Losses	5%
Runoff and Deep Percolation (Return Flows *)	7%

* Reference A defines return flows as the sum of surface runoff losses and deep percolation losses. To segregate those components requires knowing the field capacity of the soil (how much water can be stored in the root zone) and the consumptive use for the specific crop. While the above information does not distinguish between surface and deep percolation, it does give us an estimate of the evaporative losses as a percent of the total loss.

More Specific Center Pivot Data

Reference B measured runoff from center pivot irrigation over a 4 year period. The purpose of the study was to measure and predict soil erosion but the study does present surface runoff losses. The study sites were in Nebraska and dealt with heavier soils than in our study areas. The study also investigated runoff and erosion for different sprinkler head types, tillage methods and field slope. Below is a summary of that report's summary:

Sprinkler Type[1]	Plot Slope %	Tillage Method[2]	Runoff Avg %
HPI	3.0	T	1.0
		D	1.1
		S	0.1
LPI	3.5	T	0.9
		D	1.6
		S	0.3
LPS	3.3	T	5.8
		D	8.2
		S	0.7

[1] HPI = High pressure impact sprinkler head; LPI = Low pressure impact sprinkler head; and LPS = Low pressure spray nozzles.
[2] T = Till-plant; D = Disk; and S = Subtill between rows.

Reference C reports on a center pivot runoff experiment conducted near Kimberly, Idaho. As with Reference B, the research was more focused on erosion than irrigation efficiency but it does report some experimental runoff data.

The following excerpts from that report's introduction are presented to illustrate how variable runoff and erosion can be based on field topography and other factors:

"A center pivot is a traveling lateral which pivots about one end, irrigating a circular area. The system capacity (often expressed in mm/day or gpm/acre) and the length of lateral determines the application rates, which increase in direct proportion to the distance from the pivot. Thus, the greatest potential for runoff occurs near the outer edge of the field. Pivot laterals are commonly 400 meters (m) (1/4 mi) in length and irrigate about 52 hectacres (ha) (130 acres). The type of sprinkler used on the lateral also affects the application rates, which are inversely proportional to the width of the sprinkler pattern. Lower pressure sprinklers are increasingly popular, and these have reduced pattern widths. Sprinkler droplet sizes are affected by the nozzle pressure, nozzle size and sprinkler type. Large drops with large impact energy striking the soil surface produce splash erosion, which, in turn affects infiltration and runoff.

Sprinkler systems, particularly center pivots, operate on variable topography. The slope direction relative to the lateral determines how runoff can accumulate and cause erosion. If the lateral is

perpendicular to the slope, runoff will tend to move away from the lateral, reducing concentrated flow and thus reducing the distance surface runoff will travel before it infiltrates. However, if the slope is parallel to the lateral, runoff can accumulate downslope sufficiently to cause erosion. If crop ridges are present, the row direction relative to the slope and lateral also affects the runoff flow direction. It is common practice to ridge and plant row crops perpendicular to a traveling lateral or in a circular pattern under a pivot to help direct runoff away from the lateral. The pivot wheel tracks themselves (about 40m apart) provide runoff channels, further complicating the process. If the lateral is traveling upslope, runoff will move onto a previously wetted area, whereas with downslope travel, runoff can move onto dry soil. Thus a complete runoff-erosion model for center pivot sprinkler systems must be able to handle both the rainfall-runoff situation and furrow-rill flow with infiltration or any combination thereof."

The following table from Reference C presents average data for 4 irrigations of a corn crop in 2000. Slopes in the test plot ranged from 2.5% to 3.0%.

Date	Application Rate	Average Peak Runoff Rate	Average Runoff %
22 June	25 mm/hr	3.6 mm/hr	14%
29 June	25 mm/hr	4.7 mm/hr	19%
12 July	25 mm/hr	6.8 mm/hr	27%
18 July	25 mm/hr	5.6 mm/hr	22%

Excerpts from Reference C have been included in this Technical Memorandum for its background and explanatory statements. The runoff percentages measured by that study are considerably larger than reported in Reference A and B and also larger than common empirical observations in the Horse Heaven Hills and Southern Franklin County study areas. Accordingly, the runoff percentages of Reference C were not used in formulating the recommendations that follow.

Recommendation: For the area-wide evaluations it is suggested that we consider the following values for average surface runoff.

Type of Irrigation	Evaporation Losses	Surface Runoff Losses	Deep Percolation	Total Losses
Furrow (Rill)	5%	10%	20%	35%
Handline	10%	3%	12%	25%
Wheelline	10%	3%	12%	25%
Center Pivot w/o LEPA	15%	1%	4%	20%
Center Pivot w/LEPA	5%	0%	0%	5%
Drip	5%	0%	10%	15%

As the larger study progressed it became known that various combinations of irrigation systems existed in all 3 study areas (e.g. drip plus other sprinkler). Also, it became necessary to evaluated center pivots with and without LEPA (Low Energy Precision Application). Also it became

necessary to categorize deep percolation losses into pre-IWM and post-IWM (Irrigation Water Management) evaluations. As a result the following values for average irrigation were also used.

Type of Irrigation	Evaporation Losses	Surface Runoff Losses	Application Inefficiency Deep Percolation	Total Losses
Center Pivot	10%	1%	4%	15%
Center Pivot/Sprinkler	15%	1%	4%	20%
Sprinkler	10%	3%	12%	25%
Drip	5%	0%	10%	10%
Drip/Sprinkler	10%	0%	10%	20%
Rill	5%	10%	20%	35%
Wheel Line	10%	3%	12%	25%
Other	10%	3%	7.5%	20.5%

Reference A – Washington Dept. of Ecology, Water Resources Program Guidance, GUID-1210, Determining Irrigation Efficiency and Consumptive Use.

Reference B – Low Pressure Center Pivot and Soil Management Effects on Runoff by L.N. Mielke, J.R. Gilley and Wallace Wilhelm, USDA-ARS, University of Nebraska-Lincoln, 1992.

Reference C – The WEPP Model for Runoff and Erosion Prediction Under Center Pivot Irrigation by D.C. Kincaid and G.A. Lehrsch, January 2001, ASAE, St. Joseph, MI.

Appendix C

Technical Memorandum

To: Peter Schwartzman

From: Randy Asplund, P. E., Dick Erickson, P. E.

Subject: Water Particle Travel Times

Date: October 13, 2010

Introduction

Compliance requirements for the federal Endangered Species Act have motivated a great deal of research about the migration of juvenile salmon and steelhead in the Columbia River. As an element of that research hydropower organizations and fisheries agencies have studied the timing of water movement down the Columbia River. In doing so the following is one method that has been developed in order to estimate water particle transport times:

$T=V/Q * (5.04 \times 10^{-4})$

where: T is the water particle travel time between two dams (days), V is the V= volume of water stored between dams (Ac-Ft), Q is the flow rate through the dam (Kcfs), and (5.04×10^{-4}) is a unit conversion factor.

Columbia/Snake River

Using reservoir storage tables developed by Chelan PUD and the U.S. Army Corps of Engineers along with historical flow data for the Columbia River, water particle transport times were calculated for three separate dates in 2009; May 15, July 1 and September 15. These dates were selected to be representative of typical flows during the spring shoulder of the irrigation season, the peak of the irrigation season and the fall shoulder. 2009 data was used to be coinsistent with the crop and irrigation data analyzed elsewhere in these studies. Water particle travel time in the Columbia varies constantly as reservoir operations change to meet multiple needs. These dates should be an average representation of water movement during those periods of the irrigation season but are not precise.

In doing the analysis a range of 16.6 to 45.1 days is require for a water particle to move from the tailrace of Grand Coulee Dam to the forebay of John Day Dam, See Table 1. Water particle transport time in the Snake River from the tailrace of Ice Harbor Dam to NcNary Dam ranges from 1 - 3.8 days, see Table 2.

Table 1: Average Water Particle Travel Times Between Reservoirs on the Columbia River.

		Flow Rate (Kcfs)[2]			Water Particle Travel Time (days)			
	Reservior[1] Size (Ac-ft)	5/15/09	7/1/2009	9/15/2009	5/15/09	7/1/2009	9/15/2009	Range (days)
Chief Joseph	593000	124.79	84.63	49.57	2.4	3.5	6.0	2.4 - 6
Wells Dam	331200	137.78	77.06	51.1	1.2	2.2	3.3	1.2 - 3.3
Rocky Reach	382000	133.35	73.22	52.28	1.4	2.6	3.7	1.4 - 3.7
Rock Island	113700	138.43	78.52	50.31	0.4	0.7	1.1	0.4 - 1.1
Wanapum	693600	135.49	83.52	60.69	2.6	4.2	5.8	2.6 - 5.8
Priest Rapids	237100	127.52	90.76	56.88	0.9	1.3	2.1	0.9 - 2.1
McNary	1350000	239.66	193.4	77.94	2.8	3.5	8.7	2.8 - 8.7
John Day	2223500	234.73	195.33	78.03	4.8	5.7	14.4	4.8 - 14.4
				Total Time	16.6	23.8	45.1	16.6 - 45.1 days

Table 2: Average Water Particle Travel Times between Ice Harbor Dam and McNary Dam

	Flow Rate (Kcfs)[3]			Water Particle Travel Time (days)			
	5/15/09	7/1/09	9/15/09	5/15/09	7/1/09	9/15/09	Range (days)
Ice Harbor	239.66	193.4	77.94	1.0	1.3	3.8	1 - 3.8

Surface Run

The network of constructed canals, wasteways and drains in southern Franklin County make the determination of water particle travel times much more complex than for rivers. . This process is analogous to predicting the time of concentration for a drainage basin. Several methods have been developed for doing this. One method appropriate for the southern Franklin County area would be applying the velocity relationship outlined in the TR-55 and reference by V. T. Chow in *Applied Hydrology*[4]. That velocity relationship models shallow concentrated flow as a function of slope (%) and surface run-off type (e.g. pasture, concrete, grass) for an irregularly shaped waterway.

In order to calculate the time of concentration, flow path, distance the water particle traveled, and the average slope has to be estimated. This was done using a 3D surface in Autodesk Civil 3D. Using a predicted average slope and assuming that and type was "pasture" table 5.7.1 was referenced in Chow's *Applied Hydrology*[3] to obtain an average velocity. Time of concentration was then calculated by dividing the predicted distance the water particle traveled by the average velocity.

For southern Franklin County the time of concentration varied **between 1 to 4.5 days**, depending on where the initial irrigation was being applied.

For Horse Heaven Hills, a similar approximation can be made but since GIS drainage information similar to that for southern Franklin County is not available flow in a path was much more of an approximation. The approximate time of concentration is **1.5 days**, which assumes that surface runoff water reaches a conveyance channel within 6 hours.

[1] Reservoir storage capacity was obtained from Reservoir Storage Tables provided by the Army Corps of Engineers and Chelan County PUD

[2] Flow Rates were provided by the Fish Passage Center at:
http://www.fpc.org/river/flowspill/FlowSpill_Query.html

[3] Relationship established from Army Corps of Engineers McNary Flow vs. Travel Time Figure.

[4] Chow, V. T., Maidment, D. R., & Mays, L. W. (1989). *Applied Hydrology*. Boston: McGraw Hill.

Appendix D
Technical Memorandum

To: Peter Schwartzman

From: Randy Asplund, P.E.; Dick Erickson, P.E.

Subject: Southern Franklin County Study Area – Current Practices and Conservation Potential Segregated by Geologic Province

Date: October 13, 2010
Revised: July 22, 2011
Revised August 19, 2011

The Southern Franklin County (SFC) Study Area can be broken into three geologic provinces: the Basalt Area (B); the Upper Ringold Area (R); and the Quaternary Flood Deposit Area (Q). The locations of these provinces are shown in the *Conservation Screening Analysis Report*. Pacific Groundwater Group (PGG) requested RH2 Engineering, Inc. (RH2) to subdivide the irrigation, crop and conservation potential information presented in Tables 1(a) and Table 2(a) (see attachments) among the three geologic provinces (see Table 3).

Using GIS information available from Franklin Conservation District (FCD) and PGG, RH2 has distributed the overall SFC information within the three geologic provinces. The breakdown for the Quaternary Flood Deposits is reported on Tables 1(a)-Q and 2(a)-Q. (The corresponding tables for the Basalt Area are designated by as –B and for the Upper Ringold Area as –R.) Distributing the original land, water and WSDA crop data provided by FCD geographically into the three geologic provinces resulted in some minor gapping and overlapping since the geologic boundaries needed to be adjusted to the nearest township and range. As a result the totals of various data categories for the three provinces do not always match that value for the overall SFC. Overall this variation is minimal and represents in most cases approximately 1.1 to 2.8 percent among the variation between the totals for the three provinces and the total SFC Study Area.

Table 3 summarizes the three provinces. The difference between the summation of the three provinces and the SFC data is show in the final column of the table.

This table also illustrates that the province with the most potential water savings is the Quaternary Flood Deposits province. However, the conclusion is based on structural and management actions made at the surface. Geologic circumstances related to each province could influence which province yields the most meaningful conservation.

Submitted August 19, 2011

South Franklin County Study Area, Province B

Table 1(a) - B: Area wide irrigation efficiency based on present irrigation methods and method efficiency.

	1	1/Total Acres = 2	3	2 * 3 = 4
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[3]	Weighted Efficiency per Method
Center Pivot[1]	21223	83.39%	85.25%	71.09%
Center Pivot/Sprinkler	153	0.60%	80.00%	0.48%
Sprinkler (Handline/Solid set)	1977	7.77%	75.00%	5.82%
Drip	1	0.00%	85.00%	0.00%
Drip/Sprinkler	0	0.00%	80.00%	0.00%
Rill	156	0.61%	65.00%	0.40%
Wheel line	1156	4.54%	75.00%	3.41%
Other[4]	786	3.09%	79.50%	2.45%
Total Acres[6]	25452	100.0%	Weighted Average Irrigation Efficiency (WAIE)	**83.66%**
	Estimated Current Water Use[5]		3.41 Ac-ft/ac	
		SCBID water use[2]	3.57 Ac-ft/ac	

Estimated Pre-IWM Irrigation Losses	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
Center Pivot[1]	8325	471	1882	10483	21161
Center Pivot/Sprinkler	78	5	21	75	180
Sprinkler (Handline/Solid set)	674	202	809	976	2662
Drip	0	0	0	0	1
Drip/Sprinkler	0	0	0	0	0
Rill	27	53	106	77	263
Wheel line	394	118	473	571	1557
Other[4]	268	80	201	388	938
Total[6]	**9767 Ac-ft**	**930 Ac-ft**	**3493 Ac-ft**	**12572 Ac-ft**	**26762 Ac-ft**

Estimated Post-IWM Irrigation Losses	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
Center Pivot[1]	6884	389	1556	0	8829
Center Pivot/Sprinkler	65	4	17	0	86
Sprinkler (Handline/Solid set)	836	167	669	0	1673
Drip	0	0	0	0	1
Drip/Sprinkler	0	0	0	0	0
Rill	66	44	88	0	198
Wheel line	489	98	391	0	979
Other[4]	332	66	166	0	565
Total[6]	**8673 Ac-ft**	**769 Ac-ft**	**2889 Ac-ft**	**0 Ac-ft**	**12331 Ac-ft**

Reductions in Totals from Pre to Post IWM				
1094 Ac-ft	**161 Ac-ft**	**605 Ac-ft**	**12572 Ac-ft**	**14431 Ac-ft**

[1]Value is a weighted average of 35% center pivot with LEPA and 65% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]SCBID Data (1991-2009, Average of Blocks 1,13,14,15,16,17,19,161)

[3]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[4] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[5] See Table 2 (a) - B

[6] Distributing the original land, water and WSDA crop data provided by FCD geographically into three geological provinces resulted in some minor gapping and overlapping since the geological boundaries needed to be adjusted to the nearest township and range. As a result the totals of various data categories for the three provinces do not always match that value for the overall SFC.

Submitted August 19, 2011

South Franklin County Study Area, Province B

Table 2(a) - B: Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[11]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[12]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[11]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Alfalfa Hay	7704	30.3%	3.30	25396	30358	4962	21000	25103	4103	5255	4396	859
Potatoes	5210	20.5%	2.56	13321	15924	2603	11015	13168	2152	2756	2306	451
Wheat	2626	10.3%	2.17 [2]	5686	6797	1111	4702	5620	919	1176	984	192
Timothy Hay	2132	8.4%	3.48 [3]	7419	8868	1449	6134	7333	1199	1535	1284	251
Apples	1304	5.1%	3.48 [4]	4542	5430	888	3756	4490	734	940	786	154
Field Corn	1352	5.3%	2.61	3523	4211	688	2913	3482	569	729	610	119
Sweet Corn	461	1.8%	1.86	857	1024	167	708	847	138	177	148	29
Asparagus	153	0.6%	2.93 [5]	448	536	88	371	443	72	93	78	15
Cherry	286	1.1%	3.53 [6]	1011	1208	197	836	999	163	209	175	34
Green Peas	413	1.6%	1.64	678	811	133	561	671	110	140	117	23
Grass Hay	531	2.1%	3.48 [7]	1847	2208	361	1527	1825	298	382	320	62
Wine Grape	44	0.2%	2.09 [5]	93	111	18	77	92	15	19	16	3
Dry Bean	0	0.0%	2.01	0	0	0	0	0	0	0	0	0
Buckwheat	226	0.9%	1.50 [8]	338	405	66	280	335	55	70	59	11
Bluegrass Seed	613	2.4%	1.39 [5]	853	1019	167	705	843	138	176	148	29
Seed Corn	46	0.2%	1.86 [9]	85	102	17	71	84	14	18	15	3
Pasture	484	1.9%	3.48	1683	2012	329	1392	1664	272	348	291	57
Onion	129	0.5%	2.94	379	454	74	314	375	61	79	66	13
Other	1737	6.8%	2.57 [10]	4467	5339	873	3693	4415	722	924	773	151
Total	**25452**	**100%**		**72626**	**86816**	**14190**	**60054**	**71788**	**11734**	**15028**	**12572**	**2456**

[1] WA Irr. Guide, Richland, WA station (WIG)
[2] Average of winter and spring wheat values
[3] Used pasture/turf values
[4] Average of apples with cover and apples without cover
[5] 1988-1994 average from USBR-Agrimet Legrow station.
[6] Average of cherries with cover and cherries without cover
[7] Used pasture/turf values
[8] Estimate
[9] Used sweet corn values
[10] Average of above crops
[11] Estimated application volume is based on a 82.6% weighted average irrigation efficiency (WAIE), see Table 1
[12] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).
[13] Estimated current water use is the total current crop need divided by the total acres.

Current Average Crop Need	2.85 Ac-ft/Ac
Estimated Current Water Use[13]	3.41 Ac-ft/Ac
IWM Average Crop Need	2.36 Ac-ft/Ac
Estimated Water use With IWM	2.82 Ac-ft/Ac

Table 3
Provinces Summary

		Geologic Province			Sum of Areas	Difference
	SFC	Q	B	R	Q + B + R	
Acres	129,343	57,849	25,452	47,490	130,791	1,448
Current Crop Water Need (AF)	370,825	160,799	72,626	140,844	373,969	3,144
Water Lost to Application Inefficiencies (AF)	77,247	32,878	14,407	32,221	79,506	1,247
Total Saving with 100% of Area Under IWM	77,561	33,446	15,028	29,902	78,376	815

Attachments:

1) Table 1 (a, b, c)
2) Table 2 (a, b, c)

Submitted August 19, 2011

South Franklin County Study Area, Province Q

Table 1(b) - Q: Area wide irrigation efficiency based on present irrigation methods and method efficiency.

	1	*1/Total Acres = 2*	*3*	*2 * 3 = 4*
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[2]	Weighted Efficiency per Method
Center Pivot[1]	45847	79.25%	85.25%	67.56%
Center Pivot/Sprinkler	1034	1.79%	80.00%	1.43%
Sprinkler (Handline/Solid set)	6088	10.52%	75.00%	7.89%
Drip	173	0.30%	85.00%	0.25%
Drip/Sprinkler	144	0.25%	80.00%	0.20%
Rill	1293	2.23%	65.00%	1.45%
Wheel line	819	1.42%	75.00%	1.06%
Other[3]	2453	4.24%	79.50%	3.37%
Total Acres[6]	57849	100.00%	Weighted Average Irrigation Efficiency (WAIE)	**83.22%**
	Estimated Current Water Use[4]		3.34 Ac-ft/ac	
		SCBID water use[2]	3.57 Ac-ft/ac	

Estimated Pre-IWM Irrigation Losses	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
Center Pivot[1]	17610	995	3981	22059	44646
Center Pivot/Sprinkler	518	35	138	497	1188
Sprinkler (Handline/Solid set)	2033	610	2440	2929	8013
Drip	29	0	58	83	170
Drip/Sprinkler	48	0	48	69	166
Rill	216	432	863	622	2133
Wheel line	273	82	328	394	1078
Other[3]	819	246	614	1180	2859
Total[6]	**21546 Ac-ft**	**2399 Ac-ft**	**8471 Ac-ft**	**27834 Ac-ft**	**60251 Ac-ft**

Estimated Post-IWM Irrigation Losses	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	14562	823	3292	0	18677
	428	29	114	0	571
	1681	504	2018	0	4203
	24	0	48	0	72
	40	0	40	0	80
	179	357	714	0	1250
	226	68	271	0	565
	677	203	508	0	1389
Total[6]	**17817 Ac-ft**	**1984 Ac-ft**	**7005 Ac-ft**	**0 Ac-ft**	**26806 Ac-ft**

Reductions in Totals from Pre to Post IWM				
3730 Ac-ft	**415 Ac-ft**	**1466 Ac-ft**	**27834 Ac-ft**	**33446 Ac-ft**

[1]Value is a weighted average of 35% center pivot with LEPA and 65% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]SCBID Data (1991-2009, Average of Blocks 1,13,14,15,16,17,19,161)

[3]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[4] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[5] See Table 2 (b) - Q

[6] Distributing the original land, water and WSDA crop data provided by FCD geographically into three geological provinces resulted in some minor gapping and overlapping since the geological boundaries needed to be adjusted to the nearest township and range. As a result the totals of various data categories for the three provinces do not always match that value for the overall SFC.

Submitted August 19, 2011

South Franklin County Study Area, Province Q

Table 2(b) - Q: Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area.

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)[9]	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[8]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[9]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[8]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Alfalfa Hay	19041	32.9%	3.30	62771	75425	12655	51905	62369	10464	13056	10866	2191
Potatoes	11004	19.0%	2.56	28133	33805	5672	23264	27953	4690	5852	4870	982
Wheat	6744	11.7%	2.17 [2]	14600	17543	2943	12073	14507	2434	3037	2527	509
Timothy Hay	2293	4.0%	3.48 [3]	7979	9588	1609	6598	7928	1330	1660	1381	278
Apples	2180	3.8%	3.48	7593	9123	1531	6278	7544	1266	1579	1314	265
Field Corn	2203	3.8%	2.61	5741	6898	1157	4747	5704	957	1194	994	200
Sweet Corn	2296[12]	4.0%	1.86 [2,14]	4263	5122	859	3525	4236	711	887	738	149
Asparagus	1026	1.8%	2.93 [5]	3001	3606	605	2481	2981	500	624	519	105
Cherry	1156	2.0%	3.53	4085	4909	824	3378	4059	681	850	707	143
Green Peas	1924	3.3%	1.64	3159	3796	637	2612	3139	527	657	547	110
Grass Hay	97[12]	0.2%	3.48 [2]	337	404	68	278	334	56	70	58	12
Wine Grape	603	1.0%	2.09	1262	1517	254	1044	1254	210	263	218	44
Dry Bean	55	0.1%	2.01	111	134	22	92	111	19	23	19	4
Buckwheat	266	0.5%	1.50 [8]	399	479	80	330	396	66	83	69	14
Bluegrass Seed	211	0.4%	1.39	293	352	59	242	291	49	61	51	10
Seed Corn	1054	1.8%	1.86	1959	2354	395	1620	1947	327	408	339	68
Pasture	280	0.5%	3.48	976	1173	197	807	970	163	203	169	34
Onion	578[12]	1.0%	2.94 [2,13]	1698	2040	342	1404	1687	283	353	294	59
Other	4837	8.4%	2.57 [10]	12440	14947	2508	10286	12360	2074	2587	2153	434
Total	**57849**	**100%**		**160799**	**193216**	**32417**	**132965**	**159770**	**26806**	**33446**	**27834**	**5611**

[1] WA Irr. Guide, Richland, WA station (WIG)
[2] Average of winter and spring wheat values
[3] Used pasture/turf values
[4] Average of apples with cover and apples without cover
[5] 1988-1994 average from USBR-Agrimet Legrow station.
[6] Average of cherries with cover and cherries without cover
[7] Used pasture/turf values
[8] Estimate
[9] Used sweet corn values
[10] Average of above crops
[11] Estimated application volume is based on a 82.6% weighted average irrigation efficiency (WAIE), see Table 1
[12] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).
[13] Estimated current water use is the total current crop need divided by the total acres.

Current Average Crop Need	2.78 Ac-ft/Ac
Estimated Current Water Use[13]	3.34 Ac-ft/Ac
IWM Average Crop Need	2.30 Ac-ft/Ac
Estimated Water use With IWM	2.76 Ac-ft/Ac

Submitted August 19, 2011

South Franklin County Study Area, Province R

Table 1(c) - R: Area wide irrigation efficiency based on present irrigation methods and method efficiency.

	1	1/Total Acres = 2	3	2 * 3 = 4
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[2]	Weighted Efficiency per Method
Center Pivot[1]	28560	60.14%	85.25%	51.27%
Center Pivot/Sprinkler	3035	6.39%	80.00%	5.11%
Sprinkler (Handline/Solid set)	6734	14.18%	75.00%	10.63%
Drip	340	0.72%	85.00%	0.61%
Drip/Sprinkler	266	0.56%	80.00%	0.45%
Rill	1049	2.21%	65.00%	1.44%
Wheel line	5710	12.02%	75.00%	9.02%
Other[3]	1796	3.78%	79.50%	3.01%
Total Acres[6]	47490	100.00%	Weighted Average Irrigation Efficiency (WAIE)	**81.53%**
	Estimated Current Water Use[4]		3.64 Ac-ft/ac	
		SCBID water use[2]	3.57 Ac-ft/ac	

Estimated Pre-IWM Irrigation Losses	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total	
Center Pivot[1]	11947	675	2701	14662	29985	
Center Pivot/Sprinkler	1656	110	442	1558	3767	
Sprinkler (Handline/Solid set)	2449	735	2939	3457	9580	
Drip	62	0	124	175	360	
Drip/Sprinkler	97	0	97	137	330	
Rill	191	382	763	539	1875	
Wheel line	2077	623	2492	2931	8123	
Other[3]	653	196	490	922	2261	
Total[6]	**19132 Ac-ft**	**2721 Ac-ft**	**10048 Ac-ft**	**24380 Ac-ft**	**56282 Ac-ft**	**(Ac-ft)**

Estimated Post-IWM Irrigation Losses	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total	
	9879	558	2234	0	12671	
	978	91	365	0	1434	
	2169	608	2430	0	5207	
	110	0	102	0	212	
	86	0	80	0	166	
	338	316	631	0	1285	
	1839	515	2061	0	4416	
	579	162	405	0	1146	
Total[6]	**15978 Ac-ft**	**2250 Ac-ft**	**8309 Ac-ft**	**0 Ac-ft**	**26537 Ac-ft**	**(Ac-ft)**

Reductions in Totals from Pre to Post IWM				
3154 Ac-ft	**471 Ac-ft**	**1739 Ac-ft**	**24380 Ac-ft**	**29745 Ac-ft**

[1]Value is a weighted average of 35% center pivot with LEPA and 65% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]SCBID Data (1991-2009, Average of Blocks 1,13,14,15,16,17,19,161)

[3]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[4] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[5] See Table 2 (c) - R

[6] Distributing the original land, water and WSDA crop data provided by FCD geographically into three geological provinces resulted in some minor gapping and overlapping since the geological boundaries needed to be adjusted to the nearest township and range. As a result the totals of various data categories for the three provinces do not always match that value for the overall SFC.

Submitted August 19, 2011

South Franklin County Study Area, Province R

Table 2(c) - R: Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area.

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	*(1)*(3) = (4)* Current Crop Water Need (Ac-ft)[9]	*(4) / WAIE = (5)* Current Gross Application Volume (Ac-ft)[8]	*(5) - (4) = (6)* Water Lost to Current Application Inefficiencies (Ac-ft)[9]	*[(1)*(3)*(1-0.1731)] = (7)* Revised Crop Need with 100% IWM (Ac-ft)[9]	*(7) / WAIE = (8)* Revised Gross Application Volume with IWM, (Ac-ft)[8]	*(8) - (7) = (9)* Revised Water Lost to Application Inefficiencies. (Ac-ft)	*(5) - (8) = (10)* Total Savings with IWM (Ac-ft)	*(1) * (3) * 0.1731 = (11)* *ALSO* *(4) - (7) = 11* Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	*(10) - (11) = (12)* Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Alfalfa Hay	19726	41.5%	3.30	65030	79759	14729	53773	65953	12180	13806	11257	2550
Potatoes	4862	10.2%	2.56	12430	15246	2815	10278	12607	2328	2639	2152	487
Wheat	2038	4.3%	2.17 [2]	4412	5412	999	3649	4475	826	937	764	173
Timothy Hay	3297	6.9%	3.48 [1]	11472	14071	2598	9486	11635	2149	2436	1986	450
Apples	3385	7.1%	3.48 [1]	11791	14462	2671	9750	11958	2208	2503	2041	462
Field Corn	1760	3.7%	2.61	4585	5624	1039	3792	4651	859	974	794	180
Sweet Corn	2300	4.8%	1.86	4270	5238	967	3531	4331	800	907	739	167
Asparagus	793	1.7%	2.93 [1]	2319	2844	525	1917	2352	434	492	401	91
Cherry	1406	3.0%	3.53 [6]	4968	6093	1125	4108	5039	930	1055	860	195
Green Peas	75	0.2%	1.64	123	151	28	102	124	23	26	21	5
Grass Hay	1088	2.3%	3.48 [1]	3786	4644	858	3131	3840	709	804	655	148
Wine Grape	695	1.5%	2.09 [5]	1453	1782	329	1201	1473	272	308	251	57
Dry Bean	1255	2.6%	2.01	2520	3090	571	2084	2555	472	535	436	99
Buckwheat	697	1.5%	1.50 [8]	1046	1283	237	865	1061	196	222	181	41
Bluegrass Seed	221	0.5%	1.39 [5]	308	377	70	254	312	58	65	53	12
Seed Corn	59	0.1%	1.86 [9]	109	134	25	90	111	20	23	19	4
Pasture	264	0.6%	3.48	920	1128	208	761	933	172	195	159	36
Onion	335	0.7%	2.94	984	1207	223	814	998	184	209	170	39
Other	3235	6.8%	2.57 [10]	8318	10202	1884	6878	8436	1558	1766	1440	326
Total	**47490**	**100%**		**140844**	**172746**	**31902**	**116464**	**142843**	**26379**	**29902**	**24380**	**5522**

[1] WA Irr. Guide, Richland, WA station (WIG)
[2] Average of winter and spring wheat values
[3] Used pasture/turf values
[4] Average of apples with cover and apples without cover
[5] 1988-1994 average from USBR-Agrimet Legrow station.
[6] Average of cherries with cover and cherries without cover
[7] Used pasture/turf values
[8] Estimate
[9] Used sweet corn values
[10] Average of above crops
[11] Estimated application volume is based on a 82.6% weighted average irrigation efficiency (WAIE), see Table 1
[12] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).
[13] Estimated current water use is the total current crop need divided by the total acres.

Current Average Crop Need 2.97 Ac-ft/Ac
Estimated Current Water Use[13] 3.64 Ac-ft/Ac
IWM Average Crop Need 2.45 Ac-ft/Ac
Estimated Water use With IWM 3.01 Ac-ft/Ac

Appendix E
Technical Memorandum

To: Peter Schwartzman

From: Randy Asplund, P.E. and Dick Erickson, P.E.

Subject: Estimated Pre-IWM and Post-IWM Over-Application Deep Percolation Losses for Potholes East Canal 1951 to -1986

Date: May 26, 2011
Revised August 19, 2011

Attached are supplemental and revised spreadsheets for the historical Potholes East Canal (PEC) water use, efficiencies and loss pathways from 1951 to 1986. These supplements are intended to provide the additional information discussed and agreed upon in the May 23, 2011, conference call with RH2 Engineering, Inc., (RH2) Pacific Groundwater Group and Franklin Conservation District (FCD). These spreadsheets and this Memorandum are supplemental to the Memorandum and spreadsheets submitted to you by RH2 on April 20, 2011 (**Appendix G**).

The basis and approach for these supplemental spreadsheets are consistent with the following paragraphs excerpted from RH2's March 29, 2011, letter to Mr. Mark Nielson: "We have based our calculations for IWM on 2005 research by the Columbia Basin Groundwater Management Area (GWMA). This research indicates that the weighted average savings coming from IWM is 17.31 percent. For these revised estimates, the 17.31 percent improvement is applied to crop need based on the statement from the GWMA report that, "GWMA supports the Washington Irrigation Guide (WIG) as a realistic guide to micro-climate irrigation water consumption prior to the adoption and use of IWM concepts."

The crop water needs presented in the WIG were developed empirically based on historic water use with the intention for use in irrigation design. Due to the nature of the development of the WIG values, those numbers are conservative and reflect consumptive use estimates appropriate at the time they were developed and have an intrinsic factor of safety. The GWMA research concludes that IWM can improve the circumstances present in WIG by 17.31 percent.

These tables assume for all three areas that no IWM is presently in use, (Pre-IWM). The tables then estimate for all three areas the water savings possible if all acres implement IWM, (Post-IWM). Some IWM is presently in use in all three areas but the extent is not known. Also it is unlikely that all acres in all three areas will implement IWM. Basing the range of the estimates on 0 percent and 100 percent IWM establishes the end points for what may be possible.

The April 20, 2011, analyses included spreadsheets for the Monthly Water Distribution (MWD) method and for the Weighted Average Irrigation Efficiency (WAIE) method. For this supplemental analysis we have inserted a new Column 5 labeled "Crop Requirement Less Pre-IWM Over-Application," which is calculated by column 3* (100 percent-17.31 percent) to reflect GWMA's findings that the WIG crop requirement can be reduced by an average of 17.31 percent by implementing irrigation water management (IWM).

Application inefficiencies were quantified in the April 20, 2011, analyses as discussed in the technical memorandum of that date. In this analysis, the pre-IWM over- application amount is characterized as an additional loss to deep percolation, over and above that caused by application inefficiency. That is consistent with the March 29, 2011, analysis for the 2009 irrigation season. This deep percolation loss is presented in a new Column 14 on each supplemental that is labeled, "Pre-IWM Over-Application Deep Percolation Losses." It is calculated as the difference between Column 3 and the new Column 5 mentioned above.

Also attached is a spreadsheet for the 100-percent rill and 100-percent sprinkler scenarios for the measurement while drilling (MWD) method with columns added to present the pre-IWM over-application losses as an additional loss pathway. As you can see this is the same value as Column 14. For the WAIE method the additional loss pathway would also be the same as the Column 14 value on that spreadsheet.

During the May 23, 2011, conference call you anticipated using a range of deep percolation loss values for your modeling. If you do that, we recommend that you use the Column 13 values (Application Inefficiency Deep Perc Losses) as the minimum value and the sum of Columns 13 and 14 as the maximum value. That approach will be consistent with the source of the 17.31 percent IWM factor being from a number of studies with 17.31 percent being an accepted weighted average. This approach will also then be consistent with how the pre-IWM deep perc losses were handled in the March 29, 2011, analyses.

Cc: Mr. Mark Nielson, Franklin Conservation District

Attachments:

1) MWD Method Spreadsheet
2) WAIE Method Spreadsheet
3) 100 Percent Rill or Sprinkler Spreadsheet

Submitted May 26, 2011

MWD METHOD													
Year	MWD (Delivered to Farms) (Ac-ft / Ac)	Weighted Avg Crop Req (Ac-ft / Ac)	Apparent Efficiency	Crop Requirement Less Pre-IWM Over-Application (Ac-ft/Ac)	Acres Irrigated	Total Loss (Ac-ft / Ac)	Total Loss (Ac-ft)	% SCBID on Sprinklers	% SCBID on Rill	Application Inefficiency Evaporation Loss (Ac-ft/Ac)	Application Inefficiency Surface Run Off Loss (Ac-ft/Ac)	Application Inefficiency Deep Perc Loss (Ac-ft/Ac)	Pre-IWM Over-Application Deep Perc Loss (Ac-ft/Ac)
1951	3.86	3.16	81.8%	2.61	5084	0.70	3,579	10.0%	90.0%	0.12	0.19	0.40	0.55
1952	3.95	3.03	76.8%	2.51	5813	0.91	5,316	13.3%	86.7%	0.16	0.24	0.51	0.52
1953	3.97	3.07	77.4%	2.54	6838	0.90	6,122	16.7%	83.3%	0.17	0.23	0.50	0.53
1954	4.35	2.88	66.3%	2.38	13109	1.47	19,255	20.0%	80.0%	0.29	0.37	0.81	0.50
1955	4.18	2.69	64.5%	2.23	23872	1.49	35,452	23.3%	76.7%	0.30	0.37	0.82	0.47
1956	4.24	2.81	66.2%	2.32	30849	1.43	44,236	26.7%	73.3%	0.30	0.35	0.78	0.49
1957	3.99	2.89	72.3%	2.39	39711	1.10	43,820	30.0%	70.0%	0.24	0.26	0.60	0.50
1958	4.30	2.84	66.1%	2.35	48321	1.46	70,348	33.3%	66.7%	0.33	0.34	0.79	0.49
1959	3.94	2.83	71.8%	2.34	59359	1.11	65,912	36.7%	63.3%	0.26	0.25	0.60	0.49
1960	4.06	2.84	69.9%	2.35	71360	1.22	87,196	40.0%	60.0%	0.30	0.27	0.65	0.49
1961	4.17	2.85	68.2%	2.35	79369	1.32	105,093	43.3%	56.7%	0.34	0.28	0.70	0.49
1962	3.91	2.92	74.6%	2.41	86718	0.99	86,053	46.7%	53.3%	0.26	0.21	0.52	0.51
1963	4.00	2.90	72.4%	2.40	94287	1.10	104,027	50.0%	50.0%	0.30	0.22	0.58	0.50
1964	4.24	2.94	69.3%	2.43	100896	1.30	131,435	54.0%	46.0%	0.37	0.26	0.68	0.51
1965	4.19	2.94	70.2%	2.43	115199	1.25	143,684	58.0%	42.0%	0.36	0.24	0.65	0.51
1966	4.35	2.88	66.3%	2.39	125002	1.47	183,158	62.0%	38.0%	0.44	0.27	0.75	0.50
1967	4.16	2.83	68.0%	2.34	136378	1.33	181,763	66.0%	34.0%	0.42	0.24	0.68	0.49
1968	4.21	2.87	68.2%	2.38	139084	1.34	185,916	67.5%	32.5%	0.42	0.23	0.68	0.50
1969	3.91	2.98	76.3%	2.47	142485	0.93	132,044	69.0%	31.0%	0.30	0.16	0.47	0.52
1970	4.14	3.03	73.1%	2.50	143939	1.11	160,185	70.5%	29.5%	0.36	0.19	0.56	0.52
1971	3.93	3.03	77.0%	2.50	148029	0.90	133,861	72.0%	28.0%	0.30	0.15	0.46	0.52
1972	3.79	3.06	80.9%	2.53	150285	0.73	109,013	73.5%	26.5%	0.24	0.12	0.37	0.53
1973	4.26	2.98	69.9%	2.46	154111	1.28	197,576	75.0%	25.0%	0.43	0.21	0.64	0.52
1974	3.90	2.86	73.4%	2.37	165179	1.04	171,055	76.5%	23.5%	0.35	0.16	0.52	0.50
1975	3.69	2.88	78.2%	2.38	166923	0.81	134,531	78.0%	22.0%	0.28	0.13	0.40	0.50
1976	4.01	2.83	70.6%	2.34	173645	1.18	204,716	79.5%	20.5%	0.57	0.15	0.46	0.49
1977	3.96	2.90	73.3%	2.40	177703	1.06	188,227	81.0%	19.0%	0.52	0.13	0.41	0.50
1978	3.55	2.90	81.6%	2.40	178448	0.65	116,421	82.5%	17.5%	0.33	0.08	0.25	0.50
1979	3.88	2.73	70.3%	2.26	178757	1.15	205,720	84.0%	16.0%	0.58	0.13	0.43	0.47
1980	3.35	2.76	82.4%	2.28	180625	0.59	106,278	85.0%	15.0%	0.30	0.07	0.22	0.48
1981	3.56	2.75	77.3%	2.28	183117	0.81	147,876	86.0%	14.0%	0.42	0.09	0.30	0.48
1982	3.60	2.71	75.4%	2.24	184168	0.89	163,154	87.0%	13.0%	0.52	0.09	0.28	0.47
1983	3.70	2.77	74.8%	2.29	163544	0.93	152,545	88.0%	12.0%	0.55	0.09	0.30	0.48
1984	3.48	2.75	79.1%	2.28	179831	0.73	131,051	88.3%	11.8%	0.43	0.07	0.23	0.48
1985	3.82	2.76	72.3%	2.28	190705	1.06	202,023	88.5%	11.5%	0.62	0.10	0.33	0.48
1986	3.66	2.81	76.7%	2.32	187616	0.85	159,792	88.8%	11.3%	0.50	0.08	0.27	0.49

Submitted May 26, 2011

WAIE METHOD																						
														If 100% Rill				If 100% Sprinkler				
Year	Gross water Applied	Weighted Avg Crop Req (Ac-ft / Ac)	WAIE Efficiency	Crop Requirement Less Pre-IWM Over-Application (Ac-ft/Ac)	Acres Irrigated	Total Loss (Ac-ft / Ac)	Total Loss (Ac-ft)	% SCBID on Sprinklers	% SCBID on Rill	Application Inefficiency Evaporation Loss (Ac-ft/Ac)	Application Inefficiency Surface Run Off Loss (Ac-ft/Ac)	Application Inefficiency Deep Perc Loss (Ac-ft/Ac)	Pre-IWM Over-Application Deep Perc Loss (Ac-ft/Ac)	Application Inefficiency Evaporation Loss (Ac-ft/Ac)	Application Inefficiency Surface Run Off Loss (Ac-ft/Ac)	Application Inefficiency Deep Perc Loss (Ac-ft/Ac)	Pre-IWM Over-Application Deep Perc Loss (Ac-ft/Ac)	Application Inefficiency Evaporation Loss (Ac-ft/Ac)	Application Inefficiency Surface Run Off Loss (Ac-ft/Ac)	Application Inefficiency Deep Perc Loss (Ac-ft/Ac)	Pre-IWM Over-Application Deep Perc Loss (Ac-ft/Ac)
1951	4.78	3.16	66.0%	2.61	5084	1.63	8,266	10.0%	90.0%	0.27	0.44	0.91	0.55	0.24	0.49	0.97	0.55	0.42	0.13	0.50	0.55
1952	4.57	3.03	66.3%	2.51	5813	1.54	8,946	13.3%	86.7%	0.27	0.41	0.86	0.52	0.23	0.47	0.93	0.52	0.40	0.12	0.49	0.52
1953	4.61	3.07	66.7%	2.54	6838	1.54	10,499	16.7%	83.3%	0.29	0.40	0.85	0.53	0.24	0.47	0.94	0.53	0.41	0.12	0.49	0.53
1954	4.30	2.88	67.0%	2.38	13109	1.42	18,622	20.0%	80.0%	0.28	0.36	0.79	0.50	0.22	0.44	0.89	0.50	0.38	0.12	0.46	0.50
1955	4.00	2.69	67.3%	2.23	23872	1.31	31,211	23.3%	76.7%	0.27	0.32	0.72	0.47	0.21	0.41	0.83	0.47	0.36	0.11	0.43	0.47
1956	4.15	2.81	67.7%	2.32	30849	1.34	41,363	26.7%	73.3%	0.28	0.32	0.73	0.49	0.22	0.43	0.86	0.49	0.37	0.11	0.45	0.49
1957	4.24	2.89	68.0%	2.39	39711	1.36	53,942	30.0%	70.0%	0.30	0.32	0.74	0.50	0.22	0.44	0.89	0.50	0.38	0.12	0.46	0.50
1958	4.16	2.84	68.3%	2.35	48321	1.32	63,688	33.3%	66.7%	0.30	0.30	0.71	0.49	0.22	0.44	0.88	0.49	0.38	0.11	0.46	0.49
1959	4.12	2.83	68.7%	2.34	59359	1.29	76,643	36.7%	63.3%	0.31	0.29	0.69	0.49	0.22	0.44	0.87	0.49	0.38	0.11	0.45	0.49
1960	4.11	2.84	69.0%	2.35	71360	1.28	90,990	40.0%	60.0%	0.31	0.28	0.68	0.49	0.22	0.44	0.87	0.49	0.38	0.11	0.45	0.49
1961	4.10	2.85	69.3%	2.35	79369	1.26	99,907	43.3%	56.7%	0.32	0.27	0.67	0.49	0.22	0.44	0.88	0.49	0.38	0.11	0.46	0.49
1962	4.19	2.92	69.7%	2.41	86718	1.27	110,164	46.7%	53.3%	0.33	0.26	0.67	0.51	0.22	0.45	0.90	0.51	0.39	0.12	0.47	0.51
1963	4.14	2.90	70.0%	2.40	94287	1.24	117,052	50.0%	50.0%	0.34	0.25	0.65	0.50	0.22	0.45	0.89	0.50	0.39	0.12	0.46	0.50
1964	4.17	2.94	70.4%	2.43	100896	1.24	124,608	54.0%	46.0%	0.35	0.24	0.64	0.51	0.23	0.45	0.90	0.51	0.39	0.12	0.47	0.51
1965	4.16	2.94	70.8%	2.43	115199	1.21	139,814	58.0%	42.0%	0.35	0.23	0.63	0.51	0.23	0.45	0.91	0.51	0.39	0.12	0.47	0.51
1966	4.05	2.88	71.2%	2.39	125002	1.17	145,861	62.0%	38.0%	0.35	0.21	0.60	0.50	0.22	0.44	0.89	0.50	0.38	0.12	0.46	0.50
1967	3.95	2.83	71.6%	2.34	136378	1.12	152,935	66.0%	34.0%	0.35	0.20	0.57	0.49	0.22	0.43	0.87	0.49	0.38	0.11	0.45	0.49
1968	4.00	2.87	71.8%	2.38	139084	1.13	157,345	67.5%	32.5%	0.36	0.20	0.58	0.50	0.22	0.44	0.88	0.50	0.38	0.11	0.46	0.50
1969	4.15	2.98	71.9%	2.47	142485	1.17	166,127	69.0%	31.0%	0.37	0.20	0.59	0.52	0.23	0.46	0.92	0.52	0.40	0.12	0.48	0.52
1970	4.20	3.03	72.1%	2.50	143939	1.17	169,028	70.5%	29.5%	0.38	0.20	0.60	0.52	0.23	0.47	0.93	0.52	0.40	0.12	0.48	0.52
1971	4.19	3.03	72.2%	2.50	148029	1.17	172,457	72.0%	28.0%	0.38	0.19	0.59	0.52	0.23	0.47	0.93	0.52	0.40	0.12	0.48	0.52
1972	4.24	3.06	72.4%	2.53	150285	1.17	176,015	73.5%	26.5%	0.39	0.19	0.59	0.53	0.24	0.47	0.94	0.53	0.41	0.12	0.49	0.53
1973	4.11	2.98	72.5%	2.46	154111	1.13	174,079	75.0%	25.0%	0.38	0.18	0.57	0.52	0.23	0.46	0.92	0.52	0.40	0.12	0.48	0.52
1974	3.94	2.86	72.7%	2.37	165179	1.08	178,120	76.5%	23.5%	0.37	0.17	0.54	0.50	0.22	0.44	0.88	0.50	0.38	0.11	0.46	0.50
1975	3.96	2.88	72.8%	2.38	166923	1.08	179,869	78.0%	22.0%	0.37	0.17	0.54	0.50	0.22	0.44	0.89	0.50	0.38	0.12	0.46	0.50
1976	3.79	2.83	74.8%	2.34	173645	0.96	166,059	79.5%	20.5%	0.47	0.12	0.17	0.49	0.22	0.44	0.87	0.49	0.47	0.07	0.28	0.49
1977	3.87	2.90	74.9%	2.40	177703	0.97	172,399	81.0%	19.0%	0.48	0.12	0.17	0.50	0.22	0.45	0.89	0.50	0.48	0.07	0.29	0.50
1978	3.86	2.90	75.1%	2.40	178448	0.96	171,209	82.5%	17.5%	0.48	0.12	0.16	0.50	0.22	0.45	0.89	0.50	0.48	0.07	0.29	0.50
1979	3.62	2.73	75.3%	2.26	178757	0.89	159,920	84.0%	16.0%	0.45	0.10	0.14	0.47	0.21	0.42	0.84	0.47	0.46	0.07	0.27	0.47
1980	3.66	2.76	75.5%	2.28	180625	0.90	161,867	85.0%	15.0%	0.46	0.10	0.14	0.48	0.21	0.42	0.85	0.48	0.46	0.07	0.27	0.48
1981	3.64	2.75	75.6%	2.28	183117	0.89	162,453	86.0%	14.0%	0.46	0.10	0.13	0.48	0.21	0.42	0.85	0.48	0.46	0.07	0.27	0.48
1982	3.53	2.71	76.8%	2.24	184168	0.82	150,785	87.0%	13.0%	0.48	0.08	0.26	0.47	0.21	0.42	0.84	0.47	0.47	0.05	0.21	0.47
1983	3.60	2.77	77.0%	2.29	163544	0.83	135,469	88.0%	12.0%	0.49	0.08	0.26	0.48	0.21	0.43	0.85	0.48	0.48	0.05	0.21	0.48
1984	3.57	2.75	77.1%	2.28	179831	0.82	146,952	88.3%	11.8%	0.48	0.08	0.26	0.48	0.21	0.42	0.85	0.48	0.48	0.05	0.21	0.48
1985	3.58	2.76	77.1%	2.28	190705	0.82	156,066	88.5%	11.5%	0.48	0.08	0.26	0.48	0.21	0.42	0.85	0.48	0.48	0.05	0.21	0.48
1986	3.64	2.81	77.2%	2.32	187616	0.83	155,884	88.8%	11.3%	0.49	0.08	0.26	0.49	0.22	0.43	0.86	0.49	0.49	0.05	0.21	0.49

Submitted May 26, 2011

					If 100% Rill								If 100% Sprinkler							
Year	MWD (Delivered to Farms) (Ac-ft / Ac)	Weighted Avg Crop Req (Ac-ft / Ac)	Crop Requirement Less Pre-IWM Over Application	Existing WAIE	WAIE with 100% Rill Irrigation (Proposed)	Percentage Change in Irrigation Efficiency[1]	Adjusted MWD (Ac-ft/Ac)	Adjusted Loss (Ac-ft/Ac)	Application Inefficiency Evaporation Loss (Ac-ft/Ac)	Application Inefficiency Surface Run Off Loss (Ac-ft/Ac)	Application Inefficiency Deep Perc Loss (Ac-ft/Ac)	Pre-IWM Over-Application Deep Perc Loss (Ac-ft/Ac)	WAIE with 100% Sprinkler Irrigation (Proposed)	Percentage Change in Irrigation Efficiency[1]	Adjusted MWD (Ac-ft/Ac)	Adjusted Loss (Ac-ft/Ac)	Application Inefficiency Evaporation Loss (Ac-ft/Ac)	Application Inefficiency Surface Run Off Loss (Ac-ft/Ac)	Application Inefficiency Deep Perc Loss (Ac-ft/Ac)	Pre-IWM Over-Application Deep Perc Loss (Ac-ft/Ac)
1951	3.86	3.16	2.61	66.00%	65.00%	1.52%	3.92	0.76	0.11	0.22	0.44	0.55	75.00%	-13.64%	3.33	0.18	0.07	0.02	0.09	0.55
1952	3.95	3.03	2.51	66.33%	65.00%	2.01%	4.03	0.99	0.14	0.28	0.57	0.52	75.00%	-13.07%	3.43	0.40	0.16	0.05	0.19	0.52
1953	3.97	3.07	2.54	66.67%	65.00%	2.50%	4.07	0.99	0.14	0.28	0.57	0.53	75.00%	-12.50%	3.47	0.40	0.16	0.05	0.19	0.53
1954	4.35	2.88	2.38	67.00%	65.00%	2.99%	4.48	1.60	0.23	0.46	0.91	0.50	75.00%	-11.94%	3.83	0.95	0.38	0.11	0.46	0.50
1955	4.18	2.69	2.23	67.33%	65.00%	3.47%	4.32	1.63	0.23	0.47	0.93	0.47	75.00%	-11.39%	3.70	1.01	0.40	0.12	0.48	0.47
1956	4.24	2.81	2.32	67.67%	65.00%	3.94%	4.41	1.60	0.23	0.46	0.91	0.49	75.00%	-10.84%	3.78	0.97	0.39	0.12	0.47	0.49
1957	3.99	2.89	2.39	68.00%	65.00%	4.41%	4.17	1.28	0.18	0.37	0.73	0.50	75.00%	-10.29%	3.58	0.69	0.28	0.08	0.33	0.50
1958	4.30	2.84	2.35	68.33%	65.00%	4.88%	4.51	1.67	0.24	0.48	0.95	0.49	75.00%	-9.76%	3.88	1.04	0.41	0.12	0.50	0.49
1959	3.94	2.83	2.34	68.67%	65.00%	5.34%	4.15	1.32	0.19	0.38	0.75	0.49	75.00%	-9.22%	3.58	0.75	0.30	0.09	0.36	0.49
1960	4.06	2.84	2.35	69.00%	65.00%	5.80%	4.30	1.46	0.21	0.42	0.83	0.49	75.00%	-8.70%	3.71	0.87	0.35	0.10	0.42	0.49
1961	4.17	2.85	2.35	69.33%	65.00%	6.25%	4.43	1.58	0.23	0.45	0.91	0.49	75.00%	-8.17%	3.83	0.98	0.39	0.12	0.47	0.49
1962	3.91	2.92	2.41	69.67%	65.00%	6.70%	4.17	1.25	0.18	0.36	0.72	0.51	75.00%	-7.66%	3.61	0.69	0.28	0.08	0.33	0.51
1963	4.00	2.90	2.40	70.00%	65.00%	7.14%	4.29	1.39	0.20	0.40	0.79	0.50	75.00%	-7.14%	3.71	0.82	0.33	0.10	0.39	0.50
1964	4.24	2.94	2.43	70.40%	65.00%	7.67%	4.57	1.63	0.23	0.47	0.93	0.51	75.00%	-6.53%	3.96	1.03	0.41	0.12	0.49	0.51
1965	4.19	2.94	2.43	70.80%	65.00%	8.19%	4.53	1.59	0.23	0.45	0.91	0.51	75.00%	-5.93%	3.94	1.00	0.40	0.12	0.48	0.51
1966	4.35	2.88	2.39	71.20%	65.00%	8.71%	4.73	1.84	0.26	0.53	1.05	0.50	75.00%	-5.34%	4.12	1.23	0.49	0.15	0.59	0.50
1967	4.16	2.83	2.34	71.60%	65.00%	9.22%	4.54	1.72	0.25	0.49	0.98	0.49	75.00%	-4.75%	3.96	1.14	0.45	0.14	0.54	0.49
1968	4.21	2.87	2.38	71.75%	65.00%	9.41%	4.61	1.73	0.25	0.50	0.99	0.50	75.00%	-4.53%	4.02	1.15	0.46	0.14	0.55	0.50
1969	3.91	2.98	2.47	71.90%	65.00%	9.60%	4.29	1.30	0.19	0.37	0.74	0.52	75.00%	-4.31%	3.74	0.76	0.30	0.09	0.36	0.52
1970	4.14	3.03	2.50	72.05%	65.00%	9.78%	4.55	1.52	0.22	0.43	0.87	0.52	75.00%	-4.09%	3.97	0.94	0.38	0.11	0.45	0.52
1971	3.93	3.03	2.50	72.20%	65.00%	9.97%	4.32	1.30	0.19	0.37	0.74	0.52	75.00%	-3.88%	3.78	0.75	0.30	0.09	0.36	0.52
1972	3.79	3.06	2.53	72.35%	65.00%	10.16%	4.18	1.11	0.16	0.32	0.63	0.53	75.00%	-3.66%	3.65	0.59	0.23	0.07	0.28	0.53
1973	4.26	2.98	2.46	72.50%	65.00%	10.34%	4.70	1.72	0.25	0.49	0.98	0.52	75.00%	-3.45%	4.11	1.14	0.45	0.14	0.54	0.52
1974	3.90	2.86	2.37	72.65%	65.00%	10.53%	4.31	1.45	0.21	0.41	0.83	0.50	75.00%	-3.23%	3.77	0.91	0.36	0.11	0.44	0.50
1975	3.69	2.88	2.38	72.80%	65.00%	10.71%	4.09	1.20	0.17	0.34	0.69	0.50	75.00%	-3.02%	3.58	0.69	0.28	0.08	0.33	0.50
1976	4.01	2.83	2.34	74.75%	65.00%	13.04%	4.53	1.70	0.24	0.49	0.97	0.49	77.50%	-3.68%	3.86	1.03	0.59	0.09	0.35	0.49
1977	3.96	2.90	2.40	74.94%	65.00%	13.26%	4.49	1.58	0.23	0.45	0.91	0.50	77.50%	-3.42%	3.82	0.92	0.53	0.08	0.31	0.50
1978	3.55	2.90	2.40	75.13%	65.00%	13.48%	4.03	1.13	0.16	0.32	0.65	0.50	77.50%	-3.16%	3.44	0.54	0.31	0.05	0.18	0.50
1979	3.88	2.73	2.26	75.31%	65.00%	13.69%	4.41	1.68	0.24	0.48	0.96	0.47	77.50%	-2.90%	3.77	1.04	0.60	0.09	0.35	0.47
1980	3.35	2.76	2.28	75.50%	65.00%	13.91%	3.82	1.05	0.15	0.30	0.60	0.48	77.50%	-2.65%	3.26	0.50	0.29	0.04	0.17	0.48
1981	3.56	2.75	2.28	75.63%	65.00%	14.05%	4.06	1.31	0.19	0.37	0.75	0.48	77.50%	-2.48%	3.47	0.72	0.41	0.06	0.24	0.48
1982	3.60	2.71	2.24	76.83%	65.00%	15.39%	4.15	1.44	0.21	0.41	0.82	0.47	78.75%	-2.51%	3.51	0.80	0.51	0.06	0.22	0.47
1983	3.70	2.77	2.29	76.96%	65.00%	15.54%	4.28	1.51	0.22	0.43	0.86	0.48	78.75%	-2.32%	3.61	0.85	0.55	0.06	0.24	0.48
1984	3.48	2.75	2.28	77.10%	65.00%	15.69%	4.03	1.27	0.18	0.36	0.73	0.48	78.75%	-2.14%	3.41	0.65	0.42	0.05	0.18	0.48
1985	3.82	2.76	2.28	77.13%	65.00%	15.73%	4.42	1.66	0.24	0.47	0.95	0.48	78.75%	-2.09%	3.74	0.98	0.63	0.07	0.28	0.48
1986	3.66	2.81	2.32	77.17%	65.00%	15.77%	4.24	1.43	0.20	0.41	0.82	0.49	78.75%	-2.05%	3.59	0.78	0.50	0.05	0.22	0.49

[1]Caluclated by (Exisiting WAIE - Proposed WAIE)/Exisiting WAIE

Appendix F

Interim Revised Current Practices and Conservation Potential Estimates

The purpose of Appendix is to provide the reader the sense of chronology and the progression in developing the loss pathways and conservation potential that has been presented in this study since March 2010.

One topic that evolved significantly as this study progressed was the effect of irrigation water management (IWM) on deep percolation losses. The approach taken in this study regarding IWM is based on research and reports by the Columbia Basin Groundwater Management Area (GWMA). It is important for readers to be aware that this report is based on that research along with the understanding of how the deep percolation losses have been segregated into pre-IWM and post-IWM categories. To assist the reader with an understanding of the study's progression, we have included the earlier draft appendices and spreadsheets. To keep with the chronology and progression of this entire study, each spreadsheet is stamped with the date of its most recent revision.

To document and reinforce this point the following document is included to assist the reader in understanding how the final loss pathways and conservation potential values presented in this study were developed. The document presented in this appendix is a March 29, 2011 draft RH2 letter report documenting the addition of IWM into the loss pathways and the resulting conservation potential for the three study areas that was sent to Mr. Mark Nielson in draft form for his review and comment. This document provides a summary of the study's historical development regarding both the conservation pathways and the re-evaluation of IWM and its pathway as part of the total conservation potential. As a result of the comments from Mr. Nielson, this letter report was substantially revised and formed the basis for the technical memorandum presented in **Appendix A**.

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March 29, 2011

Mr. Mark Nielson
Franklin Conservation District
1533 E. Spokane, Ste. C
Pasco, WA 99301
mark-nielson@conservewa.net

Sent Via: US Mail and Email

Subject: Draft Revised Current Practices and Conservation Potential Estimates

Dear Mark:

Attached are draft revised Tables 1(a), (b) and (c), Tables 2(a), (b) and (c) and Tables 3(a), (b) and (c) for your reference. These revised tables correlate to the same tables submitted to Peter Schwartzman of Pacific Groundwater Group (PGG) on October 13, 2010. These tables and their cover memo became Appendix A of the *Draft Conservation Screening Analysis for the Walla Walla Basin, Horse Heaven Hills and Southern Franklin County Areas – October 2010* prepared by PGG. That draft analysis was presented at a December 14, 2010, review meeting in Ellensburg. Tables 1(a), (b) and (c) for the Southern Franklin county area also correlate to those tables submitted to you on January 25, 2011.

On December 21, 2010, Mark Nielson, Randy Asplund and Dick Erickson met in Othello to discuss revising the referenced tables' analyses of irrigation water management (IWM), double cropping and center pivot sprinklers with LEPA (low energy precision application). That meeting led to the January 25, 2011, revisions of the Southern Franklin County area and an explanatory cover memo of the same date. Those revisions led to further discussions and consideration regarding how IWM should be handled in the calculations. Those considerations included at least two conference calls and several emails. These revised tables reflect those considerations and this memo is written to explain the revisions, which have been made, including relevant assumptions, so that it will be easier for you to track the calculations and visualize any limitations or reservations regarding the resulting conclusions about conservation potential. We anticipate that much of this letter memorandum will eventually be used in another submittal to PGG for a revised Appendix A.

We have based our calculations for IWM on 2005 research by the Columbia Basin Groundwater Management Area (GWMA). This research indicates that the weighted average savings coming from IWM is 17.31 percent. For these revised estimates, the 17.31 percent improvement is applied to crop need based on the statement from the GWMA report that, "GWMA supports the Washington Irrigation Guide (WIG) as a realistic guide to micro-climate irrigation water consumption prior to the adoption and use of IWM concepts."

The crop water needs presented in the WIG were developed empirically based on historic water use with the intention for use in irrigation design. Due to the nature of the development of the WIG values, those numbers are conservative and reflect consumptive use estimates appropriate at the time they were developed and have an intrinsic factor of safety. The GWMA research concludes that IWM can improve the circumstances present in WIG by 17.31 percent.

These revised tables assume for all three areas that no IWM is presently in use, (Pre-IWM). The tables then estimate for all three areas the water savings possible if all acres implement IWM, (Post-IWM). Some IWM is presently in use in all three areas but the extent is not known. Also it is unlikely that all acres in all three areas will implement IWM. Basing the range of the estimates on 0 percent and 100 percent IWM establishes the end points for what may be possible. This approach also recognizes that utilization of IWM is an annual management decision made by each individual irrigator, so the extent of IWM utilization can be expected to vary annually.

For these revised tables, the areal distribution of irrigation equipment and the resulting weighted area irrigation efficiency are the same as those used in the October 13, 2010, tables except we have revised our assumptions about the extent of center pivots with LEPA. For Southern Franklin County and Walla Walla, we have assumed that 35 percent of present center pivot acreage utilize LEPA and 65 percent use center pivots with end guns without LEPA. For Horse Heaven Hills we have assumed 50 percent LEPA and 50 percent non-LEPA/end guns. All of these center pivot areal proportions, as well as the definition of LEPA, are based on our discussions at the December 21, 2010 meeting. LEPA can mean different things in different locales; for these study areas, LEPA is defined as a pivot with drop tubes, rotator (spinner) spray heads, and no end gun or corner span. With these changes factored into the calculations, a revised but very similar weighted area irrigation efficiency (WAIE) is then reported on each Table 1. This WAIE is then used to estimate the current gross application volume on each Table 2, both for the present situation with 0 percent IWM (Column 5) and with 100 percent IWM (Column 8).

For Table 2(b) for Horse Heaven Hills, we have added crop categories for double cropping of bluegrass seed followed by sweet corn, green peas followed by sweet corn, and green beans followed by sweet corn. As we discussed on December 21st, there are no overall, area-wide records for double cropping. We have used the three example farms you provided double cropping data for and applied these proportions area-wide. For each double cropping calculation, we have assumed the first crop is grown and irrigated during April, May and June, and the second crop (sweet corn) is grown and irrigated during July, August and September.

For each area, the total water savings resulting from going from 0 percent IWM to 100 percent IWM is the difference between the gross application volumes of Column 5 from the gross application volumes of Column 8 on Table 2. The resulting total savings from IWM has two components: 1) The major portion comes from reducing the crop need on 100 percent of the acreage and is the difference between Columns 7 and 4 on each Table 2; and 2) The other portion results from less water being exposed to application inefficiencies and is the difference between Columns 10 and 11.

To evaluate the timing of surface runoff and deep percolation losses, PGG needed an estimate of the relative quantities of the loss pathways. RH2's estimate for those pathways is included as Appendix B of the PGG draft report. For those estimates the values for evaporation and surface runoff are based on

published research as referenced in Appendix B. Deep percolation losses were calculated as the difference between total losses and the sum of evaporation and surface runoff. For this revision deep percolation losses are broken into two components. The first component is the result of the difference between Pre-IWM and Post-IWM. This assumes that the additional water applied before implementing IWM is lost to deep percolation. The second component of deep percolation loss is the result of application inefficiency. That loss is less after IWM because less water is exposed to loss but there is still a loss to deep percolation even after implementing IWM. For each Table 1 a table of loss pathways for the Pre-IWM situation and a table of the Post-IWM situation is presented.

In the October 13, 2010 tables, each Table 3 estimates conservation potential from irrigation equipment upgrades, and estimated the IWM conservation potential by reducing the losses by 17.31 percent. These tables are now revised to reflect that IWM conservation potential is estimated first and then the conservation potential of equipment upgrades is estimated. For the stacked bar graphs illustrating potential savings, we have only displayed those equipment upgrades that are most likely, e.g., upgrading center pivots with end gun to center pivots with LEPA or upgrading rill or wheel line to center pivot with LEPA. We anticipate that most irrigators making improvements will upgrade to center pivots with LEPA and not to some intermediate technology.

Please contact us after you've reviewed these revised tables so that we can coordinate how to proceed toward the conclusion of this report.
Sincerely,

RH2 ENGINEERING, INC.
Randy L. Asplund, P.E.
Vice President

Dick Erickson, P.E.
Senior Project Manger

cc: Mr. Peter Scwartzman, Pacific Groundwater Group

DE/RA/se/cc

Enclosures: Walla Walla Study Area
Horse Heaven Hills Study Area
South Franklin County Study Area

Submitted March 29, 2011

Horse Heaven Hills Study Area

Table 1(b): Area wide irrigation efficiency based on present irrigation methods and method efficiency.

	1	1/Total Acres = 2	3	2 * 3 = 4
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[2]	Weighted Efficiency per Method
Center Pivot[1]	124168	89.27%	87.50%	78.11%
Center Pivot/Sprinkler	146	0.11%	80.00%	0.08%
Sprinkler (Handline/Solid set)	4660	3.35%	75.00%	2.51%
Drip	8217	5.91%	85.00%	5.02%
Drip/Sprinkler	1191	0.86%	80.00%	0.68%
Rill	0	0.00%	65.00%	0.00%
Wheel line	46	0.03%	75.00%	0.02%
Other[3]	667	0.48%	79.50%	0.38%
Total Acres	139095	100.00%	Weighted Average Irrigation Efficiency (WAIE)	**86.82%**
	Estimated Current Water Use[4]		2.69 Ac-ft/ac	

Estimated Pre-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	27698	3078	13189	50126	94091
	33	4	16	59	111
	1039	115	495	1881	3531
	1833	204	873	3317	6226
	266	30	127	481	902
	0	0	0	0	0
	10	1	5	19	35
	149	17	71	269	505
Total	**31027**	**3447**	**14775**	**56152**	**105402**

Estimated Post-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	22903	2545	10906	0	36354
	27	3	13	0	43
	860	96	409	0	1364
	1516	168	722	0	2406
	220	24	105	0	349
	0	0	0	0	0
	8	1	4	0	13
	123	14	59	0	195
Total	**25656 Ac-ft**	**2851 Ac-ft**	**12217 Ac-ft**	**0 Ac-ft**	**40724 Ac-ft**

Reductions in Totals from Pre to Post IWM				
5371 Ac-ft	**597 Ac-ft**	**2558 Ac-ft**	**56152 Ac-ft**	**64677 Ac-ft**

[1]Value is a weighted average of 50% center pivot with LEPA and 50% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[3]Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[4] See Table 2 (b)

Submitted March 29, 2011

Horse Heaven Hills Study Area

Table 2(b): Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area.

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)[9]	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[8]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[9]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[8]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Potato	29137	20.9%	2.19 [2]	63859	73555	9695	52805	60822	8017	12732	11054	1678
Sweet Corn	20974	15.1%	1.98 [2]	41423	47712	6289	34253	39453	5200	8259	7170	1089
Wheat	13611	9.8%	2.53 [3]	34368	39586	5218	28419	32734	4315	6852	5949	903
Field Corn	12185	8.8%	2.48 [2]	30260	34855	4594	25022	28821	3799	6033	5238	795
Onion	10964	7.9%	2.71	29721	34234	4512	24576	28308	3731	5926	5145	781
Bluegrass Seed	7538	5.4%	1.39 [2]	10491	12083	1593	8675	9992	1317	2092	1816	276
Bluegrass Seed/Sweet Corn[11]	1932[12]	1.4%	2.28 [2,14]	4397	5064	668	3636	4188	552	877	761	116
Alfalfa Hay	6632	4.8%	3.53 [2]	23376	26925	3549	19330	22265	2935	4661	4046	614
Wine Grape	5804	4.2%	2.08	12054	13884	1830	9967	11480	1513	2403	2086	317
Green Pea	5629	4.0%	1.97 [4]	11069	12750	1681	9153	10543	1390	2207	1916	291
Green Pea/Sweet Corn[11]	1442[12]	1.0%	2.36 [2]	3399	3916	516	2811	3238	427	678	588	89
Apple	3309	2.4%	2.95	9764	11246	1482	8074	9300	1226	1947	1690	257
Mint	3189	2.3%	2.82	8990	10355	1365	7434	8562	1129	1792	1556	236
Hybrid Poplar	2743	2.0%	3.17 [5]	8686	10005	1319	7182	8273	1090	1732	1504	228
Carrot	2671	1.9%	1.89	5046	5812	766	4173	4806	634	1006	874	133
Sugar Beet	2142	1.5%	2.73	5842	6728	887	4830	5564	733	1165	1011	154
Green Bean	1305	0.9%	1.91 [2]	2490	2868	378	2059	2371	313	496	431	65
Green Bean/Sweet Corn[11]	334[12]	0.2%	1.83 [2,13]	611	703	93	505	582	77	122	106	16
Timothy	1127	0.8%	2.78 [6]	3136	3612	476	2593	2987	394	625	543	82
Other	6427	4.6%	2.40 [7]	15407	17747	2339	12740	14675	1934	3072	2667	405
Total	**139095**	**100%**		**324390**	**373640**	**49250**	**268238**	**308963**	**40724**	**64677**	**56152**	**8525**

[1] WA Irr. Guide, McNary, WA station (WIG)
[2] 1988-1994 average from USBR-Agrimet Hermiston station.
[3] Average of winter and spring wheat values
[4] Includes green pea and pea seed acreage
[5] Estimate based on Agrimet crop curves
[6] Used pasture/turf values
[7] Average of above crops
[8] Estimated application volume is based on a 84.59% weighted average irrigation efficiency (WAIE), see Table 1
[9] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).
[10] Estimated current water use is the total current crop need divided by the total acres.
[11] First crop is grown and irrigated from April to June. Second crop (Sweet corn) is grown and irrigated from July to September.
[12] Double Crop acreage was determined by taking 20.4% of the original crop acres. E.g. Total acres growing blue grass seed is 9470. Acres double cropped is 9470*20.4% = 1932. Actual acres in blue grass seed is 7538 (9470-1932).
[13] Irrigation requirement for the months of April, May, and June for Green Bean was taken from WA Irr. Guide, Richland, WA station.
[14] Irrigation requirement for the months of April, May, and June for Bue Grass seed is 50% of the total annual irrigation requirment as determined by 1988-1994 average from USBR-Agrimet Hermiston station.

Current Average Crop Need	2.33 Ac-ft/Ac
Estimated Current Water Use[10]	2.69 Ac-ft/Ac
IWM Average Crop Need	1.93 Ac-ft/Ac
Estimated Water use With IWM	2.22 Ac-ft/Ac

Sumitted March 29, 2011

Horse Heaven Hills Study Area

Table 3(b): Horse Heaven Hills Study Area upgrades matrix. Different upgrades options were evaluated. Structural irrigation upgrades were kept separate from IWM upgrades. IWM upgrades represent the entire study area adopting IWM practices. Mechanical upgrade values represent incremental recoverable water values. Calculations that are not possible are represented with a dash (-).

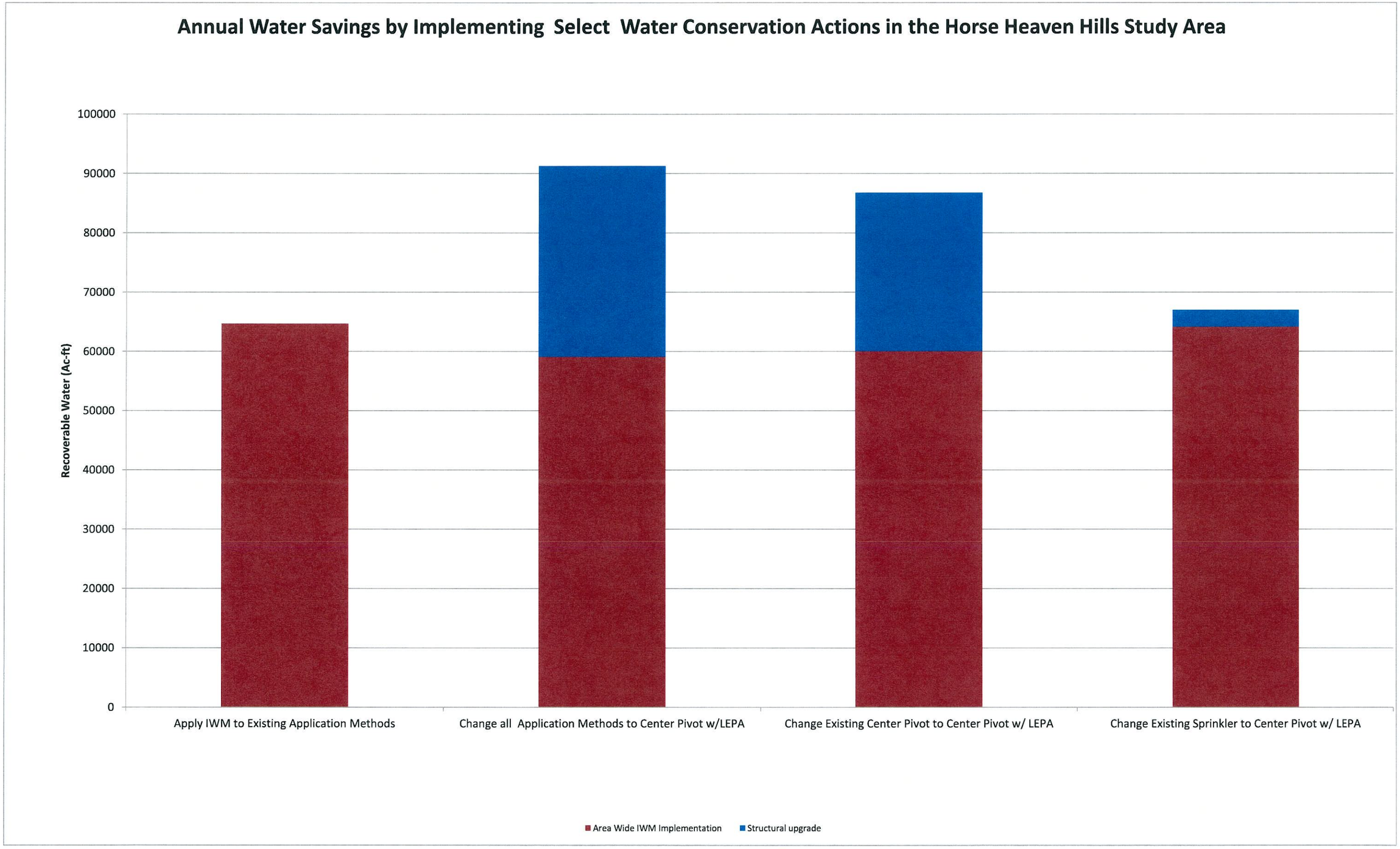
	Structural Irrigation Upgrades			Area Wide IWM[1] Irrigation Upgrade	Combined Water Recovered		
Change in irrigation method	Increase In Area Wide Efficiency	Water Recovered (Ac-ft)	Percent of Water Recovered[3]	Additional Water Recovered (Ac-ft)	Maximum Water Recoverable. Sum of IWM and Structural Upgrade (Ac-ft)	Percent of water Recovered	Unrecovered Water
Apply IWM to Existing Application Methods	-	-	-	64680	64680	17.31%	40,722
Change all Application Methods to Center Pivot w/LEPA	8.18%	32176	8.61%	59110	91280	24.43%	14,122
Change Existing Center Pivot to Center Pivot w/ LEPA	6.70%	26751	7.16%	60050	86800	23.23%	18,602
Change Existing Rill to Sprinkler	-	-	-	64680	64680	17.31%	40,722
Change Existing Rill to Center Pivot[2]	-	-	-	64680	64680	17.31%	40,722
Change Existing Rill to Center Pivot w/ LEPA	-	-	-	64680	64680	17.31%	40,722
Change Existing Sprinkler to Center Pivot[2]	0.42%	1794	0.48%	64370	66160	17.71%	39,242
Change Existing Sprinkler to Center Pivot w/ LEPA	0.67%	2861	0.77%	64180	67040	17.94%	38,362
Change Existing Sprinkler to Drip Only	0.34%	1436	0.38%	64430	65860	17.63%	39,542
Change Existing Wheel Line to Center pivot[2]	0.00%	18	0.00%	64670	64690	17.31%	40,712
Change Existing Wheel Line to Center Pivot w/LEPA	0.01%	28	0.01%	64670	64700	17.32%	40,702
Change Existing 'Other' to Center pivot[2]	0.04%	165	0.04%	64650	64810	17.35%	40,592
Change Existing 'Other' to Center Pivot w/LEPA	0.07%	320	0.09%	64620	64940	17.38%	40,462

[1] IWM - Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water management Area, 2005).

[2] Center pivot and drip irrigation have equal irrigation efficiencies. Converting a current irrigation structure to a drip system or a center pivot system would yield the same recovery quantities.

[3] Percent of water recovered – is the percentage of water that is no longer needed for irrigation purposes. It is equal to the volume of water recovered because of IWM and/or structural upgrades divided by the volume of current water use.

[4] Structural upgrade efficiency values are reported in Table 1, except center pivot with LEPA, which has an efficiency value of 95%.


Annual Water Savings by Implementing Select Water Conservation Actions in the Horse Heaven Hills Study Area
Recoverable Water (Ac-ft)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Apply IWM to Existing Application Methods
Change all Application Methods to Center Pivot w/LEPA
Change Existing Center Pivot to Center Pivot w/ LEPA
Change Existing Sprinkler to Center Pivot w/ LEPA
Area Wide IWM Implementation
Structural upgrade

Submitted March 29, 2011

South Franklin County Study Area

Table 1(a): Area wide irrigation efficiency based on present irrigation methods and method efficiency. For this study area, the estimated current water use was within 3.1% of the water use value reported by SCBID.

	1	1/Total Acres = 2	3	2 * 3 = 4
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[3]	Weighted Efficiency per Method
Center Pivot[1]	96468	74.58%	85.25%	63.58%
Center Pivot/Sprinkler	4222	3.26%	80.00%	2.61%
Sprinkler (Handline/Solid set)	14841	11.47%	75.00%	8.61%
Drip	514	0.40%	85.00%	0.34%
Drip/Sprinkler	410	0.32%	80.00%	0.25%
Rill	2498	1.93%	65.00%	1.26%
Wheel line	7812	6.04%	75.00%	4.53%
Other[4]	2578	1.99%	79.50%	1.58%
Total Acres	129343	100.0%	Weighted Average Irrigation Efficiency (WAIE)	**82.76%**
	Estimated Current Water Use[5]		3.46 Ac-ft/ac	
		SCBID water use[2]	3.57 Ac-ft/ac	

Estimated Pre-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	33416	5185	19012	47875	105488
	1462	227	832	2095	4617
	5141	798	2925	7365	16229
	178	28	101	255	562
	142	22	81	204	449
	865	134	492	1240	2732
	2706	420	1540	3877	8542
	893	139	508	1279	2819
Total	**44803**	**6952**	**25492**	**64190**	**141437**

Estimated Post-IWM Irrigation Losses					
	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	27631	4288	15721	0	47641
	1209	188	688	0	2085
	4251	660	2419	0	7329
	147	23	84	0	254
	118	18	67	0	203
	716	111	407	0	1234
	2238	347	1273	0	3858
	738	115	420	0	1273
Total	**37048**	**5749**	**21079**	**0**	**63876**

Reductions in Totals from Pre to Post IWM					
	7755 Ac-ft	**1203 Ac-ft**	**4413 Ac-ft**	**64190 Ac-ft**	**77561 Ac-ft**

[1]Value is a weighted average of 35% center pivot with LEPA and 65% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]SCBID Data (1991-2009, Average of Blocks 1,13,14,15,16,17,19,161)

[3]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[4] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[5] See Table 2 (a)

Submitted March 29, 2011

South Franklin County Study Area

Table 2(a): Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[11]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[12]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[11]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Alfalfa Hay	46363	35.8%	3.30	152845	184684	31839	126387	152715	26328	31969	26457	5511
Potatoes	20984	16.2%	2.56	53649	64825	11176	44363	53604	9241	11221	9287	1935
Wheat	11688	9.0%	2.17 [2]	25304	30575	5271	20924	25283	4359	5293	4380	912
Timothy Hay	7777	6.0%	3.48 [3]	27059	32696	5637	22375	27036	4661	5660	4684	976
Apples	6879	5.3%	3.48 [4]	23963	28955	4992	19815	23943	4128	5012	4148	864
Field Corn	5270	4.1%	2.61	13731	16592	2860	11355	13720	2365	2872	2377	495
Sweet Corn	4924	3.8%	1.86	9142	11046	1904	7559	9134	1575	1912	1582	330
Asparagus	3010	2.3%	2.93 [5]	8805	10639	1834	7281	8797	1517	1842	1524	317
Cherry	2857	2.2%	3.53 [6]	10096	12200	2103	8349	10088	1739	2112	1748	364
Green Peas	2412	1.9%	1.64	3960	4785	825	3275	3957	682	828	686	143
Grass Hay	1734	1.3%	3.48 [7]	6033	7289	1257	4988	6027	1039	1262	1044	218
Wine Grape	1342	1.0%	2.09 [5]	2808	3392	585	2322	2805	484	587	486	101
Dry Bean	1310	1.0%	2.01	2631	3179	548	2176	2629	453	550	455	95
Buckwheat	1189	0.9%	1.50 [8]	1783	2155	371	1475	1782	307	373	309	64
Bluegrass Seed	1173	0.9%	1.39 [5]	1632	1972	340	1350	1631	281	341	283	59
Seed Corn	1159	0.9%	1.86 [9]	2154	2602	449	1781	2152	371	450	373	78
Pasture	1112	0.9%	3.48	3869	4675	806	3199	3866	666	809	670	140
Onion	1043	0.8%	2.94	3061	3699	638	2531	3059	527	640	530	110
Other	7116	5.5%	2.57 [10]	18300	22112	3812	15132	18284	3152	3828	3168	660
Total	**129343**	**100%**		**370825**	**448073**	**77247**	**306636**	**370511**	**63876**	**77561**	**64190**	**13372**

[1] WA Irr. Guide, Richland, WA station (WIG)
[2] Average of winter and spring wheat values
[3] Used pasture/turf values
[4] Average of apples with cover and apples without cover
[5] 1988-1994 average from USBR-Agrimet Legrow station.
[6] Average of cherries with cover and cherries without cover
[7] Used pasture/turf values
[8] Estimate
[9] Used sweet corn values
[10] Average of above crops
[11] Estimated application volume is based on a 82.6% weighted average irrigation efficiency (WAIE), see Table 1
[12] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).
[13] Estimated current water use is the total current crop need divided by the total acres.

Current Average Crop Need 2.87 Ac-ft/Ac
Estimated Current Water Use[13] 3.46 Ac-ft/Ac
IWM Average Crop Need 2.37 Ac-ft/Ac
Estimated Water use With IWM 2.86 Ac-ft/Ac

Submitted March 29, 2011

South Franklin County Study Area

Table 3(a): South Franklin County Study Area upgrades matrix. Different upgrades options were evaluated. Structural irrigation upgrades were kept separate from IWM upgrades. IWM upgrades represent the entire study area adopting IWM practices. Mechanical upgrade values represent incremental recoverable water values. Calculations that are not possible are represented with a dash (-).

	Structural Irrigation Upgrades			Area Wide IWM[1] Irrigation Upgrade	Combined Water Recovered		
Change In Irrigation Method	Increase In Area Wide Efficiency	Water Recovered (Ac-ft)	Percent of Water Recovered[3]	Additional Water Recovered (Ac-ft)	Maximum Water Recoverable. Sum of IWM and Structural Upgrade (Ac-ft)	Percent of water Recovered	Unrecovered Water
Apply IWM to Existing Application Methods	-	-	-	77560	77560	17.31%	63,877
Change all Application Methods to Center Pivot w/LEPA	12.24%	57730	12.88%	67570	125300	27.96%	16,137
Change Existing Center Pivot to Center Pivot w/ LEPA	7.27%	36191	8.08%	71300	107490	23.99%	33,947
Change Existing Rill to Sprinkler	0.19%	1043	0.23%	77380	78420	17.50%	63,017
Change Existing Rill to Center Pivot[2]	0.39%	2113	0.47%	77200	79310	17.70%	62,127
Change Existing Rill to Center Pivot w/ LEPA	0.58%	3115	0.70%	77020	80140	17.88%	61,297
Change Existing Sprinkler to Center Pivot [2]	1.18%	6309	1.41%	76470	82780	18.47%	58,657
Change Existing Sprinkler to Center Pivot w/ LEPA	2.29%	12089	2.70%	75470	87560	19.54%	53,877
Change Existing Sprinkler to Drip Only	1.15%	6127	1.37%	76500	82630	18.44%	58,807
Change Existing Wheel Line to Center pivot [2]	0.62%	3343	0.75%	76980	80330	17.93%	61,107
Change Existing Wheel Line to Center Pivot w/LEPA	1.21%	6446	1.44%	76450	82890	18.50%	58,547
Change Existing 'Other' to Center pivot [2]	0.12%	625	0.14%	77450	78080	17.43%	63,357
Change Existing 'Other' to Center Pivot w/LEPA	0.31%	1666	0.37%	77270	78940	17.62%	62,497

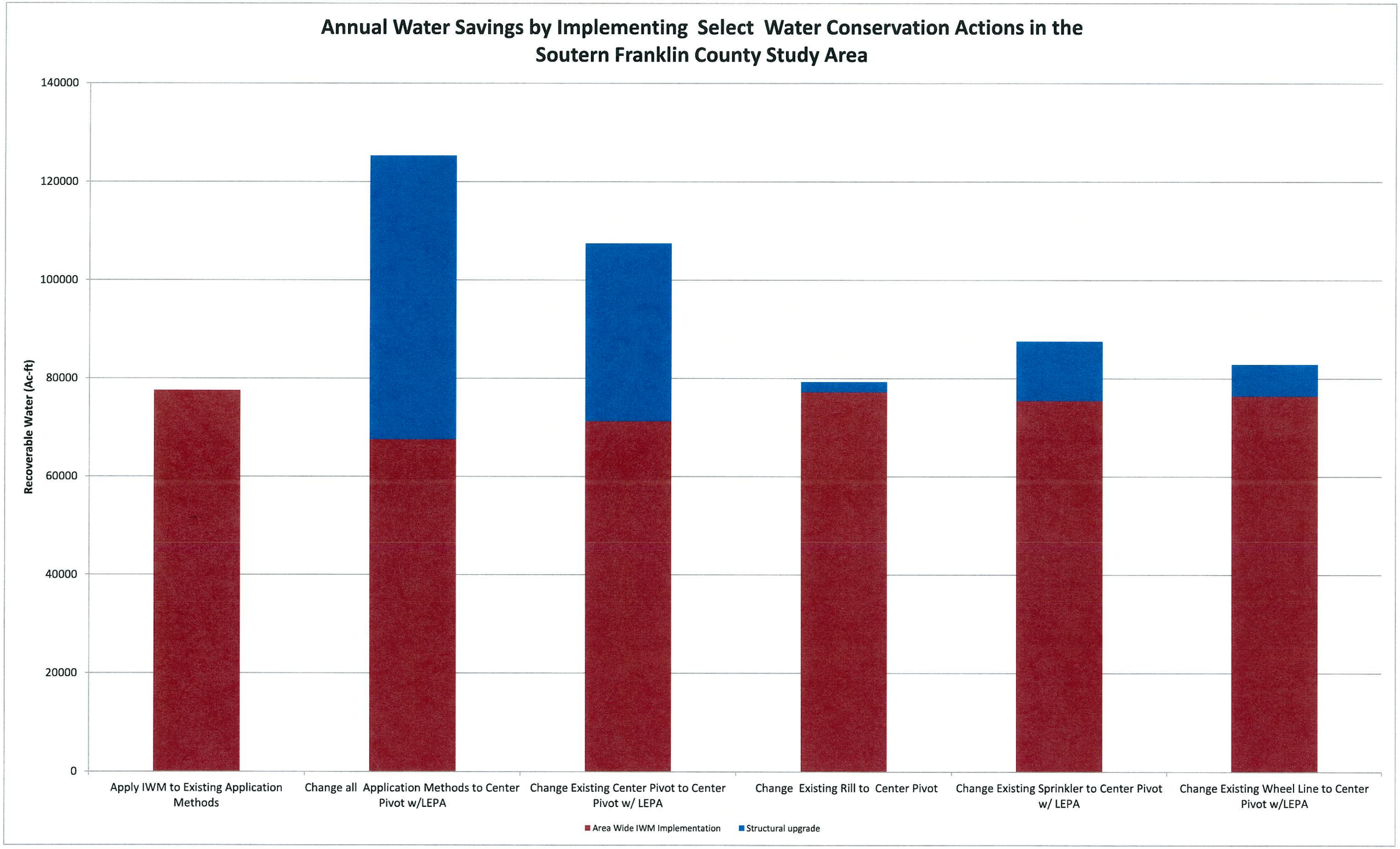
[1] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water management Area, 2005).

[2] Center pivot and drip irrigation have equal irrigation efficiencies. Converting a current irrigation structure to a drip system or a center pivot system would yield the same recovery quantities.

[3] Percent of water recovered – is the percentage of water that is no longer needed for irrigation purposes. It is equal to the volume of water recovered because of IWM and/or structural upgrades divided by the volume of current water use.

[4] Structural upgrade efficiency values are reported in Table 1, except center pivot with LEPA, which has an efficiency value of 95%.

Submitted March 29, 2011



Submitted March 29, 2011

Walla Walla Study Area

Table 1(c): Area wide irrigation efficiency based on present irrigation methods and method efficiency.

	1	1/Total Acres = 2	3	2 * 3 = 4
Estimated Irrigation Usage with Current Irrigation Methods				
Irrigation method	Acres	Percent of Area	Method Efficiency[2]	Weighted Efficiency per Method
Center Pivot[1]	2380	6.49%	83.75%	5.44%
Center Pivot/Sprinkler	45	0.12%	80.00%	0.10%
Sprinkler (Handline/Solid set)	26951	73.52%	75.00%	55.14%
Drip	0	0.00%	85.00%	0.00%
Drip/Sprinkler	767	2.09%	80.00%	1.67%
Rill	369	1.01%	65.00%	0.65%
Wheel line	5177	14.12%	75.00%	10.59%
Other[3]	966	2.64%	79.50%	2.10%
Total Acres	36656	100.00%	Weighted Average Irrigation Efficiency (WAIE)	**75.70%**
	Estimated Current Water Use[4]		3.12 Ac-ft/ac	

[1]Value is a weighted average of 25% center pivot with LEPA and 75% center pivot with end gun. Distribution estimates were provided by Franklin County Conservation District. LEPA defined as center pivot having drop tubes, rotator spray heads, and no end gun or corner span.

[2]Howell, T. A. (2003). Irrigation Efficiency. Encyclopedia of Water Science , 467-472.

[3] Average of irrigation method efficiencies reported by Howell. Average excludes methods that are reported in this table.

[4] See Table 2 (c)

Estimated Pre-IWM Irrigation Losses

Irrigation method	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
Center Pivot[1]	739	216	847	972	2774
Center Pivot/Sprinkler	14	4	16	18	53
Sprinkler (Handline/Solid set)	8366	2449	9590	11001	31406
Drip	0	0	0	0	0
Drip/Sprinkler	238	70	273	313	894
Rill	115	34	131	151	430
Wheel line	1607	470	1842	2113	6033
Other[3]	300	88	344	394	1126
Total	**11378 Ac-ft**	**3330 Ac-ft**	**13043 Ac-ft**	**14963 Ac-ft**	**42715 Ac-ft (Ac-ft)**

Estimated Post-IWM Irrigation Losses

	Evaporation Losses (Ac-ft)	Surface Runoff Losses (Ac-ft)	Application Inefficiency Deep Percolation Losses (Ac-ft)	Pre-IWM Over Application Deep Percolation Losses (Ac-ft)	Total
	611	179	700	0	1490
	12	3	13	0	28
	6918	2025	7930	0	16873
	0	0	0	0	0
	197	58	226	0	480
	95	28	109	0	231
	1329	389	1523	0	3241
	248	73	284	0	605
Total	**9409 Ac-ft**	**2754 Ac-ft**	**10786 Ac-ft**	**0 Ac-ft**	**22948 Ac-ft (Ac-ft)**

Reductions in Totals from Pre to Post IWM				
1970 Ac-ft	**576 Ac-ft**	**2258 Ac-ft**	**14963 Ac-ft**	**19767 Ac-ft**

Submitted March 29, 2011

Walla Walla Study Area

Table 2(c): Current water use per crop with current irrigation practices. Calculations were also performed to determine the water use per crop if IWM practices were implemented for the entire study area.

Crop	1 Original Acres	2 Percent of Total Area	3 Irrigation Requirement (Ac-ft/Ac)[1]	(1)*(3) = (4) Current Crop Water Need (Ac-ft)[9]	(4) / WAIE = (5) Current Gross Application Volume (Ac-ft)[8]	(5) - (4) = (6) Water Lost to Current Application Inefficiencies (Ac-ft)[9]	[(1)*(3)*(1-0.1731)] = (7) Revised Crop Need with 100% IWM (Ac-ft)[9]	(7) / WAIE = (8) Revised Gross Application Volume with IWM, (Ac-ft)[8]	(8) - (7) = (9) Revised Water Lost to Application Inefficiencies. (Ac-ft)	(5) - (8) = (10) Total Savings with IWM (Ac-ft)	(1) * (3) * 0.1731 = (11) ALSO (4) - (7) = 11 Portion of Total Saving from Revised Crop Need With IWM (Ac-ft)	(10) - (11) = (12) Water Saved because it isn't Exposed to Application Losses (Ac-ft)
Barley	236	0.6%	1.65 [2]	388	513	125	321	424	103	89	67	22
Oat	225	0.6%	1.64 [2]	370	489	119	306	404	98	85	64	21
Wheat	10005	27.3%	1.64 [2]	16425	21698	5273	13582	17942	4361	3756	2843	913
Alfalfa Hay	5556	15.2%	2.74 [1]	15209	20092	4883	12576	16614	4038	3478	2633	845
Alfalfa/Grass Hay	610	1.7%	2.74 [1]	1669	2204	536	1380	1823	443	382	289	93
Grass Hay	1070	2.9%	2.90 [3]	3106	4103	997	2568	3393	825	710	538	173
Timothy	817	2.2%	2.90 [3]	2369	3130	761	1959	2588	629	542	410	132
Pasture	2350	6.4%	2.90 [1]	6816	9005	2188	5636	7446	1810	1559	1180	379
Alfalfa Seed	10728	29.3%	2.74 [4]	29414	38858	9444	24322	32131	7809	6726	5092	1635
Golf Course/Lawn	471	1.3%	2.90 [3]	1366	1804	439	1129	1492	363	312	236	76
Onion	499	1.4%	2.58 [1]	1286	1699	413	1063	1405	341	294	223	71
Dry Pea	1452	4.0%	1.35 [5]	1954	2582	627	1616	2135	519	447	338	109
Wine Grape	618	1.7%	2.09 [6]	1293	1708	415	1069	1412	343	296	224	72
Other	2018	5.5%	2.37 [7]	4774	6307	1533	3948	5215	1268	1092	826	265
Total	**36656**	**100%**		**86439**	**114191**	**27752**	**71477**	**94425**	**22948**	**19767**	**14963**	**4804**

[1] WA Irr. Guide, Walla Walla, WA station (WIG)
[2] Average of winter and spring wheat values
[3] Used pasture/turf values
[4] Used alfalfa hay values
[5] Estimate based on Agrimet crop curves
[6] 1988-1994 average from USBR-Agrimet Legrow station.
[7] Average of above crops
[8] Estimated application volume is based on a 75.78% weighted average irrigation efficiency (WAIE), see Table 1
[9] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water Management Area, 2005).
[10] Estimated current water use is the total current crop need divided by the total acres.

Current Average Crop Need	2.36 Ac-ft/Ac
Estimated Current Water Use[10]	3.12 Ac-ft/Ac
IWM Average Crop Need	1.95 Ac-ft/Ac
Estimated Water use With IWM	2.58 Ac-ft/Ac

Submitted March 29, 2011

Walla Walla Study Area

Table 3(c): Walla Walla Study Area upgrades matrix. Different upgrades options were evaluated. Structural irrigation upgrades were kept separate from IWM upgrades. IWM upgrades represent the entire study area adopting IWM practices. Mechanical upgrade values represent incremental recoverable water values. Calculations that are not possible are represented with a dash (-).

	Structural Irrigation Upgrades			**Area Wide IWM[1] Irrigation Upgrade**	**Combined Water Recovered**		
Change in Irrigation Method	Increase In Area Wide Efficiency	Water Recovered (Ac-ft)	Percent of water Recovered[3]	Additional Water Recovered (Ac-ft)	Maximum Water Recoverable. Sum of IWM and Structural Upgrade (Ac-ft)	Percent of water Recovered	Unrecovered Water
Apply IWM to Existing Application Methods	-	-	-	19770	19770	17.31%	22,945
Change all Application Methods to Center Pivot w/LEPA	19.30%	23203	20.32%	15750	38950	34.11%	3,765
Change Existing Center Pivot to Center Pivot w/ LEPA	0.73%	1092	0.96%	19580	20670	18.10%	22,045
Change Existing Rill to Sprinkler	0.10%	152	0.13%	19740	19890	17.42%	22,825
Change Existing Rill to Center Pivot[2]	0.19%	280	0.25%	19720	20000	17.51%	22,715
Change Existing Rill to Center Pivot w/ LEPA	0.30%	454	0.40%	19690	20140	17.64%	22,575
Change Existing Sprinkler to Center Pivot[2]	6.47%	8992	7.87%	18210	27200	23.82%	15,515
Change Existing Sprinkler to Center Pivot w/ LEPA	14.70%	18575	16.27%	16550	35130	30.76%	7,585
Change Existing Sprinkler to Drip Only	7.35%	10109	8.85%	18020	28130	24.63%	14,585
Change Existing Wheel Line to Center pivot[2]	1.24%	1845	1.62%	19450	21290	18.65%	21,425
Change Existing Wheel Line to Center Pivot w/LEPA	2.82%	4108	3.60%	19060	23160	20.28%	19,555
Change Existing 'Other' to Center pivot[2]	0.11%	159	0.14%	19740	19900	17.43%	22,815
Change Existing 'Other' to Center Pivot w/LEPA	0.41%	613	0.54%	19660	20270	17.75%	22,445

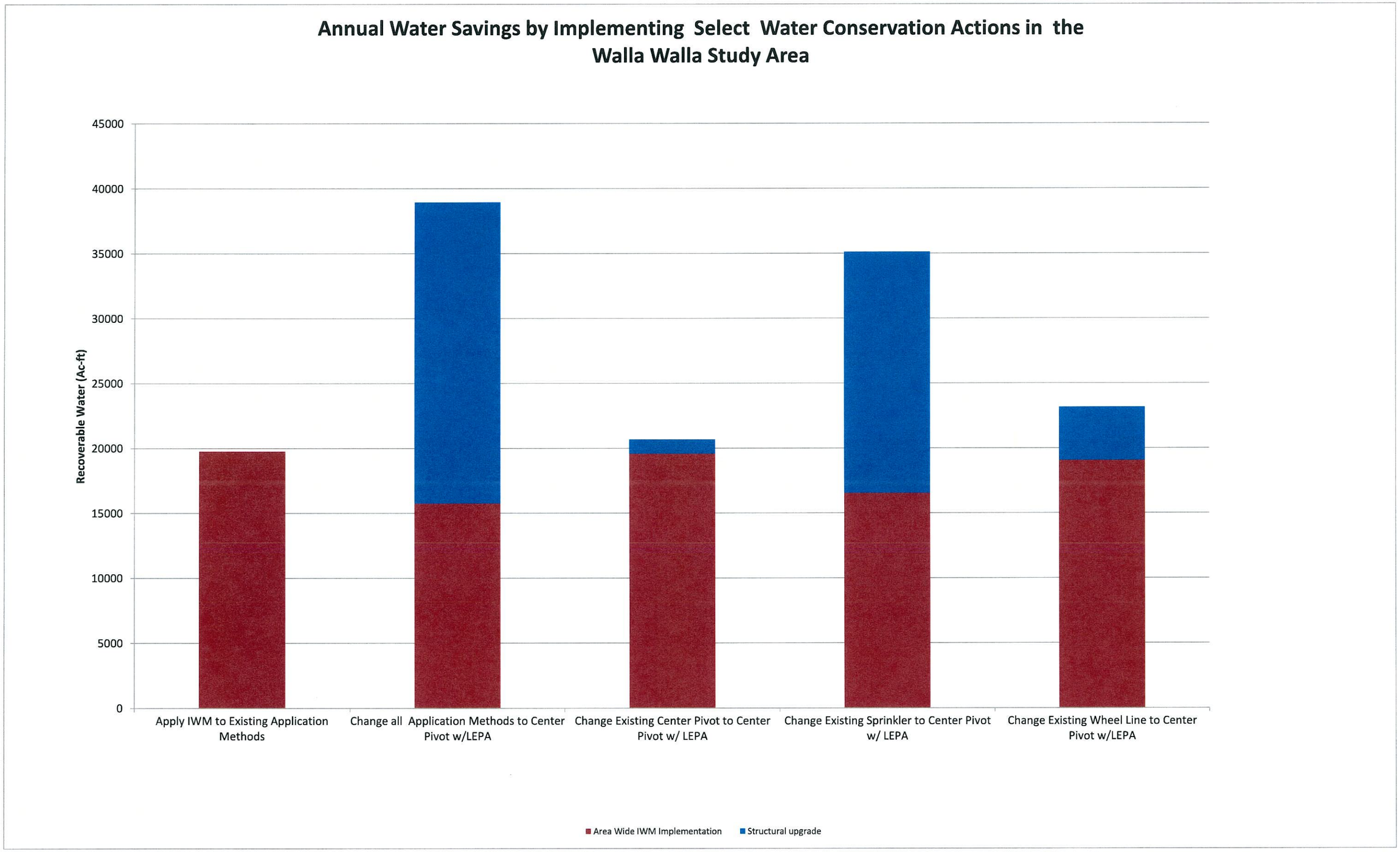
[1] IWM -Irrigation Water Management. IWM reduces the "current crop water need" by 17.31% (Columbia Basin Ground Water management Area, 2005).

[2] Center pivot and drip irrigation have equal irrigation efficiencies. Converting a current irrigation structure to a drip system or a center pivot system would yield the same recovery quantities.

[3] Percent of water recovered – is the percentage of water that is no longer needed for irrigation purposes. It is equal to the volume of water recovered because of IWM and/or structural upgrades divided by the volume of current water use.

[4] Structural upgrade efficiency values are reported in Table 1, except center pivot with LEPA, which has an efficiency value of 95%.

Submitted March 29, 2011



Appendix G

Interim Water Use, Efficiencies and Loss Pathways for the Potholes East Canal (PEC) 1951-1986

The purpose of Appendix is to provide the reader the sense of chronology and the progression in developing the loss pathways and conservation potential that has been presented in this study since March 2010.

To document and reinforce this point the following interim document is included to assist the reader in understanding how the final loss pathways and conservation potential values presented in this study were developed. This appendix is an April 20, 2011 RH2 memorandum to Mr. Mark Nielson and Mr. Peter Schwartzman regarding historical water use, efficiencies and loss pathways and the two possible approaches for calculating water use and water loss quantities for the Southern Franklin County study area. Based on the review comments from both Mr. Nielson and Mr. Schwartzman, this memorandum and tables were substantially revised into its present form as **Appendix E.** The spreadsheets originally attached to this appendix are not included as they were superseded by the revised tables presented in **Appendix E.**

Technical Memorandum

To: Mr. Mark Nielson, Franklin Conservation District (FCD)
Mr. Peter Schwartzman, Pacific Groundwater Group (PGG)

cc: Ms. Dawn Chapel, Pacific Groundwater Group

From: Mr. Randy Asplund, P.E.; Mr. Dick Erickson, P.E.

Sent Via: Email

Subject: Water Use, Efficiencies and Loss Pathways for Potholes East Canal (PEC), 1951-1986

Date: April 20, 2011

Attached are spreadsheets using two approaches to evaluate the subject information. For reference purposes we will call one approach the MWD Method and the other the WAIE Method. PGG needs the loss pathway information to calibrate its groundwater model for 1948 – 1986 and so that the model can potentially be applied to the 2009 pre-IWM and post-IWM analysis that was transmitted to FCD and PGG on March 29, 2011. We will explain the differences between the two methods and invite your decisions about which is best for modeling purposes, whether using the resulting ranges between the two approaches is reasonable and practical or whether some intermediate approach is necessary.

PGG obtained crop reports for 1951 to 1986 for the South Columbia Basin Irrigation District (SCBID) from the US Bureau of Reclamation (USBR). PGG reviewed the data and provided RH2 with the top ten crops in the district between 1951 and 1986. The top 10 crops were used to generate a composite, weighted average, crop irrigation requirement (CIR) for each year. Each individual CIR was taken from RH2's previous analysis of the 2009 water requirement and supplemented with data from the Washington Irrigation Guide (WIG) – Richland. In general the ten major crops accounted for 80+ percent of the cropped acreage each year. The resulting composite CIR values for 1951 – 1986 ranged between 2.70 AF/ac and 3.16 AF/ac. For comparison purposes the weighted average CIR used for the Southern Franklin County area for 2009 is 2.87 AF/ac. Additionally, the February 2002 Water Conservation Plan (WCP) for SCBID reports an average CIR of 2.68 AF/ac for 1992 and 2.75 AF/ac for 1999. Those values are based on WIG values for the Connell, Eltopia and Othello irrigation areas. The 2005 Columbia Basin Project (CBP) Water Supply, Use and Efficiency Report (CBP Efficiency Report) by Montgomery Water Group, Inc., reports CBP – wide CIRs for the period 1969 – 2001 in the range of 2.5 AF/ac to 2.9 AF/ac. Based on these comparisons, the CIR values developed from the crop reports by PGG and RH2 appear reasonable.

PGG also obtained annual monthly water distribution (MWD) reports from USBR for Potholdes East Canal (PEC) distribution system for the years that include 1951 – 1986. The MWD report includes an annual value for water delivered to farms expressed in AF/ac. These values ranged between 3.35 AF/ac and 4.35 AF/ac with a fair amount of scatter over the study period. The data acquired did not include MWD values for 1952 and 1953 so we have estimated those based on a five year average of actual valves for the years immediately preceding and following. The SCBID WCP reports a range of 3.57 AF/ac to 4.21 AF/ac for 1990 – 2000. The CBP Efficiency Report graphs a range of about 3.4 AF/ac to 4.5 AF/ac for the entire CBP for 1969 – 2002. The MWD farm delivery values from all three sources show comparable ranges and all have scatter.

PGG also obtained values for the amount of SCBID lands irrigated by sprinkler, expressed as a percentage of total irrigated acres, for the period of 1963 – 1986. This information is gathered as part of the annual crop reporting. The sprinklers verses rill data were not gathered prior to 1963 and the data does not distinguish between the various types of gravity irrigation or the various types of sprinkler irrigation. RH2 assumed a 10% value for the amount of sprinkler irrigation in 1951 and then did an annual linear interpolation to obtain annual estimates up to the first reported sprinkler value of 50% in 1963. The PEC was brought into service from north to south so the irrigated lands in the earlier years would have been around Othello, an area that was predominately rill irrigated for many years. Also, in the 1950s sprinkler irrigation technology was just beginning to develop.

Crop reports do not distinguish between the types of sprinkler system being used so RH2 has assumed a distribution based on past sprinkler development trends. For 1951 – 1975 RH2 assumed all sprinklers to be either handline or wheelline, both having 75% application efficiencies. For 1976 – 1981 RH2 assumed that 50% of sprinklers were handline or wheelline and 50% were non-LEPA center pivots having an application efficiency of 80%. For 1982 – 1986 those assumed ratios were 25% handline or wheelline and 75% non-LEPA center pivots. Loss pathways were adjusted accordingly. In all years the application efficiency used for rill irrigation was 65%. These application efficiency values are identical to those used for the 2009 analysis.

For each year the distribution of irrigation loss pathways was done in the same manner as was used for 2009. From the October 13, 2010 **Appendix B**, the loss pathways for the applicable irrigation methods, expressed as a percentage of total water applied are:

Type of Irrigation	Evaporation Losses	Surface Runoff Losses	Deep Percolation	Total Losses
Furrow (rill)	5%	10%	20%	35%
Handline	10%	3%	12%	25%
Wheelline	10%	3%	12%	25%
Center Pivot w/o LEPA	15%	1%	4%	20%

Expressed as a percent of the total losses the proportions are:

Type of Irrigation	Evaporation Losses	Surface Runoff Losses	Deep Percolation	Total Losses
Furrow (rill)	14.3%	28.6%	57.1%	100%
Handline	40.0%	12.0%	48.0%	100%
Wheelline	40.0%	12.0%	48.0%	100%
Center Pivot w/o LEPA	75.0%	5.0%	20.0%	100%

One of the attached spreadsheets, the MWD Method, evaluates efficiencies, losses and loss pathways using the MWD value as total water applied. The apparent efficiency is then calculated as CIR/MWD. The total loss is the difference between MWD and CIR. The loss is then allocated to the respective pathways as explained above based on the rill and sprinkler proportions for that year.

A second spreadsheet, the WAIE Method, follows the approach used for the 2009 analysis. The proportions of rill and sprinkler for each year are used to calculate weighted average irrigation efficiency (WAIE). CIR is then divided by WAIE to determine gross water applied. Loss is defined by the difference between water applied and CIR and that loss is then allocated to the various loss pathways.

We have provided a graph comparing the variations and scatter of the MWD (from the MWD Method) and the gross water applied values (from the WAIE Method). We have also provided a table comparing the irrigation efficiency values derived from the two approaches. The MWD approach is based on historic reports but has noticeable scatter. The WAIE approach is consistent with how the 2009 pre-IWM and post-IWM evaluation was done. RH2 believes both methods are technically valid. FCD and PGG should determine which method best suits the planned modeling and the needs of the overall study.

It should be noted that the geographic area for the 1951 – 1986 data differs from the 2009 study area. The 1951 – 1986 analysis is based on all irrigation blocks supplied by the PEC which is a larger area than the irrigation blocks included in the SFC area for 2009. Also the SFC area includes irrigated areas not supplied by the PEC. Also worth noting is that the crop report data and the top ten crops are for the entire SCBID which includes some areas supplied by the East Low Canal (Blocks 18 and 181) and from McNary Pool (Blocks 2 and 3). The MWD values are specific to the PEC and do not include these blocks but do include Blocks 48 and 49 of the East Columbia Basin Irrigation District. These geographic discrepancies represent minor portions of the areas being evaluated and are probably not overly significant for comparative purposes.

For modeling purposes PGG has requested hypothetical loss pathway values for areas using 100% sprinkler (0% rill) and 100% rill (0% sprinkler) from 1953 to 1986. Using the MWD approach, historical quantities of water delivered to farms were adjusted to account for the additional water needed (100% rill) or water that was not needed (100% sprinkler) because of a gain or loss in overall efficiency. To get an applicable MWD under this assumption the original yearly MWD was adjusted in accordance with the percentage change in overall efficiency that would be expected by either being 100% rill or 100% sprinkler. For example the USBR MWD for 1972 was 3.79. During this year the amount of land that was under sprinkler and rill was 73.5% and 25.5% respectively. This

corresponds to a WAIE of 72.4%. If the area was under 100% rill, the corresponding WAIE would be 65%. This is equal to a 10.1% decrease in efficiency. Since 10.1% of the water is now lost to inefficiencies, the MWD was increased by 10.1%. Total losses and loss pathways were then adjusted accordingly.

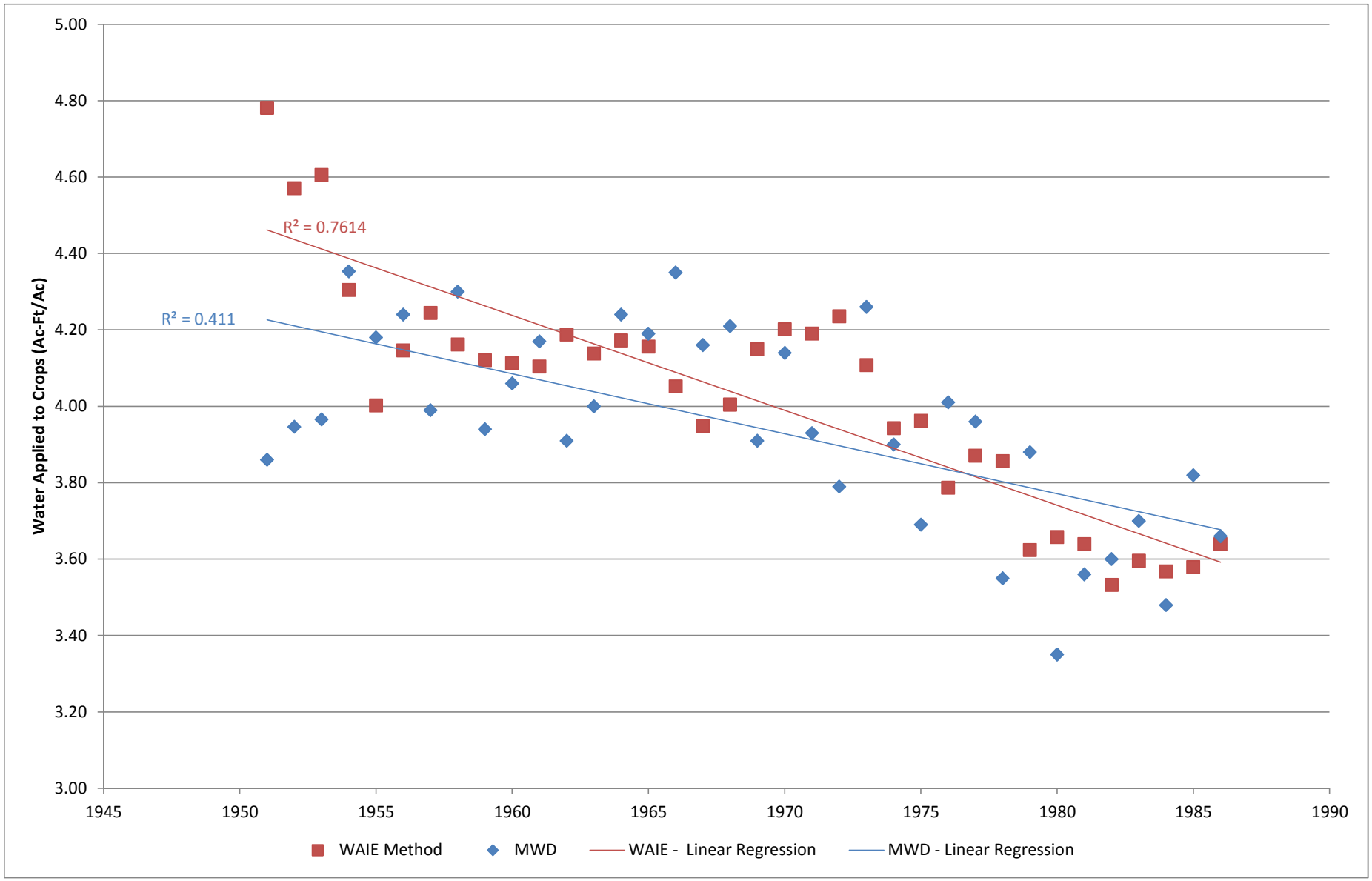
Please contact RH2 if you have further questions about how we did the evaluations of the MWD Method, the WAIE Method or the hypothetical all sprinkler and all rill evaluations. As indicated earlier, RH2 believes both the MWD Method and the WAIE Method to be technically valid. The results for both have some variations based on the scatter of the underlying data.

Year	MWD (Delivered to Farms) (Ac-ft / Ac)	Weighted Avg Crop Req (Ac-ft / Ac)	Apparent Efficiency	Acres Irrigated	Total Loss (Ac-ft / Ac)	Total Loss (Ac-ft)	% SCBID on Sprinklers	% SCBID on Rill	Evaporation Loss (Ac-ft/Ac)	Surface Run Off Loss (Ac-ft/Ac)	Deep Perc Loss (Ac-ft/Ac)
1951	3.86	3.16	81.8%	5084	0.70	3,579	10.0%	90.0%	0.12	0.19	0.40
1952	3.95	3.03	76.8%	5813	0.91	5,316	13.3%	86.7%	0.16	0.24	0.51
1953	3.97	3.07	77.4%	6838	0.90	6,122	16.7%	83.3%	0.17	0.23	0.50
1954	4.35	2.88	66.3%	13109	1.47	19,255	20.0%	80.0%	0.29	0.37	0.81
1955	4.18	2.69	64.5%	23872	1.49	35,452	23.3%	76.7%	0.30	0.37	0.82
1956	4.24	2.81	66.2%	30849	1.43	44,236	26.7%	73.3%	0.30	0.35	0.78
1957	3.99	2.89	72.3%	39711	1.10	43,820	30.0%	70.0%	0.24	0.26	0.60
1958	4.30	2.84	66.1%	48321	1.46	70,348	33.3%	66.7%	0.33	0.34	0.79
1959	3.94	2.83	71.8%	59359	1.11	65,912	36.7%	63.3%	0.26	0.25	0.60
1960	4.06	2.84	69.9%	71360	1.22	87,196	40.0%	60.0%	0.30	0.27	0.65
1961	4.17	2.85	68.2%	79369	1.32	105,093	43.3%	56.7%	0.34	0.28	0.70
1962	3.91	2.92	74.6%	86718	0.99	86,053	46.7%	53.3%	0.26	0.21	0.52
1963	4.00	2.90	72.4%	94287	1.10	104,027	50.0%	50.0%	0.30	0.22	0.58
1964	4.24	2.94	69.3%	100896	1.30	131,435	54.0%	46.0%	0.37	0.26	0.68
1965	4.19	2.94	70.2%	115199	1.25	143,684	58.0%	42.0%	0.36	0.24	0.65
1966	4.35	2.88	66.3%	125002	1.47	183,158	62.0%	38.0%	0.44	0.27	0.75
1967	4.16	2.83	68.0%	136378	1.33	181,763	66.0%	34.0%	0.42	0.24	0.68
1968	4.21	2.87	68.2%	139084	1.34	185,916	67.5%	32.5%	0.42	0.23	0.68
1969	3.91	2.98	76.3%	142485	0.93	132,044	69.0%	31.0%	0.30	0.16	0.47
1970	4.14	3.03	73.1%	143939	1.11	160,185	70.5%	29.5%	0.36	0.19	0.56
1971	3.93	3.03	77.0%	148029	0.90	133,861	72.0%	28.0%	0.30	0.15	0.46
1972	3.79	3.06	80.9%	150285	0.73	109,013	73.5%	26.5%	0.24	0.12	0.37
1973	4.26	2.98	69.9%	154111	1.28	197,576	75.0%	25.0%	0.43	0.21	0.64
1974	3.90	2.86	73.4%	165179	1.04	171,055	76.5%	23.5%	0.35	0.16	0.52
1975	3.69	2.88	78.2%	166923	0.81	134,531	78.0%	22.0%	0.28	0.13	0.40
1976	4.01	2.83	70.6%	173645	1.18	204,716	79.5%	20.5%	0.57	0.15	0.46
1977	3.96	2.90	73.3%	177703	1.06	188,227	81.0%	19.0%	0.52	0.13	0.41
1978	3.55	2.90	81.6%	178448	0.65	116,421	82.5%	17.5%	0.33	0.08	0.25
1979	3.88	2.73	70.3%	178757	1.15	205,720	84.0%	16.0%	0.58	0.13	0.43
1980	3.35	2.76	82.4%	180625	0.59	106,278	85.0%	15.0%	0.30	0.07	0.22
1981	3.56	2.75	77.3%	183117	0.81	147,876	86.0%	14.0%	0.42	0.09	0.30
1982	3.60	2.71	75.4%	184168	0.89	163,154	87.0%	13.0%	0.52	0.09	0.28
1983	3.70	2.77	74.8%	163544	0.93	152,545	88.0%	12.0%	0.55	0.09	0.30
1984	3.48	2.75	79.1%	179831	0.73	131,051	88.3%	11.8%	0.43	0.07	0.23
1985	3.82	2.76	72.3%	190705	1.06	202,023	88.5%	11.5%	0.62	0.10	0.33
1986	3.66	2.81	76.7%	187616	0.85	159,792	88.8%	11.3%	0.50	0.08	0.27

												If 100% Rill			If 100% Sprinkler		
Year	Gross water Applied	Weighted Avg Crop Req (Ac-ft / Ac)	WAIE Efficiency	Acres Irrigated	Total Loss (Ac-ft / Ac)	Total Loss (Ac-ft)	% SCBID on Sprinklers	% SCBID on Rill	Evaporation Loss (Ac-ft/Ac)	Surface Run Off Loss (Ac-ft/Ac)	Deep Perc Loss (Ac-ft/Ac)	Evaporation Loss (Ac-ft/Ac)	Surface Run Off Loss (Ac-ft/Ac)	Deep Perc Loss (Ac-ft/Ac)	Evaporation Loss (Ac-ft/Ac)	Surface Run Off Loss (Ac-ft/Ac)	Deep Perc Loss (Ac-ft/Ac)
1951	4.78	3.16	66.0%	5084	1.63	8,266	10.0%	90.0%	0.27	0.44	0.91	0.24	0.49	0.97	0.42	0.13	0.50
1952	4.57	3.03	66.3%	5813	1.54	8,946	13.3%	86.7%	0.27	0.41	0.86	0.23	0.47	0.93	0.40	0.12	0.49
1953	4.61	3.07	66.7%	6838	1.54	10,499	16.7%	83.3%	0.29	0.40	0.85	0.24	0.47	0.94	0.41	0.12	0.49
1954	4.30	2.88	67.0%	13109	1.42	18,622	20.0%	80.0%	0.28	0.36	0.79	0.22	0.44	0.89	0.38	0.12	0.46
1955	4.00	2.69	67.3%	23872	1.31	31,211	23.3%	76.7%	0.27	0.32	0.72	0.21	0.41	0.83	0.36	0.11	0.43
1956	4.15	2.81	67.7%	30849	1.34	41,363	26.7%	73.3%	0.28	0.32	0.73	0.22	0.43	0.86	0.37	0.11	0.45
1957	4.24	2.89	68.0%	39711	1.36	53,942	30.0%	70.0%	0.30	0.32	0.74	0.22	0.44	0.89	0.38	0.12	0.46
1958	4.16	2.84	68.3%	48321	1.32	63,688	33.3%	66.7%	0.30	0.30	0.71	0.22	0.44	0.88	0.38	0.11	0.46
1959	4.12	2.83	68.7%	59359	1.29	76,643	36.7%	63.3%	0.31	0.29	0.69	0.22	0.44	0.87	0.38	0.11	0.45
1960	4.11	2.84	69.0%	71360	1.28	90,990	40.0%	60.0%	0.31	0.28	0.68	0.22	0.44	0.87	0.38	0.11	0.45
1961	4.10	2.85	69.3%	79369	1.26	99,907	43.3%	56.7%	0.32	0.27	0.67	0.22	0.44	0.88	0.38	0.11	0.46
1962	4.19	2.92	69.7%	86718	1.27	110,164	46.7%	53.3%	0.33	0.26	0.67	0.22	0.45	0.90	0.39	0.12	0.47
1963	4.14	2.90	70.0%	94287	1.24	117,052	50.0%	50.0%	0.34	0.25	0.65	0.22	0.45	0.89	0.39	0.12	0.46
1964	4.17	2.94	70.4%	100896	1.24	124,608	54.0%	46.0%	0.35	0.24	0.64	0.23	0.45	0.90	0.39	0.12	0.47
1965	4.16	2.94	70.8%	115199	1.21	139,814	58.0%	42.0%	0.35	0.23	0.63	0.23	0.45	0.91	0.39	0.12	0.47
1966	4.05	2.88	71.2%	125002	1.17	145,861	62.0%	38.0%	0.35	0.21	0.60	0.22	0.44	0.89	0.38	0.12	0.46
1967	3.95	2.83	71.6%	136378	1.12	152,935	66.0%	34.0%	0.35	0.20	0.57	0.22	0.43	0.87	0.38	0.11	0.45
1968	4.00	2.87	71.8%	139084	1.13	157,345	67.5%	32.5%	0.36	0.20	0.58	0.22	0.44	0.88	0.38	0.11	0.46
1969	4.15	2.98	71.9%	142485	1.17	166,127	69.0%	31.0%	0.37	0.20	0.59	0.23	0.46	0.92	0.40	0.12	0.48
1970	4.20	3.03	72.1%	143939	1.17	169,028	70.5%	29.5%	0.38	0.20	0.60	0.23	0.47	0.93	0.40	0.12	0.48
1971	4.19	3.03	72.2%	148029	1.17	172,457	72.0%	28.0%	0.38	0.19	0.59	0.23	0.47	0.93	0.40	0.12	0.48
1972	4.24	3.06	72.4%	150285	1.17	176,015	73.5%	26.5%	0.39	0.19	0.59	0.24	0.47	0.94	0.41	0.12	0.49
1973	4.11	2.98	72.5%	154111	1.13	174,079	75.0%	25.0%	0.38	0.18	0.57	0.23	0.46	0.92	0.40	0.12	0.48
1974	3.94	2.86	72.7%	165179	1.08	178,120	76.5%	23.5%	0.37	0.17	0.54	0.22	0.44	0.88	0.38	0.11	0.46
1975	3.96	2.88	72.8%	166923	1.08	179,869	78.0%	22.0%	0.37	0.17	0.54	0.22	0.44	0.89	0.38	0.12	0.46
1976	3.79	2.83	74.8%	173645	0.96	166,059	79.5%	20.5%	0.47	0.12	0.17	0.22	0.44	0.87	0.47	0.07	0.28
1977	3.87	2.90	74.9%	177703	0.97	172,399	81.0%	19.0%	0.48	0.12	0.17	0.22	0.45	0.89	0.48	0.07	0.29
1978	3.86	2.90	75.1%	178448	0.96	171,209	82.5%	17.5%	0.48	0.12	0.16	0.22	0.45	0.89	0.48	0.07	0.29
1979	3.62	2.73	75.3%	178757	0.89	159,920	84.0%	16.0%	0.45	0.10	0.14	0.21	0.42	0.84	0.46	0.07	0.27
1980	3.66	2.76	75.5%	180625	0.90	161,867	85.0%	15.0%	0.46	0.10	0.14	0.21	0.42	0.85	0.46	0.07	0.27
1981	3.64	2.75	75.6%	183117	0.89	162,453	86.0%	14.0%	0.46	0.10	0.13	0.21	0.42	0.85	0.46	0.07	0.27
1982	3.53	2.71	76.8%	184168	0.82	150,785	87.0%	13.0%	0.48	0.08	0.26	0.21	0.42	0.84	0.47	0.05	0.21
1983	3.60	2.77	77.0%	163544	0.83	135,469	88.0%	12.0%	0.49	0.08	0.26	0.21	0.43	0.85	0.48	0.05	0.21
1984	3.57	2.75	77.1%	179831	0.82	146,952	88.3%	11.8%	0.48	0.08	0.26	0.21	0.42	0.85	0.48	0.05	0.21
1985	3.58	2.76	77.1%	190705	0.82	156,066	88.5%	11.5%	0.48	0.08	0.26	0.21	0.42	0.85	0.48	0.05	0.21
1986	3.64	2.81	77.2%	187616	0.83	155,884	88.8%	11.3%	0.49	0.08	0.26	0.22	0.43	0.86	0.49	0.05	0.21

				If 100% Rill							If 100% Sprinkler						
Year	MWD (Delivered to Farms) (Ac-ft / Ac)	Weighted Avg Crop Req (Ac-ft / Ac)	Existing WAIE	Proposed WAIE	% Change From Existing WAIE to Proposed WAIE	Adjusted MWD (Ac-ft/Ac)	Adjusted Loss (Ac-ft/Ac)	Evaporation Loss (Ac-ft/Ac)	Surface Run Off Loss (Ac-ft/Ac)	Deep Perc Loss (Ac-ft/Ac)	Proposed WAIE	% Change From Existing WAIE to Proposed WAIE	Adjusted MWD (Ac-ft/Ac)	Adjusted Loss (Ac-ft/Ac)	Evaporation Loss (Ac-ft/Ac)	Surface Run Off Loss (Ac-ft/Ac)	Deep Perc Loss (Ac-ft/Ac)
1951	3.86	3.16	66.00%	65.00%	1.52%	3.92	0.76	0.11	0.22	0.44	75.00%	-13.64%	3.33	0.18	0.07	0.02	0.09
1952	3.95	3.03	66.33%	65.00%	2.01%	4.03	0.99	0.14	0.28	0.57	75.00%	-13.07%	3.43	0.40	0.16	0.05	0.19
1953	3.97	3.07	66.67%	65.00%	2.50%	4.07	0.99	0.14	0.28	0.57	75.00%	-12.50%	3.47	0.40	0.16	0.05	0.19
1954	4.35	2.88	67.00%	65.00%	2.99%	4.48	1.60	0.23	0.46	0.91	75.00%	-11.94%	3.83	0.95	0.38	0.11	0.46
1955	4.18	2.69	67.33%	65.00%	3.47%	4.32	1.63	0.23	0.47	0.93	75.00%	-11.39%	3.70	1.01	0.40	0.12	0.48
1956	4.24	2.81	67.67%	65.00%	3.94%	4.41	1.60	0.23	0.46	0.91	75.00%	-10.84%	3.78	0.97	0.39	0.12	0.47
1957	3.99	2.89	68.00%	65.00%	4.41%	4.17	1.28	0.18	0.37	0.73	75.00%	-10.29%	3.58	0.69	0.28	0.08	0.33
1958	4.30	2.84	68.33%	65.00%	4.88%	4.51	1.67	0.24	0.48	0.95	75.00%	-9.76%	3.88	1.04	0.41	0.12	0.50
1959	3.94	2.83	68.67%	65.00%	5.34%	4.15	1.32	0.19	0.38	0.75	75.00%	-9.22%	3.58	0.75	0.30	0.09	0.36
1960	4.06	2.84	69.00%	65.00%	5.80%	4.30	1.46	0.21	0.42	0.83	75.00%	-8.70%	3.71	0.87	0.35	0.10	0.42
1961	4.17	2.85	69.33%	65.00%	6.25%	4.43	1.58	0.23	0.45	0.91	75.00%	-8.17%	3.83	0.98	0.39	0.12	0.47
1962	3.91	2.92	69.67%	65.00%	6.70%	4.17	1.25	0.18	0.36	0.72	75.00%	-7.66%	3.61	0.69	0.28	0.08	0.33
1963	4.00	2.90	70.00%	65.00%	7.14%	4.29	1.39	0.20	0.40	0.79	75.00%	-7.14%	3.71	0.82	0.33	0.10	0.39
1964	4.24	2.94	70.40%	65.00%	7.67%	4.57	1.63	0.23	0.47	0.93	75.00%	-6.53%	3.96	1.03	0.41	0.12	0.49
1965	4.19	2.94	70.80%	65.00%	8.19%	4.53	1.59	0.23	0.45	0.91	75.00%	-5.93%	3.94	1.00	0.40	0.12	0.48
1966	4.35	2.88	71.20%	65.00%	8.71%	4.73	1.84	0.26	0.53	1.05	75.00%	-5.34%	4.12	1.23	0.49	0.15	0.59
1967	4.16	2.83	71.60%	65.00%	9.22%	4.54	1.72	0.25	0.49	0.98	75.00%	-4.75%	3.96	1.14	0.45	0.14	0.54
1968	4.21	2.87	71.75%	65.00%	9.41%	4.61	1.73	0.25	0.50	0.99	75.00%	-4.53%	4.02	1.15	0.46	0.14	0.55
1969	3.91	2.98	71.90%	65.00%	9.60%	4.29	1.30	0.19	0.37	0.74	75.00%	-4.31%	3.74	0.76	0.30	0.09	0.36
1970	4.14	3.03	72.05%	65.00%	9.78%	4.55	1.52	0.22	0.43	0.87	75.00%	-4.09%	3.97	0.94	0.38	0.11	0.45
1971	3.93	3.03	72.20%	65.00%	9.97%	4.32	1.30	0.19	0.37	0.74	75.00%	-3.88%	3.78	0.75	0.30	0.09	0.36
1972	3.79	3.06	72.35%	65.00%	10.16%	4.18	1.11	0.16	0.32	0.63	75.00%	-3.66%	3.65	0.59	0.23	0.07	0.28
1973	4.26	2.98	72.50%	65.00%	10.34%	4.70	1.72	0.25	0.49	0.98	75.00%	-3.45%	4.11	1.14	0.45	0.14	0.54
1974	3.90	2.86	72.65%	65.00%	10.53%	4.31	1.45	0.21	0.41	0.83	75.00%	-3.23%	3.77	0.91	0.36	0.11	0.44
1975	3.69	2.88	72.80%	65.00%	10.71%	4.09	1.20	0.17	0.34	0.69	75.00%	-3.02%	3.58	0.69	0.28	0.08	0.33
1976	4.01	2.83	74.75%	65.00%	13.04%	4.53	1.70	0.24	0.49	0.97	77.50%	-3.68%	3.86	1.03	0.59	0.09	0.35
1977	3.96	2.90	74.94%	65.00%	13.26%	4.49	1.58	0.23	0.45	0.91	77.50%	-3.42%	3.82	0.92	0.53	0.08	0.31
1978	3.55	2.90	75.13%	65.00%	13.48%	4.03	1.13	0.16	0.32	0.65	77.50%	-3.16%	3.44	0.54	0.31	0.05	0.18
1979	3.88	2.73	75.31%	65.00%	13.69%	4.41	1.68	0.24	0.48	0.96	77.50%	-2.90%	3.77	1.04	0.60	0.09	0.35
1980	3.35	2.76	75.50%	65.00%	13.91%	3.82	1.05	0.15	0.30	0.60	77.50%	-2.65%	3.26	0.50	0.29	0.04	0.17
1981	3.56	2.75	75.63%	65.00%	14.05%	4.06	1.31	0.19	0.37	0.75	77.50%	-2.48%	3.47	0.72	0.41	0.06	0.24
1982	3.60	2.71	76.83%	65.00%	15.39%	4.15	1.44	0.21	0.41	0.82	78.75%	-2.51%	3.51	0.80	0.51	0.06	0.22
1983	3.70	2.77	76.96%	65.00%	15.54%	4.28	1.51	0.22	0.43	0.86	78.75%	-2.32%	3.61	0.85	0.55	0.06	0.24
1984	3.48	2.75	77.10%	65.00%	15.69%	4.03	1.27	0.18	0.36	0.73	78.75%	-2.14%	3.41	0.65	0.42	0.05	0.18
1985	3.82	2.76	77.13%	65.00%	15.73%	4.42	1.66	0.24	0.47	0.95	78.75%	-2.09%	3.74	0.98	0.63	0.07	0.28
1986	3.66	2.81	77.17%	65.00%	15.77%	4.24	1.43	0.20	0.41	0.82	78.75%	-2.05%	3.59	0.78	0.50	0.05	0.22

Year	Weighted Avg Crop Req (Ac-ft / Ac)	MWD (Delivered to Farms) (Ac-ft / Ac)	Apparent Efficiency	WAIE	Gross water Applied	% Difference	(Ac-ft/Ac) Difference
1951	3.16	3.86	81.8%	66.0%	4.78	15.8%	0.92
1952	3.03	3.95	76.8%	66.3%	4.57	10.5%	0.62
1953	3.07	3.97	77.4%	66.7%	4.61	10.8%	0.64
1954	2.88	4.35	66.3%	67.0%	4.30	-0.7%	-0.05
1955	2.69	4.18	64.5%	67.3%	4.00	-2.9%	-0.18
1956	2.81	4.24	66.2%	67.7%	4.15	-1.5%	-0.09
1957	2.89	3.99	72.3%	68.0%	4.24	4.3%	0.25
1958	2.84	4.30	66.1%	68.3%	4.16	-2.2%	-0.14
1959	2.83	3.94	71.8%	68.7%	4.12	3.2%	0.18
1960	2.84	4.06	69.9%	69.0%	4.11	0.9%	0.05
1961	2.85	4.17	68.2%	69.3%	4.10	-1.1%	-0.07
1962	2.92	3.91	74.6%	69.7%	4.19	5.0%	0.28
1963	2.90	4.00	72.4%	70.0%	4.14	2.4%	0.14
1964	2.94	4.24	69.3%	70.4%	4.17	-1.1%	-0.07
1965	2.94	4.19	70.2%	70.8%	4.16	-0.6%	-0.03
1966	2.88	4.35	66.3%	71.2%	4.05	-4.9%	-0.30
1967	2.83	4.16	68.0%	71.6%	3.95	-3.6%	-0.21
1968	2.87	4.21	68.2%	71.8%	4.00	-3.5%	-0.21
1969	2.98	3.91	76.3%	71.9%	4.15	4.4%	0.24
1970	3.03	4.14	73.1%	72.1%	4.20	1.1%	0.06
1971	3.03	3.93	77.0%	72.2%	4.19	4.8%	0.26
1972	3.06	3.79	80.9%	72.4%	4.24	8.5%	0.45
1973	2.98	4.26	69.9%	72.5%	4.11	-2.6%	-0.15
1974	2.86	3.90	73.4%	72.7%	3.94	0.8%	0.04
1975	2.88	3.69	78.2%	72.8%	3.96	5.4%	0.27
1976	2.83	4.01	70.6%	74.8%	3.79	-4.1%	-0.22
1977	2.90	3.96	73.3%	74.9%	3.87	-1.7%	-0.09
1978	2.90	3.55	81.6%	75.1%	3.86	6.5%	0.31
1979	2.73	3.88	70.3%	75.3%	3.62	-5.0%	-0.26
1980	2.76	3.35	82.4%	75.5%	3.66	6.9%	0.31
1981	2.75	3.56	77.3%	75.6%	3.64	1.7%	0.08
1982	2.71	3.60	75.4%	76.8%	3.53	-1.4%	-0.07
1983	2.77	3.70	74.8%	77.0%	3.60	-2.2%	-0.10
1984	2.75	3.48	79.1%	77.1%	3.57	2.0%	0.09
1985	2.76	3.82	72.3%	77.1%	3.58	-4.9%	-0.24
1986	2.81	3.66	76.7%	77.2%	3.64	-0.4%	-0.02


5.00
4.80
4.60
4.40
4.20
4.00
3.80
3.60
3.40
3.20
3.00
Water Applied to Crops (Ac-Ft/Ac)
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
R² = 0.7614
R² = 0.411
WAIE Method
MWD
WAIE - Linear Regression
MWD - Linear Regression

APPENDIX H
DOCUMENTATION OF MODELING ANALYSES FOR HORSE HEAVEN HILLS STUDY AREA

February 2012

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 IRRIGATION RECHARGE 1

3.0 VADOSE ZONE MODELING 1

3.1 VADOSE ZONE HYDRAULIC PROPERTIES 2
3.2 HYDRUS MODEL SETUP 3
3.3 HYDRUS MODEL RESULTS AND INTERPRETATION 3

4.0 CRB GROUNDWATER FLOW MODELING 4

4.1 DOMAIN AND DISCRETIZATION 5
4.2 AQUIFER PROPERTIES 5
4.3 BOUNDARY CONDITIONS 6
4.4 MODEL RESULTS 6

1.0 INTRODUCTION

This appendix describes the approaches used to model the timing of the seasonal irrigation "recharge pulse" from the root zone (field application) through the vadose zone to the water table. It also describes modeling of the recharge pulse through the saturated Columbia River Basalt (CRB) flow system. Modeling of the recharge pulse through the saturated suprabasalt flow system is described in Section 3.3.3 of the main report.

2.0 IRRIGATION RECHARGE

RH2 Engineering estimated irrigation losses (evaporation, runoff and deep percolation) for current and post-conservation conditions within the Horse Heaven Hills study area. RH2's evaluation is documented in Section 3.1.5 of the main report and in Appendices A and B. Irrigation losses for current conditions, estimated monthly over an assumed 7-month season are summarized below:

(all units in feet)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
SW Runoff	0.000	0.000	0.000	0.000	0.001	0.002	0.005	0.005	0.002	0.000	0.000	0.000	0.01
Evaporation	0.000	0.000	0.000	0.002	0.011	0.038	0.087	0.083	0.036	0.005	0.000	0.000	0.26
Total Deep Percolation	0.000	0.000	0.000	0.003	0.021	0.069	0.160	0.153	0.066	0.010	0.000	0.000	0.48
Total Losses	0.00	0.00	0.00	0.01	0.03	0.11	0.25	0.24	0.10	0.02	0.00	0.00	0.76

For post-conservation conditions, RH2 assumed that the most efficient irrigation methods are applied (center pivot with LEPA and IWM) and approximated that deep percolation would cease as a result. This represents theoretical maximum conservation of water; however, in actuality, a small amount of deep percolation will occur (and is required in order to prevent the salt buildup in the soil). In this analysis, the zero deep percolation assumption is used to estimate retiming benefit; however, it is recognized that this approach slightly over-estimates retiming benefit. Calculations will be refined once pilot sites are identified in the Horse Heaven Hills study area and actual pre- and post-conservation irrigation methods are identified for these site(s).

3.0 VADOSE ZONE MODELING

PGG used the finite-element model "Hydrus-1D" (Simunek et al, 2008) to simulate movement of the irrigation recharge pulse through the vadose zone in variably saturated fine-grained surficial soils. Note that Hydrus-1D requires that all calculations are performed in the metric system, so that this discussion employs units of centimeters and meters. The thickness and texture of the vadose zone is discussed in Section 3.2.3 of the main report.

Three vadose zone configurations and textures were evaluated with Hydrus-1D:

- Free draining loess soils,
- Loess soils with a basal capillary fringe; and,

- Free draining Touchet Beds.

Consideration of the second condition is required because the fine-grained texture of loess soils is expected to cause a significant capillary rise above an underlying water table, and similar accumulation of moisture above coarser-grained unsaturated sediments. This condition is likely to be more common than the free-draining condition for loess soils, although a free-draining condition could occur where loess overlies fine-grained sediments. Touchet Beds would also contain a basal capillary fringe over a water table or moisture accumulation over coarse-grained sediments; however, the thickness of capillary rise is expected to be less than for loess soils, and is not considered in this analysis.

PGG did not attempt quantitative assessment of recharge movement through unsaturated portions of the CRB's. Where this condition occurs, downward unsaturated flow of irrigation recharge would pass through unsaturated sequences of basalt interflow zones (rubbly basalt flow tops and bottoms), sedimentary interbeds, and tight fractures within dense basalt flow cores. Based on these conditions and the texture of overlying (unsaturated) sediments in the suprabasalt deposits, we expect that the timing of irrigation recharge reaching a water table within the CRB would be highly damped (insignificant seasonal variation). Unsaturated Saddle Mountain Basalts occur in eastern portions of the study area (Packard et al, Figure 8) which is covered by surficial loess (main report **Figure 3-2**).

3.1 VADOSE ZONE HYDRAULIC PROPERTIES

Hydraulic properties for vadose zone textures were represented using the methods of van Genuchten (1980) and Mualem (1976). Van Genuchten's method employs a variety of "fitting parameters" (e.g. θr, θs, α, n, m[1]) to represent the soil moisture characteristic curve. Mualin's method scales the unsaturated hydraulic conductivity to the saturated hydraulic conductivity (Ksat) and the shape of the soil moisture characteristic curve.

The hydraulic properties of loess soils in the Horse Heaven Hills were recently estimated based on field and laboratory measurements performed by Flurry and Sing (2011). These researchers performed grain-size analysis on 16 loess samples and field/laboratory hydraulic testing on 11 loess samples from two sites in the Horse Heaven Hills. Their measurements, as summarized on **Table H-1**, show relatively tight groupings of sand/silt/clay ratios and estimated hydraulic properties. Based on these groupings, PGG defined three parameter groups for representing the range of loess soil properties in the Hydrus model (below). The only parameter varied between groups was the saturated hydraulic conductivity (Ksat), as the other parameters should relatively less variation.

	Residual Theta θr	**Saturated Theta θs**	**Alpha α**	**n**	**Ksat**
	(cm3/cm3)	*(cm3/cm3)*	*(1/cm)*	*(no unit)*	*(cm/day)*
Central Value	0.0508	0.48949	0.00764	1.87205	50
Upper End Value	0.0508	0.48949	0.00764	1.87205	125
Lower End Value	0.0508	0.48949	0.00764	1.87205	10

[1] The parameters θr and θs represented residual and saturated water content. The parameters α, n, m are shape fitting parameters for the soil moisture retention curves.

As noted in the main report, textural and hydraulic characterization of the Touchet Beds in the Horse Heaven Hills is largely unavailable. Touchet Bed textures are expected to vary based on the specific conditions of deposition. PGG characterized a range of Touchet Bed textures and hydraulic properties in our vadose zone analysis for the Walla Walla study area (**Appendix K**). A "best estimate" set of hydraulic parameters was estimated for the Touchet Bed (layered rhythmite) deposits, as were coarser-grained and finer-grained end members ("fine sand" and "silty", respectively). This same range of textures was applied to Hydrus analysis of irrigation recharge in the Horse Heaven Hills study area. While it is likely that the hydraulic properties of the local Touchet Beds fall somewhere within this range, PGG does not have sufficient information to narrow this estimate down further.

3.2 HYDRUS MODEL SETUP

For simulation of free-draining loess soils, Hydrus-1D was used to simulate a 13-meter thick soil profile. Flux input at the top of the Hydrus model included RH2's monthly deep percolation estimates (shown above). The bottom boundary condition was specified as "free draining". The 13-meter model domain was discretized into 1.3-cm elements (1000 cells), and the annual recharge cycle was run 50 times back-to-back to ensure that the Hydrus model was in equilibrium with the irrigation recharge from year to year (a condition PGG refers to as "cyclic steady-state"). Hydrus automatically selects time-step discretization within a user-defined range to maintain model stability and accuracy. Hydrus simulation of free-draining Touchet Beds differed from above only in that a 10-meter model domain was discretized into 1-cm elements. Specification of soil hydraulic properties followed the loess parameters summarized above and the Touchet Bed parameters discussed in **Appendix K**.

For the "capillary fringe" simulations, the lower boundary condition at the base of the modeled soil column was set at a constant pressure head value of zero corresponding to a constant (atmospheric) water table condition at the bottom of the model.

3.3 HYDRUS MODEL RESULTS AND INTERPRETATION

Hydrus-1D results for 13 meters of free-draining loess soils under current (pre-conservation) conditions are shown on **Figures H-1** and **H-2**. The Hydrus predictions show increased lagging and damping of the timing of the recharge pulse moving through the vadose zone as a function of depth. PGG defined the "damping factor" as "1-R", where R is the ratio of the flux range predicted at depth in the vadose zone to the flux range specified for irrigation recharge (e.g. 100 percent damping indicates a constant flux with no seasonal variation). For the "central value" representation of the loess soils, significant (77%) damping is predicted at a free draining depth of 4 meters, and the recharge pulse is predicted to be 100% damped at a free draining depth of 13 meters. Damping and lagging are decreased with the "upper end" group of loess hydraulic parameters and increased with the "lower end" group. **Table H-2** summarizes damping and lagging predictions for the free draining loess.

Hydrus-1D results for 10 meters of free-draining Touchet Beds under current (pre-conservation) conditions are shown on **Figure H-2**. Similar to above, the Hydrus predictions show increased lagging/damping with depth. While vadose-zone retiming is likely to occur within the range of curves defined by the "fine-sand", "layered" and "silty" representations of the Touchet Beds, the lack of available local characterization of soil texture and hydraulic properties prevents PGG

from suggesting a "most likely" retiming estimate. Nevertheless, the predicted retimed irrigation pulse is considerably damped (71%-94%) for all textural representations at a depth of 10 meters and moderately damped (44%-82%) at a depth of 6 meters (**Table H-2**).

PGG conducted capillary simulations to evaluate the effect of the capillary fringe on the timing of recharge transmission through the vadose zone. Increasing water content with depth through the capillary zone increases the rate at which pulses of irrigation recharge migrate downward through the vadose zone. Timing was investigated by running a series of Hydrus-1D configurations with soil profile thicknesses ranging from 1 to 14 meters over a "water table" boundary condition at the bottom of the model profile. The effect of the capillary fringe on the timing or water transmission in the vadose zone was evaluated by comparing fluxes at observation points at discrete heights above the water table within the capillary fringe simulations and between the capillary fringe and the free-draining simulations. Hydrus model runs consistently indicated that the vertical flux at observation points within 4 meters of the water table differed between the capillary-fringe and the free-draining results. Additionally, *within* the capillary model simulations, predicted fluxes at observation points within 3 meters of the water table were nearly identical. For example, for a simulation of a 7 meters deep water table in loess soils, the flux curves for the 4-, 5- and 6-meter observation points were nearly identical (**Figure H-3**). These observations suggest that once percolating water reached 4m above the water table, the remaining transmission to the water table was rapid and retiming was negligible. Capillary zone height was independent of the depth to water, was independent of the loess Ksat values listed above, and was consistent within the range of modeled recharge. Model results above 4m above the water table were similar to free draining model results (**Table H-2**). It is therefore assumed that throughout the loess portion of the Horse Heaven Hills no retiming benefit occurs where a water table exists within 4m of ground. This is a conservative approach to addressing damping in the vadose zone because it does not include the modest damping and retiming from the upper portions of the capillary zone.

Based on the results described above, PGG adopted the conservative assumption that the lower 4m of vadose zone provides no retiming of infiltrating recharge where saturated conditions are present in loess soils. This assumption allows all vadose zone retiming to be estimated from a single free-draining model rather than modeling the flux for each depth to saturation explicitly by subtracting 4m from the assumed depth to the water table. It should be noted that a similar moisture buildup of capillary fringe is expected where fine-grained loess deposits overlie substantially coarser grained sediments.

4.0 CRB GROUNDWATER FLOW MODELING

PGG evaluated the timing of subsurface return flow through the CRB's by developing a MODFLOW model representing a north-south vertical slice through the CRB flow system between the Horse Heaven Hills anticline and the Columbia River (a distance of approximately 20 miles). The "slice model" employs CRB aquifer properties (Kh, anisotropy, S and saturated thickness) based on model calibration by Packard et al (1994). The slice model configuration has several conservative features that will tend to under-predict lagging and damping relative to the Packard model:

- Irrigation recharge can only propagate linearly from the irrigated area to the river (rather than radially outward from the irrigated area).

- The slice model does not include any low permeability barriers to groundwater flow associated with structural features such as faults.
- Recharge input to the slice model does not include retiming from the vadose zone. For the purpose of this analysis, recharge from the deep percolation schedule developed by RH2 (above) was input to the model.

The slice model, however, does omit some local aquifer property variations represented in the Packard model. This may result in localized areas where the slice model will over-predict lagging/damping relative to the Packard model. The "slice model" also employs greater vertical discretization (more layers) than the Packard model. Packard represents each major basalt unit (Saddle Mountains, Wanapum and Grande Ronde) as single layers, with anisotropy identified *between* the major units rather than *within* them. PGG's model configuration represents anisotropy *within* the major basalt units. However, PGG performed a sensitivity simulation without anisotropy in the Saddle Mountains Basalt, and showed that these two different representations of anisotropy had insignificant effects on model predictions.

The slice model was run to estimate the timing of groundwater discharge to the Columbia River from a 1-acre application of irrigation located 1 mile away. The model indicated highly damped return flow to the Columbia River (damping factor = 98%). Damping will increase with increased distance from the river.

Modeling was performed using the USGS numerical code MODFLOW 2000 (Harbaugh et al, 2000); and with Groundwater Vistas (ESI, 2011) as the graphical user's interface. The following sections describe the model design and predictive simulations.

4.1 DOMAIN AND DISCRETIZATION

The model domain covers a 20 mile wide "slice" of the CRB flow system between the Horse Heaven Hills anticline (a natural groundwater divide) and the Columbia River. The slice is 1000 feet wide (an arbitrary value that doesn't effect model predictive results) and 1200 feet thick. It represents both the Saddle Mountains Basalt (300 feet saturated thickness) and the Wanapum Basalt (900 feet saturated thickness).

Figure H-4 shows the grid of the slice model. The model includes 18 layers: the top 6 layers are all 50 feet thick and collectively represent the Saddle Mountains Basalt; the bottom 12 layers transition from 50 to 100 feet thick and represent the Wanapum Basalt. All layers are simulated as "confined", which makes the model mathematically linear and assumes that the single application of irrigation recharge simulated during predictions does not significantly change the saturated thickness of the CRB's. The single model row is 1000 feet thick (as noted above), and spacing of the 100 model columns ranges from 500 feet near the Columbia River to 1000 feet near the axis of the anticline.

4.2 AQUIFER PROPERTIES

Aquifer properties in the slice model were based on calibrated aquifer properties from Packard et al (1994). Specifically:

- Packard's Figure 8 shows that the saturated thickness of the Saddle Mountains and Wanapum Basalts are reasonably represented at 300 and 900 feet in the FCD study area (eastern portion of the USGS model domain). The Saddle Mountains Basalt is unsaturated in some areas, and PGG ran a supplemental model run to assess this condition. However, as noted above, significant damping of the recharge pulse is expected within unsaturated portions of the basalt.
- Packard's Figure 23 shows that large regions of the FCD study area are represented with horizontal hydraulic conductivity (Kh) values of 10^{-5} ft/sec (0.9 ft/d).
- Packard's Figure 19 shows that large regions of the the FCD study area are represented with vertical hydraulic conductivity (Kv) values of 10^{-7} and 10^{-9} ft/sec between the Saddle Mountains and Wanapum aquifers, thus leading to anisotropy values of 100 to 10,000. One area is represented as 10^{-6}-10^{-7} ft/sec. Packard also notes an anisotropy (Kh/Kv) of 160 between the Saddle Mountains and Wanapum basalts, and 500 between the Wanapum and Grande Ronde basalts.
- Packard states that model calibration produced storage coefficient (S) values of 0.01 to 0.03 for the Saddle Mountains Basalt and 0.001 for the Wanapum Basalt.

Aquifer properties specified for the slice model are summarized below.

	Saddle Mountains Basalt	Wanapum Basalt
Kh	0.9 ft/d	0.9 ft/d
Kh/Kz	400	400
Saturated Thickness	300 ft	900 ft
S	.02	.001

Several additional configurations were simulated to assess the sensitivity of the model to the values/assumptions listed above. These "sensitivity simulations" are discussed in Section 3.4.

4.3 BOUNDARY CONDITIONS

Boundary conditions employed in the model include constant head cells for the Columbia River and a specified flux cell for addition of irrigation recharge to the top layer of the model at a distance of one mile from the river (**Figure H-4**). The river is represented as constant head cells in all model layers (full penetration), although PGG performed a supplemental simulation where the river penetrates only the Saddle Mountains Basalt (as suggested by geologic mapping). Values of constant head (and initial heads for model simulations) were set to the top elevation of the model.

4.4 MODEL RESULTS

PGG ran the model as described above and model results predicted 99% damping of the irrigation recharge pulse over the one-mile distance between a hypothetical site and the Columbia River (**Figure H-5**). Additional damping is expected due to retiming in the vadose zone, which is not included in the slice model simulation, and at greater distances from the river.

In order to assess the influence of some of the simplifying assumptions used in the model design, PGG ran the following supplemental model simulations:

1) The Saddle Mountains Basalt was assigned an anisotropy of 160 rather than 400 (160 was stated in Packard et al's characterization, whereas model calibration includes numbers ranging from 100 to 10,000).
2) The Columbia River represented as partially penetrating in model layers 1 through 6 (Saddle Mountains Basalt) rather than fully penetrating both basalt units. This depiction is more consistent with geologic mapping.
3) The Saddle Mountains Basalt was assigned an anisotropy of 1 rather than 400 in order to force the effective anisotropy to occur *between* the Saddle Mountains and Wanapum basalts rather than *within* the Saddle Mountains Basalt. This evaluation was performed because PGG's model divides the Saddle Mountains Basalt into 6 layers (rather than 1 layer in the Packard model). Anisotropy within the 6-layer representation could tend to prevent the recharge pulse from penetrating into the full thickness of the unit. Furthermore, Packard's aquifer property values were calibrated based on no resistance to flow within the entire aquifer unit.

All three supplemental simulations showed the same results as the primary simulation. In areas where the Saddle Mountains Basalt is fully unsaturated (eastern portion of model domain), significant vadose zone damping is expected within the Saddle Mountains Basalt. The model would predict significantly less damping if RH2's schedule of deep percolation were "injected" directly to the Wanapum Basalt (due to its lower storage coefficient of 0.001 rather than 0.02); however, this scenario is considered unrealistic due to the overlying suprabasalt and basalt vadose zone.

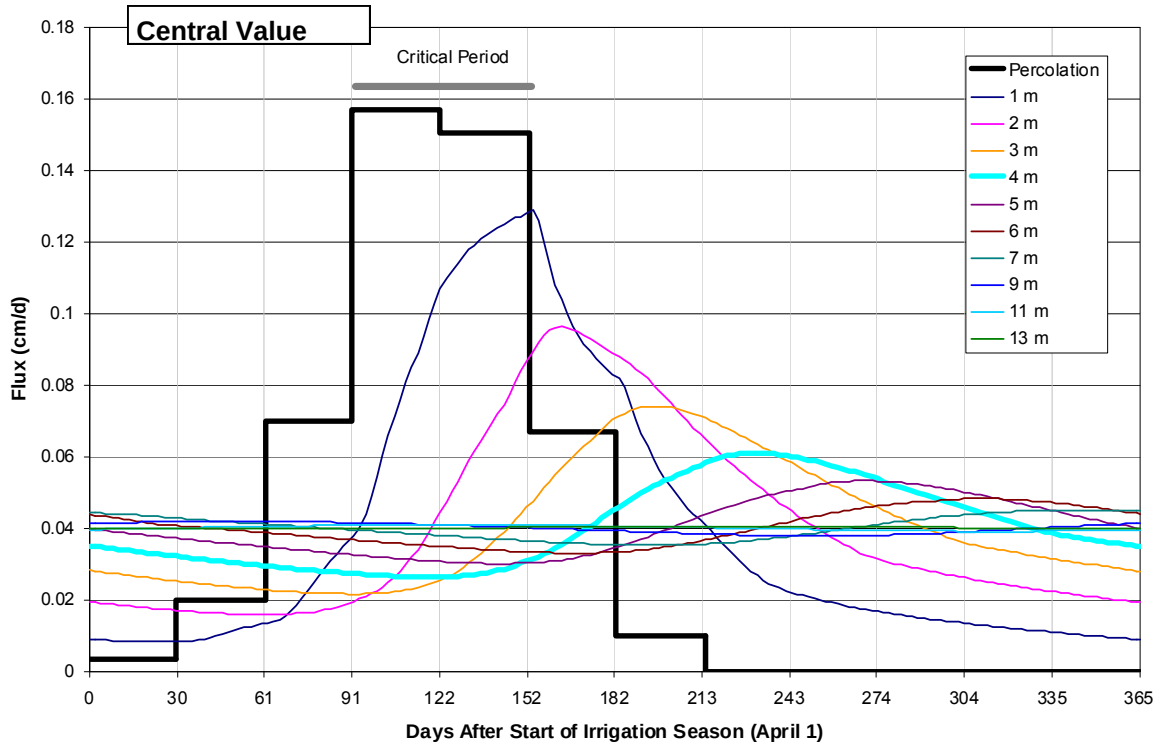
Table H-1 Textural and Hydraulic Properties of Loess Soils in the Horse Heaven Hills
(Flurry and Singh, 2011)

Description	Depth	Sand	Silt	Clay	Bulk Density	Theta (Resid)	Theta (Sat)	Alpha	N	Ksat (lab)	Ksat (field)
	cm	*%*	*%*	*%*	*gr/cm3*	*cm3/cm3*	*cm3/cm3*	*(1/cm)*	*(no unit)*	*cm/d*	*cm/d*
East Site Conv Till Ap (dust mulch)	0-15	56	31	13	1.08	0.06	0.57	0.0081	2.08	94	123
East Site Conv Till A	15-30	55	31	14	1.26	0.04	0.52	0.0084	1.80	nr	8
East Site Conv Till B1	30-40	58	28	14	1.28	0.07	0.51	0.0076	2.06	nr	44
East Site Conv Till B2	50-70	57	30	13	nr	nr	nr	nr	nr	nr	nr
East Site Fallow A1	0-15	57	29	14	1.26	0.04	0.52	0.0089	1.76	77	29
East Site Fallow A2	15-30	54	31	15	1.3	0.06	0.50	0.0076	1.99	nr	nr
East Site Fallow B1	30-40	56	30	14	1.24	0.06	0.52	0.0077	1.99	92	44
East Site Fallow B2	50-70	56	32	12	nr	nr	nr	nr	nr	nr	nr
West Site Conv Till Ap (dust mulch)	0-15	51	32	18	1.26	0.05	0.50	0.0087	1.95	57	21
West Site Conv Till A	15-30	47	35	18	1.38	0.05	0.47	0.0084	1.83	37	15
West Site Conv Till B1	30-40	51	33	16	1.44	0.05	0.44	0.006	1.77	38	30
West Site Conv Till B2	50-70	56	32	12	nr	nr	nr	nr	nr	nr	nr
West Site Fallow A1	0-15	51	30	19	1.31	0.05	0.49	0.0079	1.97	57	7
West Site Fallow A2	15-30	50	32	18	1.38	0.05	0.47	0.0072	1.94	30	84
West Site Fallow B1	30-40	53	32	15	1.42	0.03	0.46	0.0067	1.62	27	43
West Site Fallow B2	50-70	65	25	10	nr	nr	na	na	na	nr	nr
					average	0.051	0.50	0.0078	1.90	56.56	40.73
									max	94	123
									min	27	7
									count	9	11

Table H-2 Vadose Zone Retiming Estimates for the Horse Heaven Hills Study Area

Loess Soils											
Capillary Fringe Depth		*5 m*	*6 m*	*7 m*	*8 m*	*9 m*	*10 m*	*11 m*	*13 m*	*15 m*	*17 m*
Free Draining Depth		*1 m*	*2 m*	*3 m*	*4 m*	*5 m*	*6 m*	*7 m*	*9 m*	*11 m*	*13 m*
Central Value	damping	22%	48%	66%	77%	85%	90%	94%	97%	99%	100%
	lag (days)	32	42	74	108	144	182	214	285	347	453
Upper End	damping	18%	39%	58%	70%	79%	85%	89%	95%	97%	99%
	lag (days)	30	36	56	84	112	144	174	228	279	379
Lower End	damping	30%	63%	80%	89%	93%	96%	98%	99%	100%	100%
	lag (days)	34	70	108	156	214	265	311	407	509	608
Touchet Beds											
Free Draining Depth		*1 m*	*2 m*	*3 m*	*4 m*	*5 m*	*6 m*	*7 m*	*8 m*	*9 m*	*10 m*
Layered	damping	8%	18%	39%	55%	63%	70%	75%	78%	82%	84%
	lag (days)	30	38	60	98	132	164	196	228	265	301
Fine Sand	damping	6%	10%	18%	27%	36%	44%	51%	58%	65%	71%
	lag (days)	2	32	44	62	82	102	124	146	170	196
Silty	damping	13%	37%	55%	67%	76%	82%	87%	90%	92%	94%
	lag (days)	32	44	82	120	160	200	228	277	319	355

Note: smaller lag values (e.g. < 90 days) are less accurate due to lack of a well defined peak in irrigation recharge at the land surface.



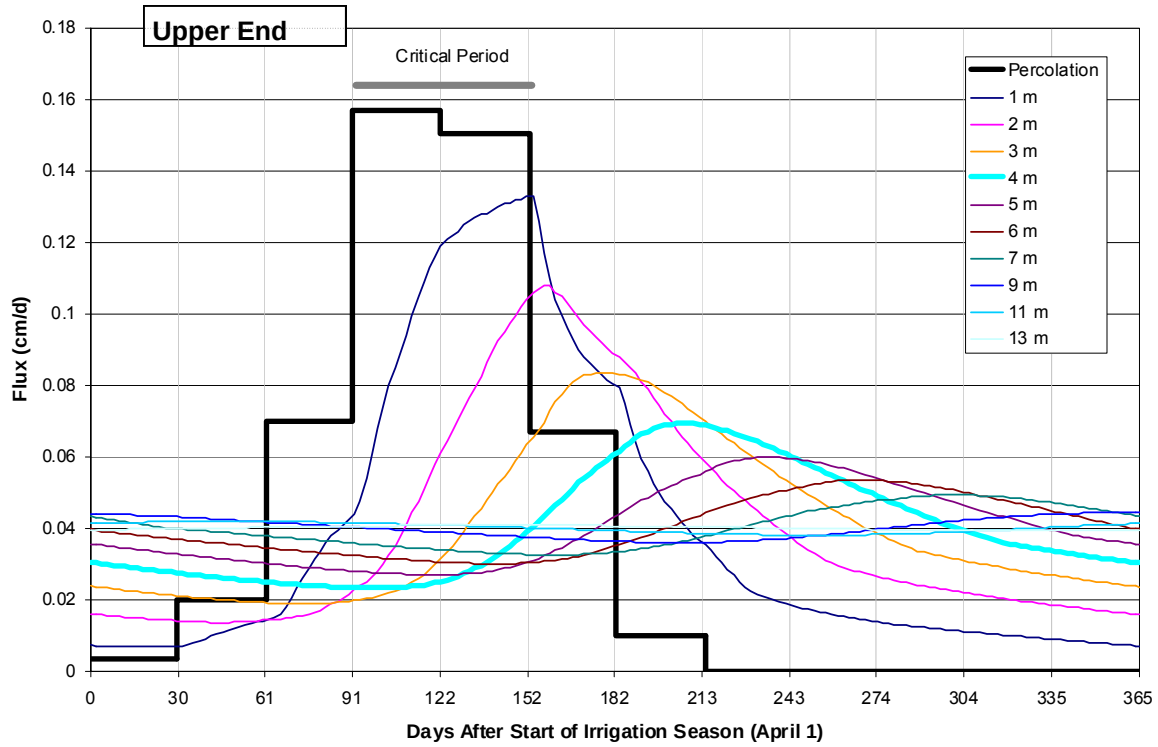
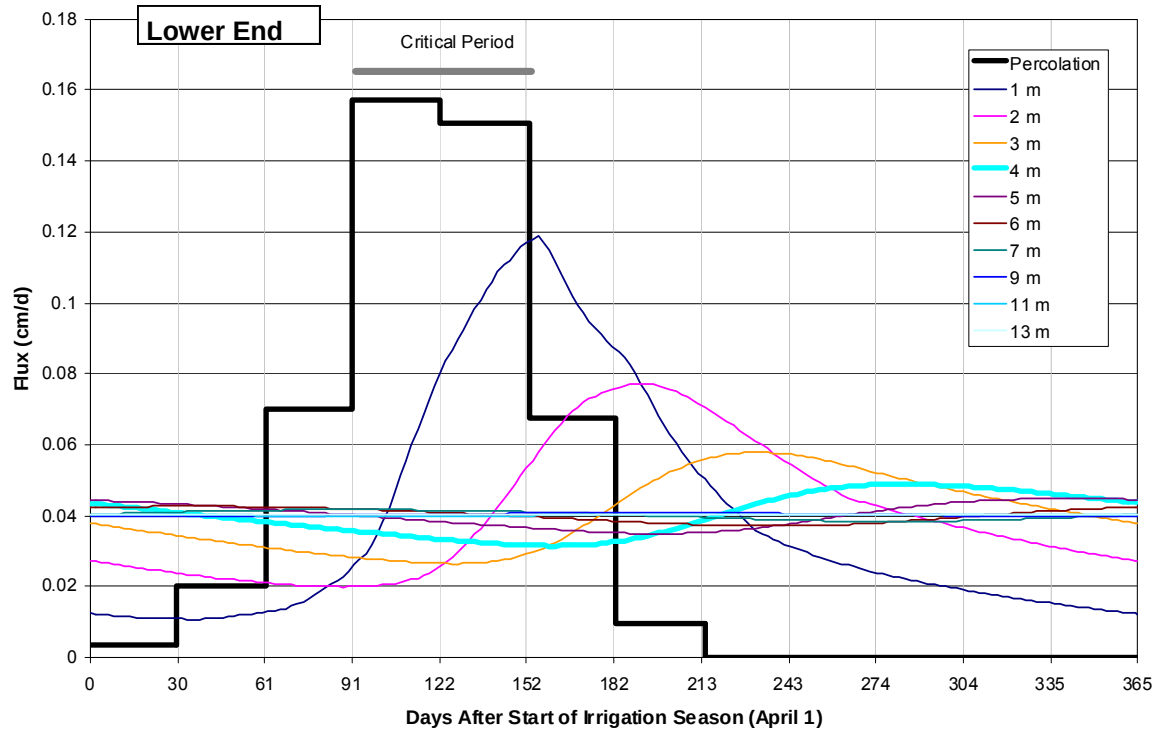


Figure H-1
Vadose Zone Flow Thru Several Representations of Loess

Franklin Conservation District
Retiming Benefits Analysis

PgG



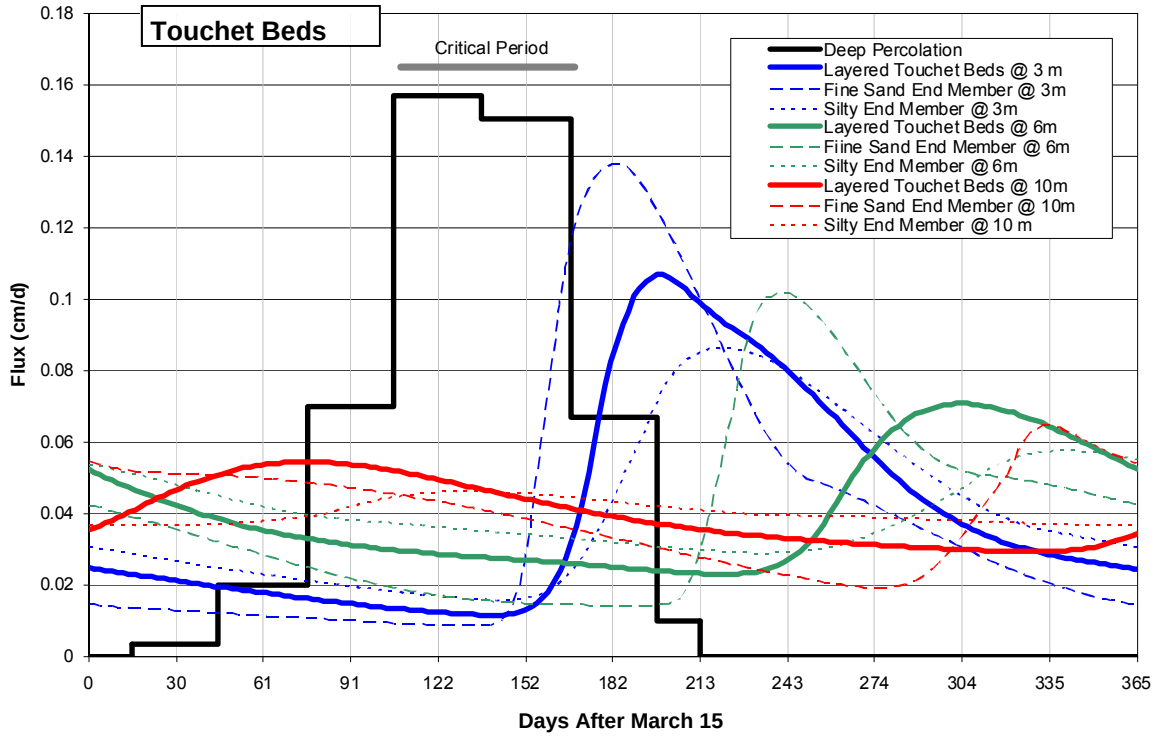


Figure H-2
Vadose Zone Flow Thru "Lower End" Loess and Touchet Beds

Franklin Conservation District
Retiming Benefits Analysis

PgG

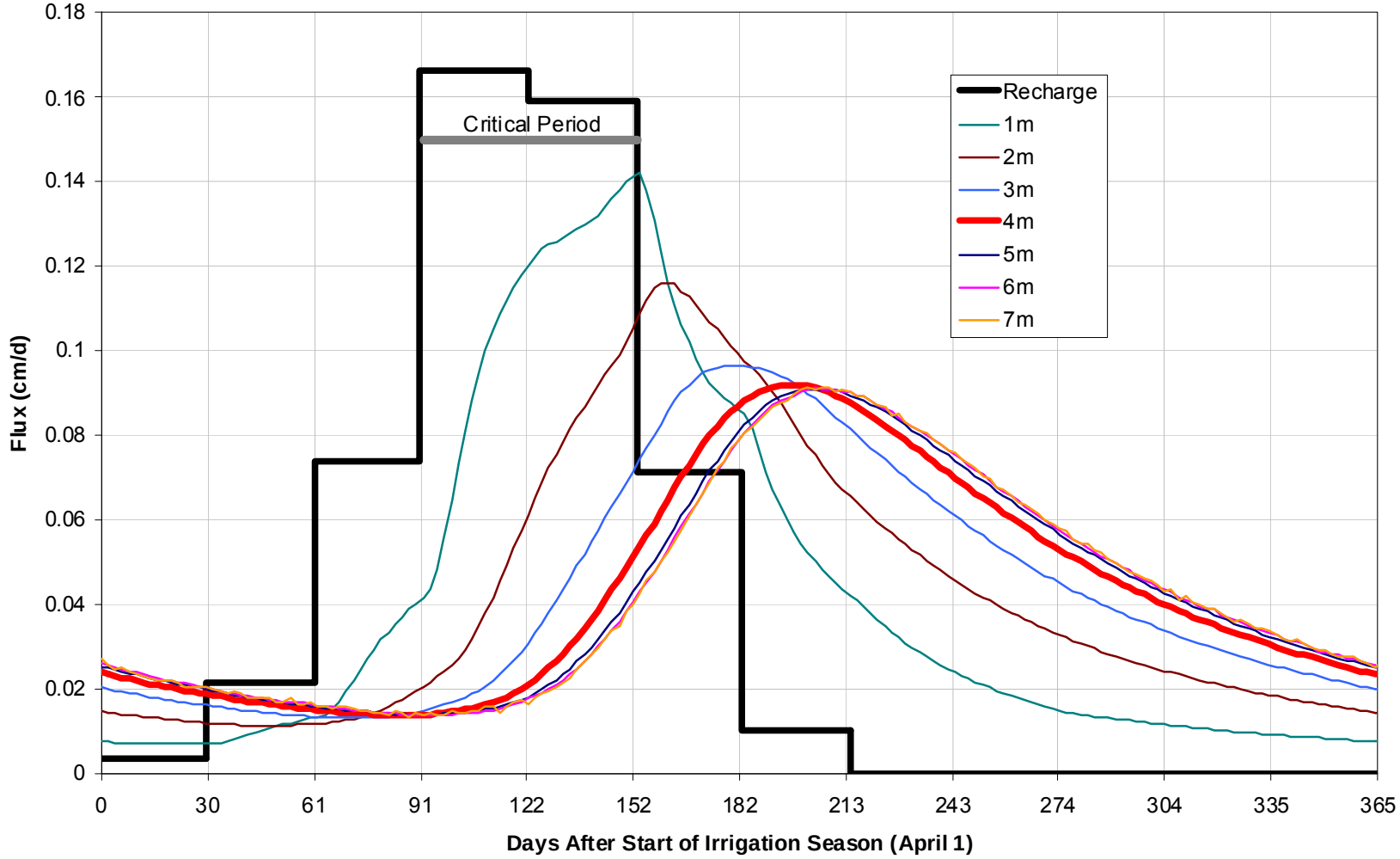


Figure H-3
Hydrus "Capillary" Predictions with Water Table Boundary Condition at 7 Meters

Franklin Conservation District
Retiming Benefits Analysis

PgG

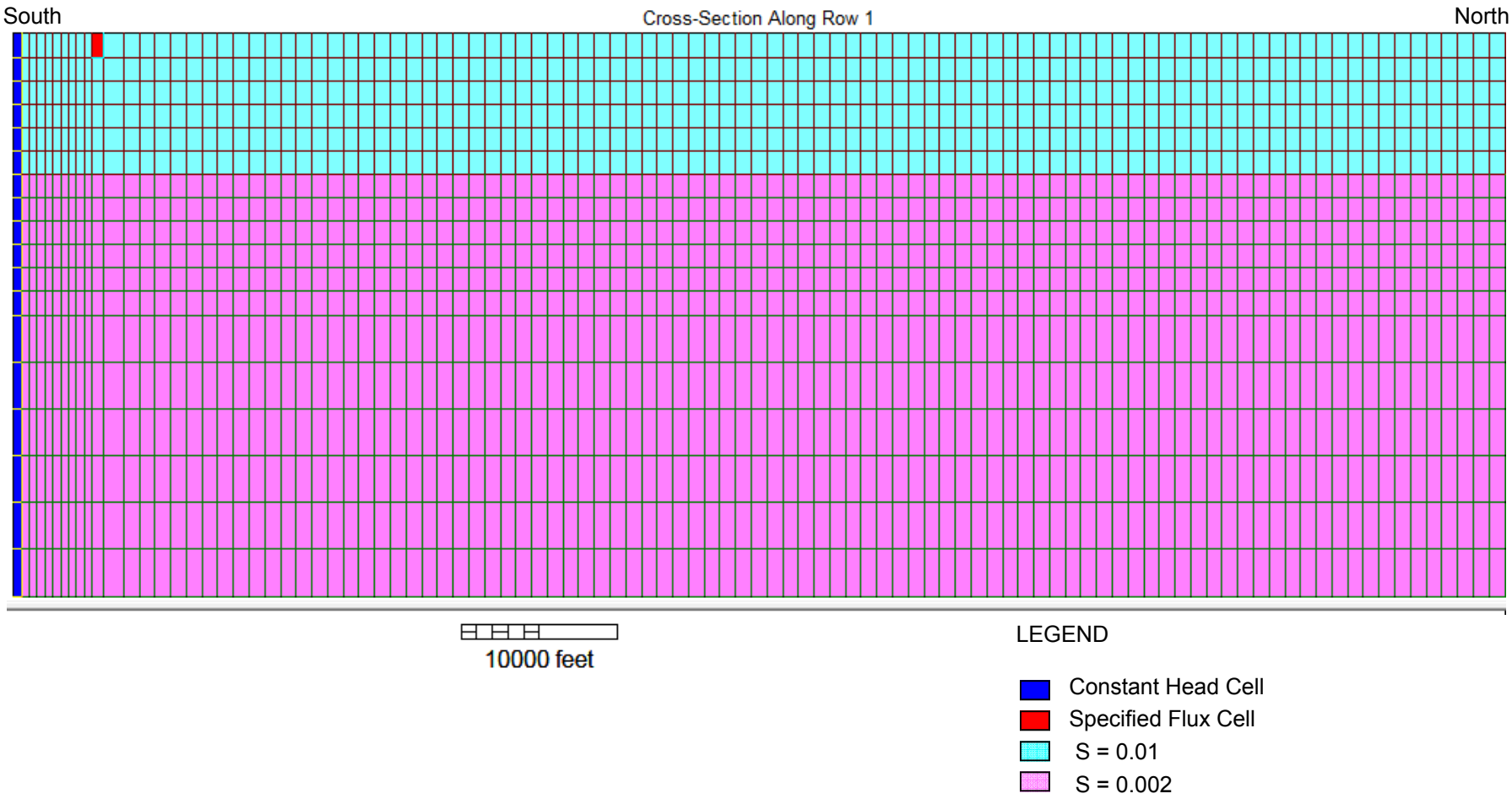


Figure H-4
Horse Heaven Hills Slice Model Grid, Properties and Boundary Conditions

Franklin Conservation District
Retiming Benefits Analysis

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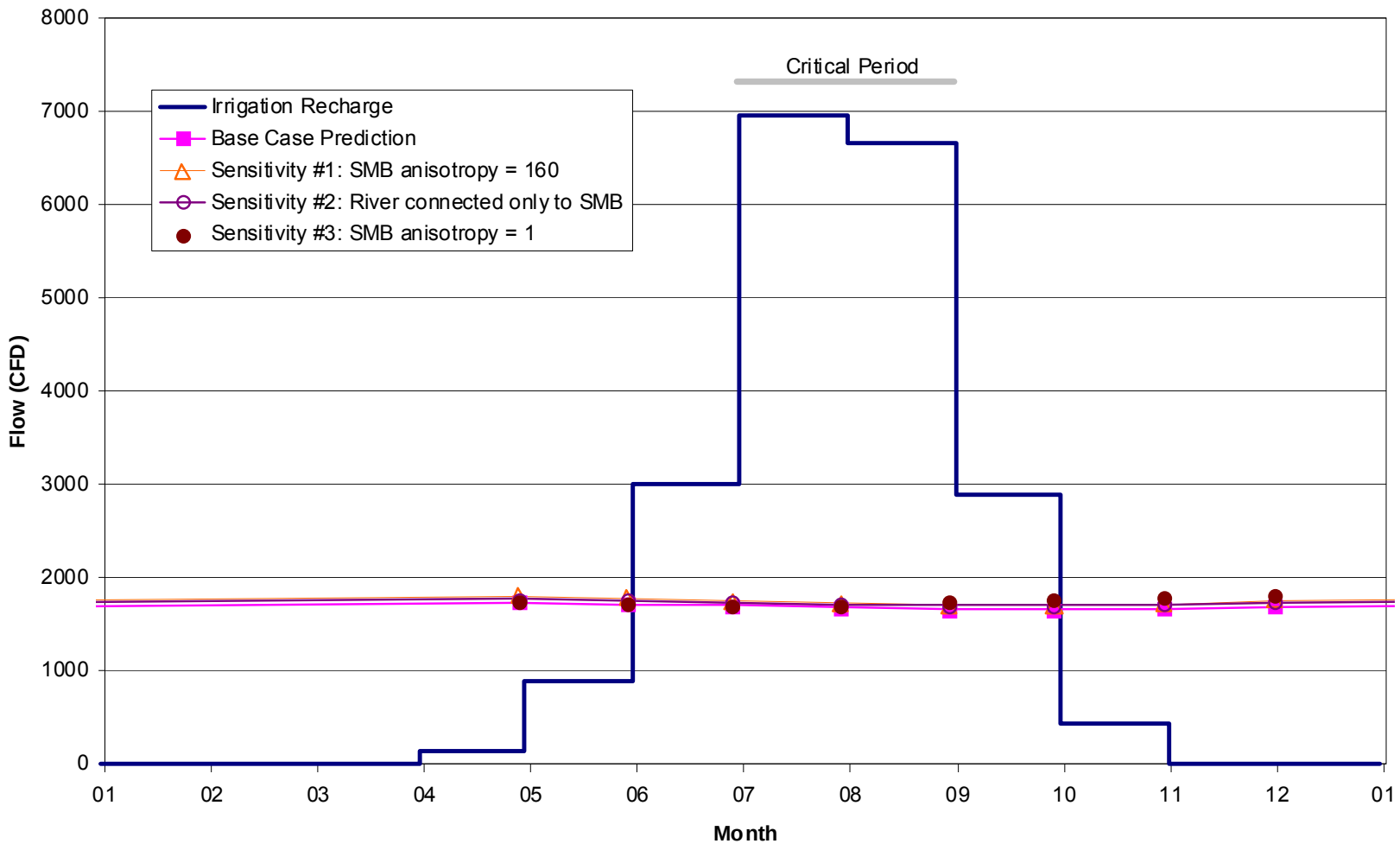


Figure H-5
Horse Heaven Hills Slice Model Predictions and Sensitivity Analysis

Franklin Conservation District
Retiming Benefits Analysis

PgG

APPENDIX I
DOCUMENTATION OF VADOSE-ZONE MODELING FOR SFC QUATERNARY PROVINCE

February 2012

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 IRRIGATION RECHARGE 1

3.0 VADOSE ZONE MODELING 2

3.1 VADOSE ZONE HYDRAULIC PROPERTIES 3
3.2 HYDRUS MODEL SETUP 4
3.3 HYDRUS MODEL RESULTS AND INTERPRETATION 4

1.0 INTRODUCTION

This appendix describes the approaches used to model the timing of the seasonal irrigation "recharge pulse" associated with field applications from the root zone through the vadose zone (between the root zone and the water table). The analysis employs a water budget approach to estimate irrigation recharge and numerical models to evaluate flow in the vadose zone. The analysis is applied to three hypothetical sites within the Quaternary Province of the Southern Franklin County study area: "Block 1", "Block 17", and "Greenbelt".

2.0 IRRIGATION RECHARGE

Deep percolation losses under current (pre-conservation) conditions vary for each hypothetical conservation site. Monthly estimates of current (2009) pre-conservation irrigation applications and losses were prepared by RH2 for each hypothetical site based on the methods outlined in **Appendices A** and **B**. Under current conditions, RH2 assumed that:

- Block 1 employs 70.4% center pivot (35% LEPA), 19.6% sprinkler methods (hand line, wheel line, and solid set), and 10% rill;
- Block 17 employs 78.2% center pivot (35% LEPA), 21.8% sprinkler methods (hand line, wheel line, and solid set), and no rill;
- The Greenbelt employs 90% center pivot (35% LEPA), 10% sprinkler methods (hand line, wheel line, and solid set), and no rill.

RH2 also prepared monthly estimates of post-conservation applications and losses for the entire SFC study area. Deep percolation for the post-conservation condition was based on the same final irrigation method at all sites (center pivot with LEPA and IWM), and was assumed to be zero to illustrate the maximum theoretical conservation effect. In actuality, a small amount of deep percolation is expected for the post-conservation condition. Post-conservation deep percolation return flows are expected to have just a small impact on estimated retiming benefits. Once actual pilot sites are selected and actual pre-conservation and post-conservation methods are identified, PGG's analysis can be refined for actual (rather than hypothetical) conditions.

The following tables summarize RH2's pre-conservation and post-conservation irrigation applications and losses for all three sites:

Block 1 Pre-Conservation

(All values in af/ft)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Crop Requirement	0.000	0.000	0.013	0.092	0.417	0.574	0.751	0.592	0.330	0.109	0.000	0.000	2.878
SW Runoff	0.000	0.000	0.000	0.002	0.010	0.014	0.018	0.014	0.008	0.003	0.000	0.000	0.071
Evaporation	0.000	0.000	0.002	0.012	0.055	0.076	0.099	0.078	0.043	0.014	0.000	0.000	0.379
Total Deep Percolation	0.000	0.000	0.003	0.023	0.103	0.141	0.185	0.145	0.081	0.027	0.000	0.000	0.707
Total Application	0.000	0.000	0.016	0.114	0.513	0.705	0.923	0.727	0.405	0.134	0.000	0.000	3.537

Block 17 Pre-Conservation

(All values in af/ft)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Crop Requirement	0.000	0.000	0.013	0.092	0.417	0.574	0.751	0.592	0.330	0.109	0.000	0.000	2.878
SW Runoff	0.000	0.000	0.000	0.001	0.005	0.008	0.010	0.008	0.004	0.001	0.000	0.000	0.038
Evaporation	0.000	0.000	0.002	0.013	0.057	0.078	0.102	0.081	0.045	0.015	0.000	0.000	0.393
Total Deep Percolation	0.000	0.000	0.003	0.021	0.094	0.129	0.169	0.133	0.074	0.025	0.000	0.000	0.649
Total Application	0.000	0.000	0.016	0.111	0.502	0.690	0.902	0.711	0.397	0.131	0.000	0.000	3.459

Greenbelt Pre-Conservation

(All values in af/ft)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Crop Requirement	0.000	0.000	0.013	0.092	0.417	0.574	0.751	0.592	0.330	0.109	0.000	0.000	2.878
SW Runoff	0.000	0.000	0.000	0.001	0.004	0.006	0.008	0.006	0.003	0.001	0.000	0.000	0.030
Evaporation	0.000	0.000	0.002	0.012	0.056	0.077	0.101	0.079	0.044	0.015	0.000	0.000	0.386
Total Deep Percolation	0.000	0.000	0.003	0.020	0.089	0.123	0.161	0.127	0.071	0.023	0.000	0.000	0.615
Total Application	0.000	0.000	0.016	0.110	0.495	0.680	0.890	0.701	0.391	0.129	0.000	0.000	3.412

Post-Conservation (All Locations)

(All values in af/ft)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Crop Requirement	0.000	0.000	0.011	0.076	0.345	0.475	0.621	0.489	0.273	0.090	0.000	0.000	2.380
SW Runoff	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Evaporation	0.000	0.000	0.001	0.004	0.018	0.025	0.033	0.026	0.014	0.005	0.000	0.000	0.125
Total Deep Percolation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Application	0.000	0.000	0.011	0.080	0.363	0.500	0.654	0.515	0.287	0.095	0.000	0.000	2.505

Deep percolation for the months of March and October were assumed to occur in the second and first half of these months (respectively), based on a 7-month irrigation season from March 15 through October 15. RH2's monthly deep percolation estimates were converted into average daily rates, and used as input for evaluation of the vadose zone.

3.0 VADOSE ZONE MODELING

PGG used the variably saturated, finite-element model "Hydrus-1D" (Simunek et al, 2008) to simulate movement of the irrigation recharge pulse from field applications through the vadose zone. The thickness and texture of the vadose zone for each of the three sites was represented as:

- 155 feet (47 meters) of gravel at the Block 1 Site
- 105 feet (32 meters) of sandy gravel at the Block 17 Site
- 65 feet (20 meters) of sandy gravel at the Greenbelt Site

The above vadose-zone thicknesses were based on depths to the water table, as shown in **Figure 4-3** of the main report. (Note that Hydrus-1D requires that all calculations are performed in the metric system, so that this discussion employs units of centimeters and meters.) As noted in Section 4.2.2 of the main report, the Pasco gravels are dominated by sandy gravels, gravelly sands and coarse sands. However, some areas of the Pasco gravels exhibit higher gravel contents (e.g. locations along the Columbia River and paleo-channels of the Missoula floods). Sedimentary facies mapping performed for the GWMA suggests that Block 1 occurs in a particularly gravelly location (Section 4.2.5 of the main report).

The following sections describe the hydraulic properties used to represent "sandy gravel" and "gravel" discussed above, modeling procedures for simulating transmission of the irrigation re-

charge pulse through the vadose zone, and model results for current, pre-conservation irrigation recharge (post-conservation recharge was not modeled due to the assumed zero value).

Although not addressed in this appendix, it should be noted that recharge transmission through the vadose zone will differ beneath irrigated fields and irrigation conveyances. The lower rates of irrigation recharge associated with fields are expected to concentrate flow within the sandy fractions of the Pasco Gravels, thus allowing for damped transmission of the recharge pulse. Higher rates of recharge, such as leakage from an *unlined* wasteway, can cause higher saturation and/or preferential flow through gravelly zones, both leading to more rapid transport of irrigation recharge from the land surface to the water table. This prediction is consistent with observed correlations between sedimentary textures and vadose zone flow dynamics at the Hanford reservation (personal communication, Ward 2011). Vadose zone transmission of seepage losses from *lined* conveyances will vary based on the associated rate of leakage.

3.1 VADOSE ZONE HYDRAULIC PROPERTIES

Hydraulic properties for vadose zone textures were represented using the methods of van Genuchten (1980) and Mualem (1976). Van Genuchten's method employs a variety of "fitting parameters" (e.g. θr, θr, α, n, m) to represent the soil moisture characteristic curve. Mualin's method scales the unsaturated hydraulic conductivity to the saturated hydraulic conductivity (Ksat) and the shape of the soil moisture characteristic curve.

The hydraulic properties of the Pasco gravels were evaluated and characterized in great detail at the Hanford site (across the river from the SFC study area). The "Hanford gravels" were deposited under the same conditions as the Pasco gravels, and are therefore considered to be a good representation of Pasco gravel textures and properties. **Table I-1** presents a summary of Hanford gravel textural classes and associated hydraulic properties (Last et al, 2006). The textural classes were based on grain-size analysis of 286 samples taken from 17 sites across the Hanford reservation. It should be noted that the "gravel" unit ("Hrg" on **Table I-1**, >60% gravel) is not common among the samples evaluated, and is noted as primarily occurring along the Columbia River in the "100 Areas". Based on descriptions of textural classes within the Hanford gravels, PGG considers use of the "Hrg" to be appropriate for Block 1 (close to the Columbia River), and use of "Hg" (sandy gravels, <60% gravel) to be appropriate for Block 17 and the Greenbelt (more distant from the river). Hrg will provide the most rapid flow transmission of any of the Hanford textural classes, and while appropriate for near-river gravelly facies, would not be appropriate for the sandier sediments that make up the bulk of the Hanford gravels. Hg will provide the most rapid flow transmission of all the remaining textural classes defined at Hanford for the Block 17 and Greenbelt sites.

The hydraulic properties (van Genuchten parameters) of the various textural classes evaluated at Hanford are corrected for gravel content, so they can be used "as-is" for vadose zone modeling. In order to evaluate the uncertainty associated with how textural variability affects vadose zone calculations, PGG performed a sensitivity analysis in which RH2 estimates of monthly irrigation recharge were input to the Hydrus model for a range of soil textures (Hrg, Hg, Hgs (gravelly sands) and Hcs (coarse sands) on **Table I-1**).

3.2 HYDRUS MODEL SETUP

Hydrus-1D was set up to simulate a 10-meter thick, free draining vadose zone. In order to simulate greater thicknesses, output from one 10-meter simulation was used as input to another 10-meter simulation, achieving total simulated thicknesses of as much as 60 meters. Flux input at the top of the (first in series) Hydrus model was based on RH2's monthly deep percolation estimates (discussed above). The output from each Hydrus run was generalized into an annual series of 2-week averages to be used as input to the next Hydrus run (and ultimately to the MODFLOW model). The 10-meter model domain was discretized into 1-cm elements and the annual recharge cycle was run 50 times back-to-back, to ensure that the Hydrus model was in equilibrium with the irrigation recharge from year to year (a condition PGG refers to as "cyclic steady-state"). Hydrus automatically selects time-step discretization to maintain model stability and accuracy.

3.3 HYDRUS MODEL RESULTS AND INTERPRETATION

Figure I-1 presents the results of PGG's sensitivity analysis, in which the timing of irrigation recharge is compared at depths of 10, 20 and 30 meters for Hg, Hgs and Hcs and for depths of 10 to 60 meters for Hrg soils. Both lagging and moderate damping is observed for the Hg, Hgs and Hcs soils at a depth of 10 meters. Lagging and damping both increase with depth, such that a moderately high damping is predicted at 20 meters and high damping is predicted at 30 meters depth. At any given depth, damping and lagging increase as one progresses from Hg (sandy gravels) to Hgs (gravelly sands) to Hcs (coarse sands) – with predictions for Hcs considerably more damped than the (more similar) Hg and Hgs predictions. Much less damping and lagging (i.e. faster transmission of the recharge pulse) is predicted for the Hrg (gravel) soils through the 30-meter depth. However, the predicted Hrg flux curves for 50 and 60-meter depths show similar damping/lagging as for shallower depths in the Hg, Hgs and Hcs soils.

As noted above, it would not be reasonable to represent the sandy gravels that comprise the most common facies of the Pasco Gravels with the Hrg hydraulic properties. Thus, Hg is the next "step down" in representing the Block 17 and Greenbelt sites with relatively fast transmission of the irrigation recharge pulse through the vadose zone.

Figure I-2 shows the Hydrus pre-conservation predictions for the three hypothetical sites using the model setup described above. All 3 sites have relatively high predicted damping factors for vadose zone water reaching the water table, with values of 82%, 93% and 87% for Block 1, Block 17 and the Greenbelt (respectively). As discussed in **Appendix J**, the saturated flow model is predicted to further increase damping of the predicted return flows.

Description of Hydraulic-Property Soil Classes

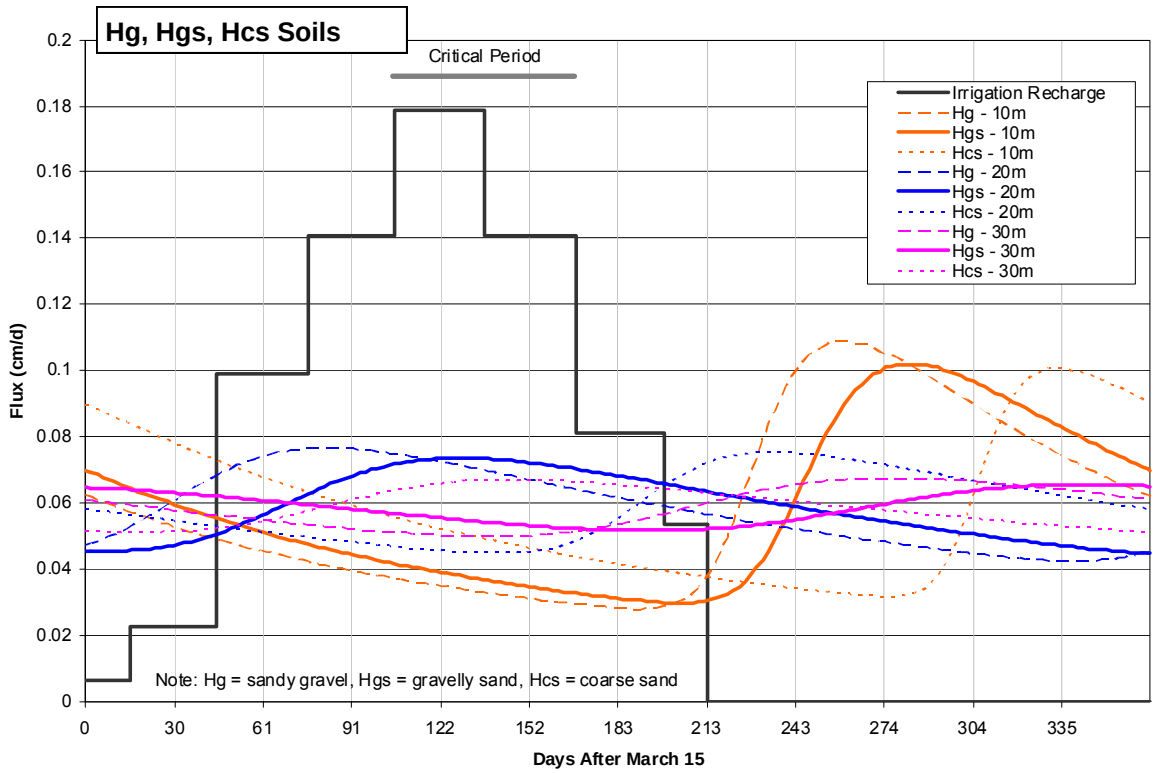
Formation	Soil Class	Code	Description	Hydrostratigraphic Unit Code(s)
Holocene Deposits	Backfill	Bf	Sand and gravel mixed with finer fraction. Same as the SSG soil category identified by Khaleel and Freeman (1995)	HDb
Hanford formation	Silty Sand	Hss	Sand mixed with finer fraction, containing >50% fine sands, silt, and clay, with >15% silt and clay. Derived from the SS soil category identified by Khaleel and Freeman (1995)	HISSD/HSD(f)
	Fine Sand	Hfs	Sand, containing 35-70% fine sand, silt, and clay, with <15% silt and clay. Derived from the S soil category identified by Khaleel and Freeman (1995)	HSD-Sm
	Coarse Sand	Hcs	Sand, containing >60% coarse sand. Derived from the S soil category identified by Khaleel and Freeman (1995)	HSD-Sh(c)
	Gravelly Sand	Hgs	Gravelly sand. Same as the GS soil category identified by Khaleel and Freeman (1995)	HSD(c)
	Sandy Gravel	Hg	Sandy gravel for which gravel content is approximately <60%. Same as the SG1 soil category identified by Khaleel and Freeman (1995)	HGD
	Gravel	Hrg	Very high gravel content soils (>60% gravel) from the 100 areas (along the river).	HGD(c)

Statistical Mean Values for Site-Wide Samples

Site Wide									
Soil Class	Count	α (1/cm)	n	θ_R (cm^3/cm^3)	θ_s (cm^3/cm^3)	K_s (cm/sec)	S_r	% gravel	Bulk Density (g/cm^3)
Bf	6	0.019	1.400	0.030	0.262	5.98E-04	0.103	33.5	1.94
Hss	38	0.008	1.915	0.072	0.445	8.58E-05	0.162	0.2	1.61
Hfs	36	0.027	2.168.	0.032	0.379	3.74E-04	0.086	0.6	1.60
Hcs	81	0.061	2.031	0.027	0.349	2.27E-03	0.080	2.6	1.67
Hgs	16	0.014	2.120	0.033	0.238	6.65E-04	0.140	25.8	1.94
Hg	28	0.017	1.725	0.022	0.167	3.30E-04	0.134	51.4	1.93
Hrg	40	0.007	1.831	0.020	0.102	1.46E-03	0.200	67.6	1.97
PPlz	9	0.005	2.249	0.040	0.419	5.57E-05	0.097	0.4	1.68
PPlc	14	0.011	1.740	0.054	0.281	8.45E-04	0.185	16.7	1.72
Rg	18	0.008	1.660	0.026	0.177	4.13E-04	0.135	46.1	1.90

Tables excerpted from Last, 2006 .

Table I-1 Generalized Textures and Hydraulic Properties of Hanford Gravels



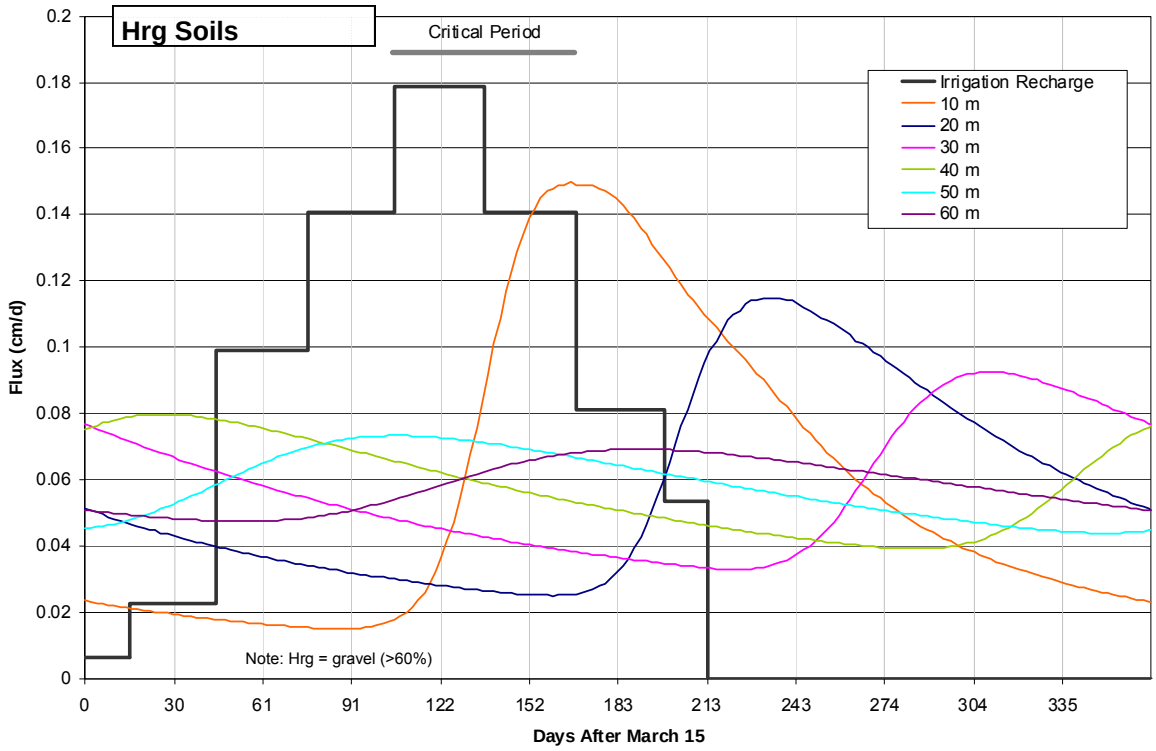


Figure I-1
Sensitivity Analysis: Vadose Zone Flow Thru Several Hanford Gravel Textures

Franklin Conservation District
Retiming Benefits Analysis

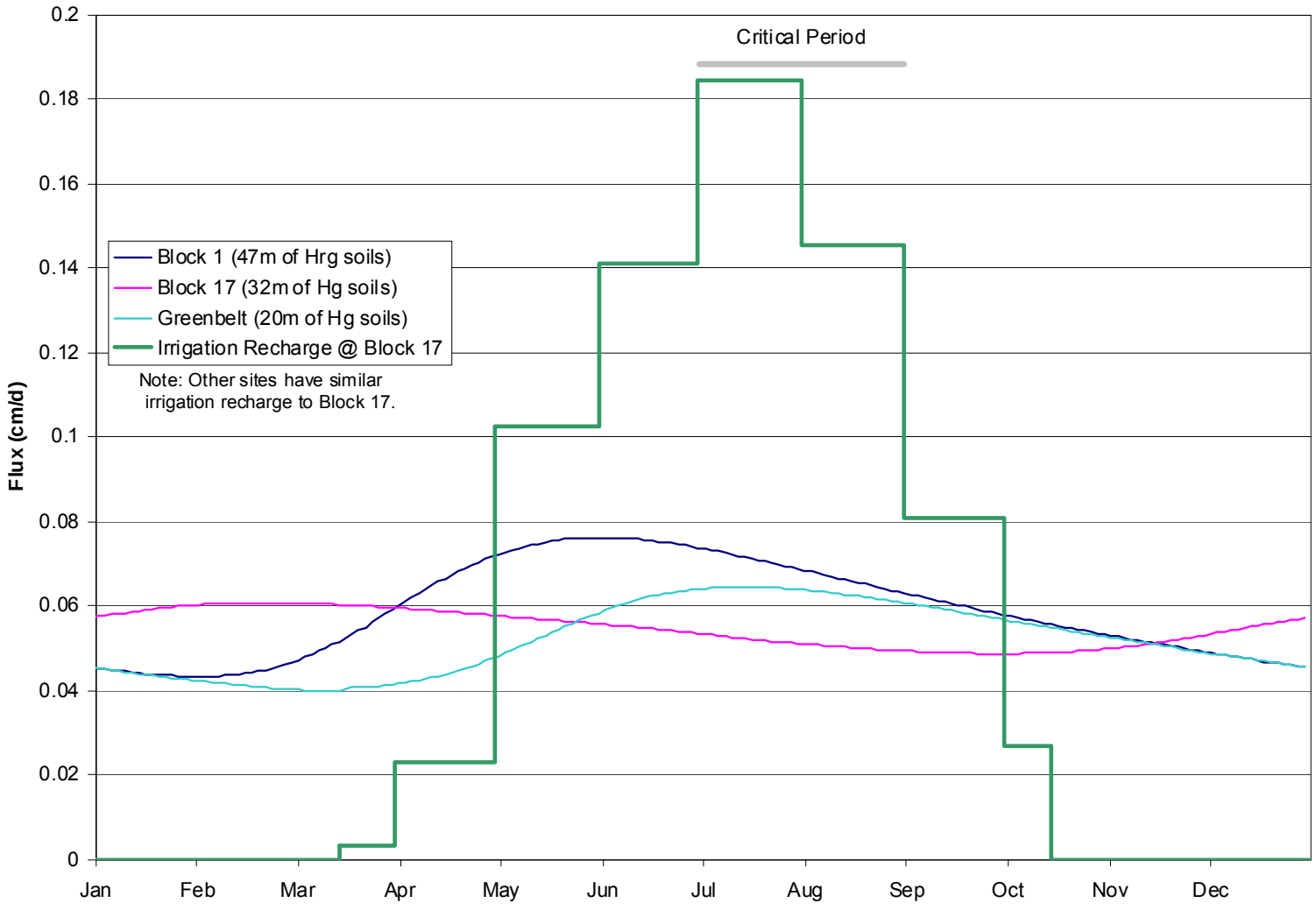


Figure I-2
Pre-Conservation Hydrus Results for 3 Hypothetical Conservation Sites

Franklin Conservation District
Retiming Benefits Analysis

PgG

APPENDIX J
DOCUMENTATION OF GROUNDWATER FLOW MODEL FOR SFC QUATERNARY PROVINCE

February 2012

TABLE OF CONTENTS

1.0 MODEL OVERVIEW 1

2.0 CONCEPTUAL MODEL AND HYDROSTRATIGRAPHIC UNITS 2

3.0 MODEL CONSTRUCTION 3

3.1 MODEL CODE 3
3.2 MODEL DOMAIN, GRID AND LAYERS 3
3.3 MODEL BOUNDARY CONDITIONS 4
3.3.1 Recharge 4
3.3.2 No-Flow Boundaries 12
3.3.3 Specified Flux (Subflow) Along Model Boundaries 12
3.3.4 Rivers 13
3.3.5 Drains 14
3.3.6 Wells 15
3.4 AQUIFER PROPERTIES 15
3.4.1 Hydraulic Conductivity 16
3.4.2 Storage Coefficient 17

4.0 MODEL CALIBRATION 17

4.1 TIME DISCRETIZATION 18
4.2 HEAD TARGETS 18
4.3 CALIBRATION PROCEDURE 18
4.4 CALIBRATION RESULTS 19
4.4.1 Final Calibrated Model Parameters 19
4.5 SENSITIVITY ANALYSIS 20
4.5.1 Sensitivity Analysis Procedure 21
4.5.2 Sensitivity Analysis Results 21

5.0 MODEL PREDICTIONS 21

5.1 PREDICTIVE MODEL APPROACH BLOCK 1 AND BLOCK 17 22
5.2 PREDICTIVE MODEL APPROACH GREENBELT 23
5.3 PREDICTIVE RESULTS 24

1.0 MODEL OVERVIEW

A groundwater flow model was developed for the suprabasalt aquifers in the "Quaternary Province" of the Southern Franklin County (SFC) study area. The calibrated model was used to assess the retiming benefits of irrigation conservation applied to three hypothetical locations. PGG's analysis of irrigation recharge retiming in the vadose zone is presented in *Appendix I*, and used as input to this groundwater flow model.

The study-area hydrogeologic conceptual model is presented in Section 4.2 of the main report. Sections below describe how the conceptual model was represented in the numerical model. Key hydrologic features represented in the model include:

- Recharge from both natural precipitation, irrigated fields and irrigation conveyances;
- Groundwater discharge and recharge from the Columbia and Snake Rivers
- Groundwater discharge to irrigation wells;
- Subflow into the model from aquifers not explicitly represented in the model; and,
- Groundwater discharge to into the lower reaches of Esquatzel Coulee Wasteway (represented as Drains)

The model was set up to simulate the growth of irrigation in the study area from 1945-to-1986. This setup was used to calibrate the model to observations of both long-term changes in groundwater levels (over the course of years) and short-term seasonal changes in groundwater levels (variation *within* a year). Calibration targets included long-term records from seventeen wells compiled from the U.S. Geological Survey's "National Water Information System" (http://waterdata.usgs.gov/usa/nwis/gw). The model was set up so that a single model simulation included an initial steady-state stress period for 1945 to represent "pre-irrigation" conditions, followed by annual transient stress periods from 1946-to-1985 to simulate long-term changes in groundwater levels due to the growth and development of irrigation, followed by monthly stress periods for 1986 to simulate seasonal changes in groundwater levels. The 1945-to-1986 timeframe was chosen because it encompasses the major growth of irrigation in the study area and associated rise in groundwater levels. Irrigation developed rapidly during the 1950's with the arrival of the Southern Columbia Basin Irrigation District (SCBID) and expanded throughout the 1960's and 1970's. The year 1986 was chosen for the seasonal simulation because of the availability of high resolution groundwater monitoring data collected by the USGS that year.

A relatively good calibration was achieved for much of the active model domain. Several calibration targets near the northernmost edge of the model domain did not achieve good matches, likely due to hydrogeologic complexity (e.g. heterogeneities and perched aquifer conditions) not included in the stratigraphic model developed by the GWMA (2009). An effort to include these complexities was not undertaken since the model assessment focused on hypothetical sites located further to the south where relatively good calibration was achieved.

The calibrated model was used to predict the timing of subsurface irrigation return flow from the hypothetical sites to the Columbia and Snake rivers. The predictive analysis includes an uncertainty analysis based on reasonable ranges of aquifer properties.

2.0 CONCEPTUAL MODEL AND HYDROSTRATIGRAPHIC UNITS

The study-area hydrogeologic conceptual model was described in Section 4.2 of the main report. As described in the main report, the study area can be divided into three hydrogeologic provinces based on the unit, or units, that dominate vadose and groundwater flow system:

- The Quaternary Province (Q) dominated by the Pasco gravels and Middle Ringold Formation;
- The Upper Ringold Province (R) dominated by the fine-grained Upper Ringold Formation; and,
- The Basalt Province (B) dominated by the Columbia River Basalt (CRB).

As described in the main report, the Quaternary Province has the greatest potential for retiming benefits and the least hydrogeologic uncertainty. Retiming benefits in the Upper Ringold and Basalt Provinces are more difficult to calculate because of the hydrogeologic complexities associated with irrigation drains, uncertainty in the details of subsurface return flow pathways, and flow into adjacent aquifers. The groundwater flow model was therefore developed to only assess retiming benefits in the Quaternary Province. The hydrostratigraphic units associated with the study-area provinces were represented in the model as follows (**Figure J-1**):

<u>The Quaternary Province</u> was explicitly represented in the model as active model cells in model layer 1 (Pasco Gravels) and layer 2 (Middle Ringold).

<u>The Upper Ringold Province</u> wass not explicitly represented in the model. As described in the main report, the groundwater pathways in this province are complex and difficult to decipher. Instead, estimates of lateral groundwater flow from this province into the adjacent Quaternary deposits were simulated as a specified flux line source along the edge of the Quaternary Province, and estimates of vertical flow into the underlying Middle Ringold Formation are simulated as areal recharge to the underlying Middle Ringold Formation (see Section 3.3.1 below).

<u>The Basalt Province</u> was not explicitly represented in the model. Instead, irrigation applied to fields over the basalt in the eastern portion of the study area that may recharge and migrate laterally into the Quaternary deposits was estimated and represented as a specified flux line source along the edges of the Quaternary deposits (see Section 3.3.3 below).

As described in the main report, the Lower Ringold Formation is a low-permeability aquitard below the Middle Ringold with occurrence generally restricted to areas near the Columbia River. Where present, the top of this unit was represented as a no-flow boundary in the model and defined the bottom limits of layer 2 (Middle Ringold). In areas where the Lower Ringold Formation is absent, the top of basalt defined the bottom limits of layer 2 and was represented as a no-flow boundary.

3.0 MODEL CONSTRUCTION

3.1 MODEL CODE

The finite difference code "MODFLOW-NWT" (Niswonger et al, 2011) was selected for this model because of it's capability to solve groundwater-flow problems that are nonlinear due to model cells going dry. This functionality was required for this study area given the large change in groundwater levels over time and model cells drying and wetting during the simulation. MODFLOW-NWT is a standalone version of MODFLOW-2005 (Harbaugh, 2005). PGG used Groundwater Vistas 6.0, a Graphic User Interface (GUI), for processing and viewing input and output MODFLOW files (ESI, 2011).

MODFLOW-NWT comes with the option to allow for automatic reduction of well pumping rates. This modification of the well input files may be required in cases where a well is pumping from a dry or thinly saturated model cell and precluding model convergence. The reduction is based on a cubic formula which is implemented when the simulated head drops below a user-specified percentage of cell thickness (in this case 25% of the thickness). This option was required in order to achieve model convergence; however, the amount of pumping reduction required for convergence was relatively small (5%) compared to the assigned pumping rates and considered insignificant.

3.2 MODEL DOMAIN, GRID AND LAYERS

The total model domain covers approximately 425 square miles, with the active part of the domain representing the Quaternary Province (**Figure J-1**). The active model area is bounded on the west and south by the Columbia and Snake Rivers and on the east by the Basalt Province. To the north the model was extended to the estimated limits of the Middle Ringold Formation (GWMA, 2009). This is approximately coincident with the Ringold Coulee and considered far enough to the north so as to avoid significant groundwater boundary effects within the Quaternary Province further south in the area of interest.

The model consists of two layers with 127 rows and 93 columns and a uniform grid spacing of 1000-ft by 1000-ft. Gridded model layer elevations were assembled in ROCKWORKS (Rockware, 2006). The model coordinate system is State Plane South NAD 83 and the vertical datum is NAVD 88.

The active model cells in Layer 1 represent the Pasco Gravels and are simulated as unconfined (LAYCON =1). The Upper Ringold Province is represented in the northern half of layer 1 as no-flow cells. Although the Upper Ringold is not actively simulated in the model, recharge to the Upper Ringold is distributed to active model cells in model layers 1 and 2based on a water balance approach (see Section 3.3.1). The top elevation of Layer 1 is defined as the land surface elevation based on the 30-meter Digital Elevation Model. The bottom elevation of layer 1 is set as the top elevation of the Middle Ringold as defined by the GWMA (2009).

The active model cells in Layer 2 represent the Middle Ringold and are simulated as unconfined/confined convertible (LAYCON 3), depending on if the layer is partially or fully saturated. The top elevation of the Middle Ringold is defined by the bottom elevation of layer 1. The bottom elevation of the Middle Ringold is set to the top elevation of the underlying basalt as defined by the GWMA, with the following modifications:

- The bottom of the model domain was adjusted upward from the top elevation of the basalt to account for the Lower Ringold fine unit, as mapped by the USGS (Drost, 1997). The USGS created a 50-ft contour map of the Lower Ringold extent and thickness in the study area. This map was digitized and gridded in a GIS and added to the top of basalt defined by the GWMA.
- Model cells in layer 2 with thicknesses of zero were adjusted to 1-ft thickness by lowering the elevation of layer 2. These areas represent locations where the Middle Ringold unit pinches against bedrock highs in the subsurface. Although these areas do not represent significant locations for groundwater flow in the Middle Ringold, a minimum cell thickness of 1-ft is still required for continuity in the finite difference model formulation.
- The bottom elevation of layer 2 was adjusted downward in the vicinity of the Franklin County Irrigation District (FCID) based on review of a number of location-verified well logs. Well-log verification was required, because the water-level elevations of several calibration targets in the suprabasalt aquifer were below the GWMA bottom elevation of layer 2. This discrepancy occurred in an area where the GWMA interpreted a broad structural anticline in the underlying basalt. Based on our review of well-logs, this interpretation appears to overestimate the basalt top elevation in some locations. The model bottom was adjusted downward to be consistent with our additional review of this area.
- The bottom elevation of layer 2 was also adjusted downward in a small area of the northern model domain (near Target T-14 as shown on **Figure J-4**) where the GWMA interpreted a broad bedrock high based on a single well log. This interpreted feature showed the top of basalt over 50-ft higher than surrounding well logs. This area was adjusted downward by about 60-ft based on the assumption that the well log was either incorrect or the bedrock high represents an isolated bedrock knob.

Maps showing final bottom elevations of layers 1 and 2 are shown on **Figure J-2**.

3.3 MODEL BOUNDARY CONDITIONS

Boundary conditions are user specified hydrogeologic conditions within the numerical model. There are three general types of boundary conditions: specified head, specified flux, or head-dependent flux. Boundary conditions represented in the SFC model are described below.

3.3.1 Recharge

Modeled groundwater recharge (specified flux) is derived from four different sources:

- Precipitation recharge,
- Recharge from applied irrigation to fields,
- Recharge from canal leakage,
- Recharge from infiltration below wasteways; and,
- Recharge from groundwater in the overlying Upper Ringold Province in the northern part of the model.

The dominant source of recharge in the model is derived infiltration below unlined wasteways (about 60%), followed by field irrigation (16%), and canal leakage (9%). The remaining recharge sources make up less than 20% of the total recharge in the model (**Figure J-3**)[1].

All recharge values in the model are assigned to the top of layer 1; however, if a model cell in layer 1 is dry or defined as no-flow, the model automatically applies the recharge to the underlying cell in layer 2.

Single recharge values for each stress period in the model were calculated for each model cell by adding the various recharge sources that occur in a particular model cell. This was accomplished using a computer database for performing the calculations and creating the model recharge input files.

The following section provides a summary of irrigation development in the study area and how it was represented in the model. Subsequent sections summarize the methods for simulating the different recharge sources listed above.

3.3.1.1 Model Representation of Irrigation Development

Four types of irrigation zones were identified for the study area in order to simulate the development of irrigation development over time (**Figure J-4**):

- South Columbia Basin Irrigation District (SCBID) Blocks
- Pasco Greenbelt
- Franklin County Irrigation District (FCID)
- City of Pasco

These zones are discussed below.

SCBID Blocks

As described in the main report, the vast majority of irrigation water for the SFC study area is provided by Columbia River water distributed by the SCBID. The SCBID irrigation network is comprised of irrigation canals and wasteways conveying water to and from irrigated fields. The network is broken up into distinct irrigation blocks. Each block developed at different times as the SCBID irrigation network was constructed. The two main SCBID irrigation blocks simulated in the model are Blocks 1 and 17 (**Figure J-4**). Other irrigation blocks partially simulated are 15, 16, 19, 20 and 161. Irrigation blocks located within the Upper Ringold Province (14, 15, 16, and 161) were not explicitly simulated; but rather a mass balance approach was employed to calculate recharge to the underlying Middle Ringold.

Pasco Greenbelt

Irrigation in the Pasco Greenbelt area, located in the central area of the model, is provided by local groundwater withdrawals. Groundwater withdrawals are predominantly from the underlying suprabasalt aquifer. Irrigation development of this area occurred mainly during the 1970's.

[1] These statistics are for recharge sources only, and do not include subflows. Recharge accounts for 94% of total model inflows and subflow accounts for the remaining 6%.

FCID

A mixture of agricultural and residential irrigation occurs immediately east of the City of Pasco and is supplied mainly with local Columbia River water administered by the Franklin County Irrigation District (FCID). Irrigation within the FCID was historically dominated by agriculture but converted to residential over time as development expanded outward from the City of Pasco. The FCID area was divided into three zones (west, central, and east) based on conversations with FCID staff (Burns & Wright, personal communication, 2011) about the spatial development of irrigation practices in this area (**Figure J-4**):

- The west FCID zone was largely agricultural irrigation up to mid-1970 before conversion to pasture and residential irrigation. By 1986, 20% of the irrigated land in this zone is assumed to remain under agricultural irrigation (Drost, 1997).
- The central FCID zone was largely agricultural irrigation up to the 1960's before conversion to pasture and residential irrigation. By 1986, 20% of the irrigated land in this zone is assumed to remain under agricultural irrigation (Drost, 1997).
- The eastern FCID zone was largely agricultural irrigation up to the 1960's before conversion to mainly residential irrigation as the City of Pasco grew and expanded. By 1970, no agricultural irrigation is assumed to occur in this zone.

Additional assumptions regarding canal leakage in the FCID were incorporated into the recharge rates for the three FCID areas (see Section 3.3.1.4 below).

City of Pasco

The City of Pasco was divided into a "high density" and a "low density" zone for the purposes of representing recharge in the model:

- The High Density City of Pasco zone is represented by the growth of residential irrigation. By 1960, no agricultural irrigation is assumed and all irrigation is represented as residential. Irrigation in this zone is supplied by local surface water sources (personal communication, Strebel, 2011).
- The Low Density City of Pasco zone is represented by a few agricultural irrigation fields within the City limits, assumed to be supplied by local groundwater sources.

Historical Development of Irrigation in the SFC study area

Irrigation development in the SFC study area progressed over time according to the following time line. This historical time-line is based on information presented in Drost (1997) and from conversations with Mark Nielson of the Franklin Conservation District and with John Burns and Roger Wright of the Franklin County Irrigation District.

1922:	FCID, first irrigation
1948:	Block 1, first irrigation (supplied by local Columbia River water)
1954:	Block 1, first irrigation (supplied by SCBID irrigation network)
1954:	Esquatzel Coulee Wasteway

1955: Block 16, first irrigation (supplied by SCBID irrigation network)

1955: Potholes Canal

1956: Block 19, first irrigation (supplied by SCBID irrigation network)

1957: Block 14, first irrigation (supplied by SCBID irrigation network)

1959: Block 20, first irrigation (supplied by SCBID irrigation network)

1959: Esquatzel Diversion Canal

1963: Eltopia Branch Canal

1964: Block 17, first irrigation (supplied by SCBID irrigation network)

1964: Smith Canyon Wasteway begins receiving wastewater

1966: Block 161, first irrigation (supplied by SCBID irrigation network)

1970's: Dominant time of irrigation development in Pasco Greenbelt and Pasco Low Density zones (supplied by local withdrawals from groundwater).

The historical time-line of irrigation development presented above was used to initiate model recharge in the different irrigation zones described above.

3.3.1.2 Precipitation Recharge

Steady-state precipitation recharge rates were assigned to layer 1 based on values estimated by the USGS (Drost, 1997). The USGS mapped an average areal distribution of precipitation recharge in the study area based on the results of the U.S. Geological Survey deep percolation model. The USGS model used data from 1956-1977 (precipitation, temperature, landuse and soil type) and calculated an average recharge for the period of record. Spatial distribution of precipitation recharge ranged from less than 1 in/yr to 5 in/yr with an average study area value of 0.45 in/yr. The USGS map was digitized and gridded into a GIS for import to the model.

3.3.1.3 Applied Field Irrigation Recharge

Field irrigation recharge rates assigned to the model are based on annual calculations of irrigation losses to deep percolation from 1951 to 1986 presented in **Appendix G**. Deep percolation values for years prior to 1951 were not calculated because crop data for earlier years was not available. As described in **Appendix B**, irrigation losses (evaporation, surface runoff, and deep percolation) are a function of irrigation method, crop requirement, and field application rates.

Annual calculations presented in **Appendix G** employ one of two methods for calculating field application rates:

- The Monthly Water Delivery (MWD) method uses the Annual Potholes Summary for monthly water deliveries to SCBID farms.
- The Weighted Average Irrigation Efficiency (WAIE) method uses the weighted average crop requirement[2] and WAIE to calculate irrigation application rates.

[2] The weighted average crop requirement is based on a weighted average of the top ten crops for each year calculated from annual crop reports provided by the USBR.

The two methods result in fairly similar estimates of deep percolation over time (see **Appendix G**). For the model calibration, deep percolation values using the MWD method were used for 1954-1986. The MWD method for years prior to 1954 was not used because SCBID irrigation delivery (which the MWD method is based on) did not reach the SFC study area until 1954. The WAIE method was therefore used for years 1951 to 1953. For years prior to 1951, deep percolation for Block 1 (starting in 1948) and the FCID area (starting in 1922) was estimated using the average crop requirement from the first five years from the WAIE method (1951-1954).

Deep percolation values presented in **Appendix G** are dependent on the relative percentage of sprinkler and rill irrigation methods. Based on conversations with Mark Nielson from the Franklin Conservation District, the following irrigation-method distribution was assumed for the 1945-1986 model simulation:

- SCBID Block 17: 100% Sprinkler
- Pasco Greenbelt: 100% Sprinkler
- SCBID Block 1: 100% Rill

The distribution of sprinklers and rill in all other SCBID areas were assumed to be consistent with the area wide distribution presented in **Appendix G**. Irrigation fields within the Pasco Low Density area were assumed to be 100% sprinkler, similar to the nearby Pasco Greenbelt area.

Based on conversation with FCID staff (Burns and Wright, 2011), conversion from rill to sprinkler irrigation in the FCID and City of Pasco area was assumed to develop linearly as follows:

- West-FCID and Central-FCID areas:
  - 1945 to 1950 = all rill
  - By end of 1950's = 20% sprinkler
  - By end of 1960's = 80% sprinkler
  - By end of 1970's = 90% sprinkler
  - By 1986 = 95% sprinkler
- East-FCID area:
  - 1945 = all rill
  - By end of 1960's = 100% Sprinkler (all residential)
- Pasco High Density area
  - 1945 = 10% Sprinkler
  - By end of 1950's = 100% Sprinkler (all residential)

Field irrigation recharge rates for all irrigation zones except the FCID and the Pasco High Density areas were calculated using the following GIS approach. The model grid was intersected with a GIS coverage of irrigation fields and irrigation zones (**Figure J-4**). From this intersection, each model cell was assigned to an irrigation zone and the total field area within each model cell was calculated. The volumetric field irrigation recharge rate (ft^3/day) for each model cell was then

calculated by multiplying the cell's field area (ft^2) by the deep percolation rate (ft/day) for that irrigation zone. Volumetric rates were then divided by the area of the model cell to derive a linear recharge rate (ft/day) for import into the model. A recharge database was created to facilitate the construction of transient recharge input files for the model (see section 3.3.1.7 below).

A different approach was used to apply field irrigation recharge rates in the FCID and Pasco High Density zones. Based on conversations with FCID staff, the total irrigation area in these zones has remained relatively constant since 1945 (about 65% of the total area). Therefore, rather than apportion field recharge to specific fields, a uniform field recharge rate was assumed for all model cells in these two zones with deep percolation applied to 65% of the model cell area. Deep percolation values were calculated assuming the relative distribution of sprinklers presented above and employing the methods presented in **Appendix G**. Field irrigation recharge rates for each cell in the FCID and Pasco High Density zones were also combined with estimates of recharge from canal leakage for these two zones (see section 3.3.1.4 below).

The simulated start date for a particular irrigated field was based on which irrigation zone the field was located. For fields located within SCBID irrigation blocks, fields were assumed to be fully established within four years after the start of the irrigation block (see time line above). This assumption is based on conversations with Mark Nielson with the Franklin Conservation District and review of historical air photos which indicate irrigation fields within SCBID blocks were established relatively quickly once irrigation water was available. The four year development was assumed to occur uniformly throughout the irrigation block. This was accomplished by assigning a fraction of the field irrigation recharge rate for each field over the first four years such that years 1, 2, 3, and 4 received 25%, 50%, 75% and 100% of the calculated recharge respectively.

Individual fields located within the Pasco Greenbelt and Pasco Low Density areas were assigned start dates based on review of historical air photos. Most fields in the Pasco Greenbelt zone (about 75%) and Pasco Low Density zone (about 90%) were established during the 1970's.

SCBID irrigation Block 1 is unique in that irrigation to this zone was developed in 1948 prior to the arrival of the SCBID irrigation network in 1954. Between 1948 and 1954, irrigation water for Block 1 was derived from a local Columbia River water source. Given a local source of irrigation water during these early years, irrigation application rates were assumed to be somewhat higher than typical rates. The deep percolation rates for Block 1 were therefore adjusted upward for years 1948 to 1954 during the model calibration.

Transient annual average values of field irrigation recharge were used for the 1945 to 1985 long-term simulation. Transient values for the 1986 monthly seasonal simulation used a mixed approach between field irrigation recharge assumed to occur only during the irrigation season and field irrigation recharge assumed to occur year round. Application of seasonal versus year-round field recharge values were based on the thickness of the vadose zone (see discussion in **Appendix I**). Using this approach, field recharge values were assumed to be seasonal in the FCID and Pasco High Density area where the depth to groundwater is generally less than 40-feet. For these areas the annual 1986 field recharge value was apportioned equally between the 7 irrigation months (April-October[3]). All other irrigation field areas, where the depth to water is greater,

[3] Model time-stepping was based on monthly stress periods. Although the irrigation season begins in mid-March and ends in mid-October, the 7-month irrigation season was offset slightly to conform with the model stress periods.

were set to annual constant rates for the 1986 condition. The sensitivity of model results to this assumption was tested during the model calibration by running all field recharge as seasonal and observing that the simulated heads at calibration targets were not very sensitive to the timing of field recharge. Field recharge only accounts for about 16% of the total recharge in the model (**Figure J-3**).

3.3.1.4 Canal Leakage Recharge

Canal recharge is from leakage to the groundwater from irrigation canals and laterals. The method for developing modeled canal recharge rates associated with the SCBID network is described below. A different approach was developed for estimating canal recharge associated with the FCID and described afterwards.

Leakage rates for canals and laterals associated with the SCBID network are based on seepage studies by the USGS for different types of lined canals in the study area (Drost, 1997). The USGS estimated a range of canal leakage rates from 0.2 to 0.7 ft/day for the Pasco gravels, depending on the type of canal lining. Using the results of the USGS study, a leakage rate of 0.4 ft/day was assigned to concrete-lined canals and laterals and a leakage rate of 0.7 ft/day was assigned to all other types of canals and laterals. These rates were adjusted by up to 50% during the calibration process; however, model results were relatively insensitive to those changes, so leakage rates were set back to their original values.

Canal recharge values for each model cell was calculated using a similar GIS approach as was adopted for calculating field irrigation recharge. The model grid was intersected with a GIS coverage of irrigation canals and wasteways (**Figure J-4**) and from this intersection, canal type and associated lengths were apportioned to each model cell. Canal widths, assumed to be constant for each canal type, were estimated from published widths where available (USBR, 2011), spot measurements from air photos, and checked by comparison to mass balance calculations conducted by the USGS (Drost, 1997). Conveyance widths varied from 5-feet for small laterals to 40-feet for major laterals and wasteways. The volumetric recharge rate (ft^3/day) for each model cell was then calculated by multiplying the length (ft) and width (ft) of each canal type within the model cell by the leakage rate (ft/day). For model cells with more than one canal type, the volumetric recharge rates were summed. Total volumetric recharge rates were then divided by the area of the model cell to derive linear recharge rates (ft/day) for import into the model.

Simulated start dates for canal recharge were based on the irrigation zone start date in which the canal is located with the exception of major canals and wasteways that extend through multiple irrigation zones. Start dates for major canals and wasteways are listed above (Section 3.3.1.1).

Once initiated in the model, canal recharge rates were assumed to be constant during the long-term annual simulation from 1945 to 1985. With the start of the monthly simulation in 1986, seasonal canal recharge rates were simulated as follows. For all canals except the Esquatzel Coulee wasteway and Esquatzel Diversion canal, the annual canal recharge was equally apportioned to irrigation months April-October and set to zero for non-irrigation months (November-February). Seasonal canal recharge from the Esquatzel Coulee wasteway and Esquatzel Coulee Diversion canal were adjusted to represent the observed year round flow in those canals. The seasonal distribution was adjusted during the calibration process with final values resulting in 70% of the annual canal recharge apportioned to the irrigation months and 30% apportioned to the non-irrigation months. The assumption of seasonal canal recharge is based on observations of seasonal changes in groundwater elevations. This adjustment of seasonal recharge from the Esquatzel

Coulee Wasteway and Diversion canal improved the seasonal model calibration of nearby head targets.

Canal Leakage Recharge in FCID and High Density Pasco Irrigation Zones

A different approach was used to estimate canal leakage and simulate canal recharge in the FCID and High Density Pasco irrigation zones. Estimates of canal leakage were based on historical information provided to PGG FCID staff (personal communication, Burns & Wright, 2011). In general, leakage from the FCID irrigation canal and laterals is assumed to be relatively minimal because the main canal has always been concrete lined and considered to be in relatively good condition, and the laterals are composed of enclosed pipes. The irrigation laterals; however, have been known to leak to varying degrees over the years. The original system of laterals was composed of wooden pipes which were replaced with thin-walled steel pipes in the early 1960's. Over time, corrosion of the thin-walled pipes led the FCID to either replace or slip-line the pipes with concrete beginning in the early 1990's. Using FCID operation readings of pumped water to the laterals in the early 1990's and estimates of pump efficiency, the FCID annual irrigation delivery was estimated to be about 5.5 to 7.5 feet. Using this estimate of irrigation delivery, canal leakage in the early 1990's was calculated as the difference between irrigation delivery and irrigation consumption (i.e. crop consumption and estimates of losses to evaporation, surface water runoff, and deep percolation using the methods presented in **Appendix A**). Historical pipe leakage was then estimated as a percentage of the 1990's leakage based on qualitative descriptions provided to PGG on the historical conditions of the lateral pipes. Estimates of pipe leakage were added to the field irrigation recharge rates assigned to the FCID and High Density Pasco zones (see section 3.3.1.3). This resulted in the field irrigation recharge rates for these two zones being about 5% to 50% higher than field irrigation recharge rates for the other irrigation zone; however, field irrigation recharge from the FCID and Pasco High Density area accounts for less than 10% of the total recharge in the model (**Figure J-3**).

3.3.1.5 Wasteway Leakage Recharge

Wasteway leakage rates were not included in the USGS seepage study discussed above; however, leakage rates below wasteways are assumed to be relatively high compared to canals and laterals, particularly below the Esquatzel Coulee Wasteway and Smith Canyon Wasteway where field observations indicate large quantities of wastewater fully infiltrate before reaching the river. The USGS study measured discharge into the Smith Canyon wasteway between March 1986 and February 1987 (Drost, 1997). Based on those measurements and assuming all wastewater fully infiltrates, an average annual leakage rate of 2.5 ft/day was estimated for the Smith Canyon wasteway. Field observations of head targets near wasteways were used during the calibration process to adjust wasteway leakage rates.

3.3.1.6 Recharge from Upper Ringold Province

The Upper Ringold Province is not explicitly represented in the model (**Figure J-1**) due to the complexities of the groundwater flow system in this area (see Section 4.2 of main report). Instead, vertical discharge of groundwater from this province into the underlying Middle Ringold and lateral discharge into the Quaternary Province to the south were estimated using a water budget analysis for 1986 conditions (see Section 4.2.6 of main report). With this approach, PGG estimated 8,200 af/yr discharges laterally as subflow into the Quaternary Province and 5,400 ac-ft-yr discharges vertically into the underlying Middle Ringold. Lateral subflow to the Quaternary Province was simulated using specified flux boundary conditions (see Section 3.3.3 below).

Vertical discharge to the underlying Middle Ringold was simulated as recharge and uniformly apportioning to model cells within the Upper Ringold Province.

The simulated start date for recharge from the Upper Ringold Province was based on the start date of irrigation blocks located within the province. About 90% of the Upper Ringold Province is occupied by SCBID irrigation blocks 15 (start date 1954) and 16 (start date 1955). The simulated start date was therefore assumed to be 1955.

3.3.1.7 Recharge Database

A Microsoft Access Database was created to calculate and sum the various transient recharge sources and apportion them to the appropriate model cells and model stress periods. The database allowed for transient recharge output files to be created relatively easily, which facilitated the calibration process as recharge parameters were adjusted to match head targets and test the sensitivity of the model.

Total recharge over time, applied to the final calibrated model for simulation years 1945-1985, is shown in **Figure J-5**. Maps of the simulated recharge distribution for years 1945 and 1985 are shown in **Figure J-6**.

3.3.2 No-Flow Boundaries

No-flow boundaries are a special case where model cells are assigned a specified flux of zero. Groundwater flow is not simulated in these cells. Based on the hydrogeologic conceptual model described above and in the main report, no flow boundaries were assigned to the Upper Ringold and Basalt Province (**Figures J-1** and **J-7**). Instead, groundwater discharging from these zones into the Quaternary Province was simulated as recharge or specified flux (Sections 3.3.1.6 and 3.3.3). No-flow conditions were also assigned to model cells on the opposite side of the Columbia and Snake rivers (i.e. across from the active model domain).

3.3.3 Specified Flux (Subflow) Along Model Boundaries

Subsurface lateral groundwater fluxes (subflow) from the Upper Ringold and Basalt Provinces into the Quaternary Province was simulated as specified flux using the MODFLOW well boundary condition (**Figure J-7**).

The sensitivity of model results to subflow fluxes was tested during the model calibration by running the model without flux boundaries and observing that the simulated head targets were not very sensitive to this boundary condition.

Estimates and methods for assigning specified flux from these two provinces are summarized below.

3.3.3.1 Subflow from Upper Ringold Province

Groundwater discharge pathways from the Upper Ringold Province were estimated using a water budget analysis for 1986 conditions (Section 4.2.6 of main report). With this approach, PGG estimated 8,200 af/yr discharges laterally as subflow into the Quaternary Province. The lateral discharge was apportioned uniformly to model cells in layer 1 located along the boundary between the Upper Ringold and Quaternary Province (**Figures J-1** and **J-7**).

The simulated start date for subflow from the Upper Ringold Province was set to 1955 based on the start date of the dominant irrigation blocks within the province. Once initiated in the model, the subflow flux was assumed to be constant throughout the duration of the simulation.

3.3.3.2 Subflow from the Basalt Province

Lateral subflow from the Basalt Province is assumed to be derived primarily from irrigation applied to fields over the basalt in the eastern portion of the study area (see Section 4.2.6 of the main report). Subflow fluxes were therefore quantified using estimates of irrigation field recharge in the Basalt Province area. Field irrigation recharge was estimated by quantifying the irrigated field areas in the Basalt Province and estimating deep percolation losses following the methods outlined in **Appendix D**. Historical air photos were also reviewed to estimate field start dates. Using this approach, field irrigation recharge in the adjacent Basalt Province is estimated to range from 200 af/yr in 1964 to 9,500 af/yr in 1986. As mentioned above, the sensitivity of the model results to subflow fluxes was tested during the calibration process and simulated heads were not very sensitive to this boundary condition.

3.3.4 Rivers

The Columbia and Snake Rivers were simulated using the River Package in MODFLOW; a head-dependent boundary condition. The River Package simulates the flow of water between the aquifer and river. The volumetric flux (Q_{riv}) between the two is dependent on the difference between the groundwater head and river elevation and the river bed conductance (resistance to flow):

$Q_{riv} = C_{riv}$ * (River Stage – Groundwater Head)

C_{riv} = Conductance = K_{riv}*L*W/M

Where K_{riv} = hydraulic conductivity of the river bed sediments (ft/day)
L = length of river in model cell (ft)
W = width of river in model cell (ft)
M = thickness of river bed sediments

If the simulated groundwater head is greater than the river stage, the flux is towards the river and water is removed from the model domain. If the simulated groundwater head is lower than the river stage, the flux is towards the aquifer and water is added to the model domain. If the groundwater head drops below the bottom of the river, the flux added to the model is a constant rate set equal to:

Qriv = Criv* (River Stage – River Bottom)

For the SFC model, the length and width of the River was set equal to the dimensions of the model cell (1000-ft). The thickness of river bed sediments was estimated to be 25-ft and the hydraulic conductivity was set to 10 ft/day. The hydraulic conductivity value assumes the river bed is composed of fine to medium grained sand. These values result in a river conductance value of $4x10^{-5}$ ft^2/day. The sensitivity of the model to river bed conductance was tested during the sensitivity analysis and the results showed that unless the conductance is reduced by at least a factor of 200, the simulated heads are relatively insensitive this parameter (Section 4.5).

Model cells assigned as River boundary conditions are coincident with the footprint of the Columbia and Snake Rivers within the active model domain (**Figure J-7**). River cells were assigned to either layer 1 or layer 2 based on the estimated river bottom elevation and whether it occurs within the Pasco Gravels (layer 1) or the Middle Ringold (layer 2).

River stage elevations were estimated for both pre and post-construction of the McNary Dam and associate Lake Wallula (1954). Pre-dam river stages and river bottom elevations were estimated from USGS 7.5 minute topographic maps showing bathymetric contours of land elevation and water depth. Land elevation contours below the river were assumed to represent areas where the land was exposed above the river before the dam was constructed and therefore the lowest contour represents the pre-dam river elevation. Areas of pre-dam land exposure were also confirmed with review of historic air photos. The water depth contours on the 7.5 minute maps indicates a post-dam depth of about 30-ft near the confluence of the Columbia and Snake Rivers. This value was used to estimate the bottom elevation of the river and a corresponding pre-dam water depth of 7.5-ft near the confluence of the two rivers. River bottom elevations were calculated for the upstream river reaches assuming a constant pre-dam water depth of 7.5-ft, which was subtracted from the pre-dam river stages. River bottom elevations were assumed to be the same under pre and post-dam conditions.

Post-dam river stages were assigned the long-term average Lake Wallula level from 1961 to 1985 (342-ft NAVD-88) and apportioned to those river cells estimated to be within the footprint of Lake Wallula. Lake Wallula was estimated to extend up the Columbia River to approximately the City of Richland and up the Snake River to the edge of the model domain. Seasonal fluctuations in Lake Wallula levels were not simulated. Seasonal fluctuations are generally about 2 to 3 feet and based on review of hydrographs from near river wells, these fluctuations did not appear to have a significant impact on groundwater levels.

The construction of Lake Wallula was assumed to occur instantaneous at the beginning of simulation year 1954. This assumption is based on historical information that indicates the lake took less than a year to fill. The resultant rise in river stage is as much as 25-ft near the confluence of the Columbia and Snake Rivers.

3.3.5 Drains

The lower reaches of the Esquatzel Coulee Wasteway is known to be a groundwater discharge area along certain reaches of the wasteway (based on conversations with Mark Nielson with the Franklin Conservation District). Water that collects in the Esquatzel Coulee Wasteway either eventually discharges back into the aquifer further downgradient, or it is pumped to the Esquatzel Diversion Canal.

The MODFLOW Drain Package was used to simulate discharge of groundwater in this area (**Figure** J-**7**). The Drain package is a head dependent boundary condition and works similar to the River package, except that water can only flow from the aquifer to the drain. Water cannot flow from the drain to the aquifer. Groundwater flux from the aquifer to the drain (Q_{drain}) only occurs if the groundwater head is above the Drain stage:

$Q_{drain} = C_{drain} * (\text{Drain Stage} - \text{Groundwater Head})$

The drain conductance was set relatively high to a value of $5x10^7$ (i.e. flux was not limited by a low permeable "skin" around the drain). The addition of drains along this stretch of the waste-way improved the model calibration to some of the nearby head targets.

3.3.6 Wells

Groundwater pumping supplies most the irrigation in the Greenbelt zone. Groundwater pumping in this zone was represented with transient Analytic Element wells in the model with all wells assigned to layer 2 (**Figure J-7**). Although wells may be completed in either or both layers, the assignment to layer 2 enhanced the model stability. Furthermore, given the high aquifer trans-missivities, this has little effect on the model results.

Well locations assigned to the model were based on the location of irrigation fields in the Green-belt zone supplied by groundwater. A 1970's Department of Ecology map of the Greenbelt zone shows that many fields are irrigated by a single well in the center of the field. Since exact well locations are not documented for the wells, it was assumed that each field is associated with a single pumping well.

Transient pumping rates assigned to each well were based on the field application rates described in Section 4.1.5 of the main report. As mentioned above, the growth of irrigation in the Green-belt zone is based on review of historical air photos, which indicates most of the Greenbelt zone developed during the 1970's (**Figure J-8**).

Groundwater pumping rates associated with each field were assigned transient annual rates during the long-term annual simulation from 1945 to 1985. With the start of the monthly simulation in 1986, seasonal pumping rates were simulated based on the relative percentage seasonal (monthly) field application rates developed by RH2 (main report Section 4.1.5). With this approach the 1986 field application rate was apportioned seasonally between March and October as follows:

- March = 0.8%
- April = 4.1%
- May = 13.6%
- June = 20.0%
- July = 26.9%
- August = 21.2%
- September = 10.6%
- October = 2.8%

3.4 AQUIFER PROPERTIES

Aquifer properties assigned in the model include hydraulic conductivity and storage coefficient. Aquifer property values were adjusted during the calibration process within reasonable ranges assumed for the aquifer. Aquifer properties are discussed in detail in the main report (Section 4.2.4).

3.4.1 Hydraulic Conductivity

Hydraulic conductivity (K) zones were specified in the model based on PGG's analysis of hydraulic conductivity using specific capacity data collected from 275 wells completed in the suprabalt sedimentary units in the SFC study area (**Figure J-9**). K estimates were based on the methods of Ferris et al (1962), Carnahan et al (1969) and Bear (1979), as outlined by the USGS (Thomas et al, 1999). The specific capacity data were compiled from Ecology's on-line well log database, and wells were grouped by aquifer based on well depths and hydrostratigraphic interpretation.

PGG's analysis found that:

- The Pasco Gravel wells (66 total) had K values ranging from 2 ft/day to 98,000 ft/day with a median value of 300 ft/day, a 25th percentile value of 125 ft/d and 75th percentile value of 780 ft/day.
- The Middle Ringold wells (209 total) had K values ranging from 1 ft/day to 87,000 ft/day, with a median value of 340 ft/day, a 25th percentile value of 96 ft/d and a 75th percentile value of 970 ft/day.

The similar distribution of interpreted K values form the Pasco Gravels and Middle Ringold may reflect uncertainty in using well depths to apportion the wells to specific hydrostratigraphic units and/or the influence of inaccurate measurements of small drawdowns noted in many of the pump tests recorded on well logs. Median K values estimated from specific capacity data are lower than median K values for the Pasco Gravels estimate by Drost (1997) (880 ft/day), and higher than Drost's median K estimate for the Middle Ringold (180 ft/day).

The spatial distribution of K values from both well groupings show higher values in the central portion of the study area and along Smith Canyon to the east (**Figure J-10**). The occurrence of gravel quarries in both these areas suggests the presence of higher permeability sediments. Also, both the Esquatzel Coulee and the Smith Canyon wasteways loose large quantities of wastewater through infiltration as the wasteways enter these higher permeability zones. The high permeable zone associated with Smith Canyon (Zone 6) is assumed to penetrate both layers of the model.

Based on the spatial distribution of hydraulic conductivity from specific capacity data, the model was divided into seven hydraulic conductivity zones in both layers (**Figure J-11**). Although both layers in the model have the same zonation, the K values in layer 1 (Pasco Gravels) were assumed to be relatively higher than the K values in layer 2 (Middle Ringold). This assumption is based on observations of prevalent cementation within portions of the older Middle Ringold unit that likely contributes to that aquifer having lower permeabilities.

Initial K-values assigned to the model were based on median estimates by the USGS (Drost, 1997) and later adjusted during the model calibration. The K-value zonation in the model helped with the calibration. During the calibration, the distribution of relative K-values mapped with the specific capacity data was generally honored. Acceptable ranges of K-values during the calibration were within an order of magnitude from Drost's median values. The final calibrated K-values were somewhat higher than Drost's median values (**Figure J-11**).

3.4.2 Storage Coefficient

Storage coefficient (S) zones were distributed in the model similar to the hydraulic conductivity zones (**Figure J-12**); however, the values of S were not directly or inversely correlated to the K values.

As summarized in the main text, the storage coefficient is largely controlled by the occurrence of either confined or unconfined conditions. For unconfined conditions the storage coefficient is defined by specific yield (Sy). For confined conditions the storage coefficient is defined by the product of specific storage (Ss) and aquifer thickness (b). Unconfined storage coefficients are typically several orders of magnitude higher than confined storage coefficients with values of Sy generally ranging from 0.03 to 0.3 (Domenico and Schwartz, 1990) and values of Ss generally less than 0.0001 ft^{-1} (Fetter, 1994).

The top layer of the model (Pasco Gravels) is simulated as unconfined and therefore only the specific yield value is used to define the storage coefficient. The bottom layer of the model (Middle Ringold) is defined as unconfined/confined convertible depending on if the layer is partially or fully saturated. If the layer is partially saturated the layer is simulated as unconfined and the storage coefficient is defined by the specific yield. If the layer is fully saturated the layer is simulated as confined and the storage coefficient is defined by the specific storage and aquifer thickness.

For the SFC model, the specific storage (Ss) was set equal to 0.0001 ft^{-1} throughout both layers of the model domain. Model results were not very sensitive to this parameter (Section 4.5 below). The specific yield (Sy) value was initially set to 0.2 in both layers of the model and later adjusted during the model calibration. Acceptable ranges of Sy used during the model calibration were 0.15 to 0.30. These values are within the ranges reported in from other nearby studies and discussed in the main report (Section 4.2.4).

4.0 MODEL CALIBRATION

The model calibration consisted of simulating the historical growth of irrigation in the study area from 1945-to-1985 and associated long-term rise in groundwater levels. Long-term monitoring shows that groundwater levels increased 25 to 50 feet over most of the study area in response to irrigation development and the creation of Lake Wallula (Section 4.2.3 of main report). The model calibration also consisted of simulating seasonal variations in groundwater levels under 1986 conditions. Seasonal monitoring in 1986 shows that groundwater levels vary as much as 3 to 4 feet in response to seasonal irrigation.

Model input parameters were adjusted within reasonable ranges in order to find the best match between observed groundwater levels (head targets) and simulated groundwater levels.

During the model calibration, the sensitivity of model results to different model input parameter values was qualitatively assessed. The qualitative assessment showed that the model results were most sensitive to horizontal hydraulic conductivity and wasteway recharge rates and moderately sensitive to specific yield and pumping withdrawals. Parameters that had relatively little impact on model results were vertical hydraulic conductivity, river conductance, field recharge, specific storage (Ss), and subflow boundary fluxes. A formal sensitivity analysis was performed after the model calibration to quantify the model's sensitivity to various input parameters (Section 4.5).

4.1 TIME DISCRETIZATION

To achieve calibration in a single simulation, the model was set up with an initial steady-state stress period for 1945 to represent "pre-irrigation" conditions, followed by annual transient stress periods from 1946-to-1985 to simulate long-term changes in groundwater levels due to the growth and development of irrigation in the study area. The annual transient period was then followed by monthly stress periods for 1986 to simulate seasonal changes in groundwater levels. The 1986 condition was run repeatedly for five years to allow convergence towards cyclic steady-state conditions. A cyclic steady-state solution consists of a groundwater head solution that changes month to month but is consistent from one year to the next.

The transient model calibration consisted of 101 stress periods total. Each stress period represents a discretization of time where model input parameters are held constant. The use of stress periods allows model input parameters (such as recharge and pumping) to vary from one stress period to the next.

The first stress period in the model was set to steady-state and represents 1945 "pre-irrigation" equilibrium conditions, which served as initial heads for the following transient stress periods. Stress periods 2-41 were set to annual transient periods each representing 365.25 days to simulate years 1946-to-1985. Each annual stress period was divided into 25 time steps with a multiplier of 1.2. Stress periods 42-101 were set to monthly transient periods with the length of each stress period set to the number of days in a particular month. Stress periods 42-101 simulate the year 1986 five times (cycles). Each monthly stress period was assigned 15 times steps with a multiplier of 1.2.

4.2 HEAD TARGETS

Calibration head targets consisted of seventeen long-term observation wells with groundwater levels obtained from the USGS National Water Information System. The targets are fairly evenly distributed throughout the model domain, with the exception of areas in the central and northeast part of Block 17 (**Figure J-4**). Groundwater levels from most of these wells were collected intermittently from the early to mid 1950's to 1985. Higher resolution seasonal measurements were collected from most of these wells beginning in 1986. The seasonal responses are predominantly influenced by either pumping (water-level declines during the irrigation season) or irrigation recharge (water-level rises during the irrigation season); with most wells in the Greenbelt zone being pumping dominated.

Hydrographs of observed head targets and simulated heads from the final calibrated model are shown in **Figure**s **J-13** through **J-21**. Note that the period 1986 to 1991 shown on the graphs is actually 1986 conditions repeated 5 years to achieve semi-cyclic steady state.

4.3 CALIBRATION PROCEDURE

The calibration procedure employed a trial and error approach of adjusting model input parameters within reasonable ranges to achieve the best match between observed and simulated groundwater heads. The calibration goal was to find the best match to all head targets for all three simulated conditions: pre-irrigation groundwater levels, increases in groundwater levels as irrigation developed, and seasonal changes in groundwater levels in 1986. In some cases during the process

an improved calibration to the long-term increase in groundwater levels would diminish the calibration to the seasonal changes in groundwater levels or an improved calibration for one target would diminish the calibration for another target. The approach was to find a balance for achieving the best overall match. Based on the qualitative sensitivity analysis described above, the calibration process focused on adjustment of these key parameters to achieve the best match.

4.4 CALIBRATION RESULTS

Hydrographs of observed head targets and simulated heads from the final calibrated model are shown in **Figures J-13** through **J-21**. Note that the period 1986 to 1991 shown on the graphs is actually 1986 conditions repeated 5 years to achieve semi-cyclic steady state. Simulated groundwater heads increased by about 25-ft over most of the model domain between 1945 and 1985. Maps of modeled groundwater elevations for the end of 1945 and 1985 are shown in **Figure J-22**. A mass balance of model fluxes for the end of 1985 is shown in **Figure J-23**. The mass balance shows discharge from the model is dominantly to the Columbia River (**Figure J-23**).

A relatively good calibration was achieved for most targets over much of the central and southern portions of the active model domain, where the hydrogeology is less complex and fairly well represented in the model. A few calibration targets to the north near the southern boundary of the Upper Ringold Province; however, displayed responses that were difficult to match (Targets T-12, T-13, and T-14). These targets are located along the model boundary, where hydrogeologic complexities (i.e. aquifer heterogeneities and perched aquifer conditions) were not represented in the model.

Targets T-12 and T-14 are located within a mile of each other (**Figure J-4**) and the simulated groundwater levels were about 50 feet too low at both locations (**Figure**s **J-18** and **J-19**). The observed long term rise in groundwater levels at T-12 is 90-ft, which is at least 50-ft higher than the long-term rise in groundwater levels at other target locations. These observations suggest that a low-permeability confining/perching layer may be holding groundwater levels up in this area. Well logs for T-12 and T-14 were available and indicate layers of silty, fine to medium grained sand with some clay. These finer grained sediments may be causing groundwater levels to mound up in this area.

Target T-13 is located about 2.5 miles west of T-12 and T-14 (**Figure J-4**) and, in contrast to T-12 and T-14, the simulated groundwater level was about 15-feet too high (**Figure J-19**). Target T-13 is also unique from other model targets in that the observed groundwater levels do not display a seasonal response during 1986 even though it is located in areas with sources of seasonal recharge. It is not clear why groundwater levels would be unresponsive in this area. A well log for T-13 was not available.

An effort to include the hydrogeologic complexities near the boundary with the Upper Ringold Province was not undertaken since the model assessment focused on hypothetical fields located further south in the model domain where a relatively good calibration was achieved.

4.4.1 Final Calibrated Model Parameters

The final calibrated values of hydraulic conductivity and specific yield are shown in **Figure J-11** and J-**12** and tabulated values are provided in **Table J-1**.

Calibrated values of Kh varied from 1000 ft/day to 6000 ft/day for the Pasco Gravels (Layer 1) and 400 ft/day to 4000 ft/day for the Middle Ringold (Layer 2). Areas of high and low Kh-values were similar to the relative distribution observed in specific capacity data (**Figure J-10**) and value are within the range of values from specific capacity data, but most zones are somewhat higher than the reported median value (see Section 4.2.4 of main report). Higher zones of hydraulic conductivity generally dominate the groundwater flow system and it is our experience that many water supply wells are not always completed in the higher K zones and therefore specific capacity data may underestimate the hydraulic conductivity of the aquifer system.

The final calibrated values of vertical hydraulic conductivity (Kz) were set to maintain anisotropy ratios (Kz/Kh) of 0.1 in all zones except for zone 11 (Layer 1) and zone 7 (Layer 2), where an anisotropy ratio of 0.01 was assigned. These two zones cover the northeast quadrant of the model domain where the presence of Ringold fines may limit the vertical hydraulic connection between the Pasco gravels and Middle Ringold (Section 4.2 of main report). In general, model results were not very sensitive to anisotropies or Kz values (Section 4.5 below).

The final calibrated values of specific yield (Sy) varied from 0.15 to 0.30. Specific storage (Ss) was set to a uniform value of 0.0001 throughout the model domain. As discussed in the sensitivity analysis, the model was relatively insensitive to values of Ss.

Final values of leakage rates for canals, laterals, and wasteways are shown in **Table J-1**. Leakage rates to canals and laterals were set to 0.4 ft/dy or 0.7 ft/day with the lower rates assigned to concrete lined canals. These values are based on estimates from seepage studies conducted by the USGS (Drost, 1997). Leakage rates to canals and laterals were adjusted by up to 50% during the calibration process; however, model results were relatively insensitive to those changes, so leakage rates were set back to their original values.

Leakage rates to wasteways were adjusted during calibration to match head targets and final values were 2 ft/day or 3 ft/day for all wasteways except the Smith Canyon Wasteway, which had a final value of 6 ft/day. The higher value for the Smith Canyon wasteway was required to achieve calibration to nearby head targets and results in a volumetric flux approximately 2.5 times higher than reported by the USGS for the Smith Canyon wasteway in 1986 (Drost, 1997).

One other adjustment made during the model calibration was to the recharge input in the FCID. The total recharge (precipitation, irrigation, and canal leakage) was increased by about 50% in order to match nearby head targets. Based on conversations with Mark Nielson at the Franklin Conservation District, residential irrigation is typically significantly higher than agricultural irrigation and a 50% increase was considered reasonable for this area.

4.5 SENSITIVITY ANALYSIS

An automated sensitivity analysis was performed to test the sensitivity of the model results to model input parameters. Input parameters tested in the sensitivity analysis were increased and decreased within reasonable ranges above and below the final calibrated values. Input parameters varied were: horizontal hydraulic conductivity (Kh), vertical hydraulic conductivity (Kz), specific yield (Sy), specific storage (Ss), recharge (R), pumping wells (Q), and river conductance (Criv). The results of the sensitivity analysis are shown in **Figure J-24** and discussed below.

4.5.1 Sensitivity Analysis Procedure

The Automatic Sensitivity Analysis feature in Groundwater Vistas 6.0 was employed to perform the analysis. Overall model sensitivity was assessed using the weighted sum of squared residuals (SSR) of the model targets. The lower the SSR statistic, the better the model matches the observed targets. The model targets are weighted between 0 and 1 for relative importance in the statistical calculation. As discussed in the calibration results, a few targets to the north near the Upper Ringold Province (T-12, T-14 and T-13) displayed long-term responses that were difficult to simulate and may reflect complexities in the hydrogeologic model that were not represented in the numerical model (e.g. hydrogeologic heterogeneities and perched aquifer conditions). An effort to include these complexities was not undertaken since the model assessment focused on hypothetical sites located further south in the model domain where a relatively good calibration was achieved. These targets were therefore assigned a weighted value zero. Furthermore, two additional head targets (T-5 and T-15) were assigned a weighted value of zero because actual water-level data for these targets included numerous fluctuating data points that may be due to the cycling on and off of a nearby pump (**Figure J-15** and **Figure J-20**).

4.5.2 Sensitivity Analysis Results

The results of the automated sensitivity analysis shows that adjusting calibrated values higher or lower generally results in a diminished match to observed targets, indicating the model is fairly well calibrated. The analysis showed that model results are most sensitive to recharge and horizontal hydraulic conductivity and least sensitive to vertical hydraulic conductivity and values of river conductance within reasonable ranges (model results were relatively insensitive to river conductance unless it is reduced by a factor of at least 200). Model results were somewhat sensitive to pumping and specific yield. The results suggest that a slightly higher value of specific yield may provide an overall improved match to absolute heads; however the specific yield values were already set relatively high throughout most of the model domain (**Figure J-24**) and values greater than 0.30 were considered outside acceptable ranges.

5.0 MODEL PREDICTIONS

The calibrated model was used to predict the retiming benefits associated with three hypothetical conservation sites (**Figure J-4**). Retiming benefits are evaluated with the groundwater flow model by assessing the damping and retiming associated with subsurface return flows to the Columbia and Snake Rivers. Damping and retiming in the vadose zone was simulated with an unsaturated flow model (**Appendix I**). Output from the vadose zone simulation was used as input for the predictive groundwater flow simulations.

Each hypothetical conservation site consisted of a single irrigation field:

- Block 1 Hypothetical Conservation Site (144 acres)
- Block 17 Hypothetical Conservation Site (162 acres)
- Greenbelt Hypothetical Conservation Site (113 acres)

Irrigation in Blocks 1 and 17 are sourced entirely by surface water, and retiming of subsurface irrigation return flow can be estimated by comparing the predicted timing of current (pre-conservation) and post-conservation return flow. As discussed in Section 4.1 of the main report,

RH2 assumed the maximum *theoretical* conservation and estimated post-conservation values of zero for irrigation recharge. Thus, retiming of irrigation recharge associated with a hypothetical site was evaluated based on just the estimated timing of pre-conservation irrigation recharge at the site(s). Conservation benefits associated with the Greenbelt (groundwater sourced irrigation) were assessed by evaluating the change in subsurface impacts from the combined effects of deep percolation and pumping under pre-conservation and post-conservation conditions.

The predictive model assumes 2009 irrigation rates (**Appendix A**); however, the total irrigated field areas in the model were not adjusted from 1986 conditions, largely because the small change in recharge to the model (1.5%) would not affect the predictive results.

The predictive model approaches for the two types of conservation assessments are presented below. Each predictive simulation was run using the calibrated model parameters. Uncertainties in the predictive results were assessed by performing each model simulation with higher and lower values of aquifer diffusivity. The aquifer diffusivity is the ratio of aquifer transmissivity to storativity (T/S), which is a measure of how fast a transient stress to the aquifer (i.e. recharge) will be transmitted though the aquifer system. Higher values of aquifer diffusivity result in less damping and retiming of subsurface return flow. Calibrated model parameters were adjusted for the uncertainty analysis as follows:

High Diffusivity: Hydraulic conductivity values in the calibrated model were *increased* by 50% and specific yield (Sy) was set to a relatively *low* value of 0.10.

Low Diffusivity: Hydraulic conductivity values in the calibrated model were *decreased* by 50% and specific yield (Sy) was set to a relatively *high* value of 0.30.

5.1 PREDICTIVE MODEL APPROACH BLOCK 1 AND BLOCK 17

PGG's approach for estimating the timing of subsurface return flow from hypothetical sites at Blocks 1 and 17 involved running a steady-state "base-case" simulation (without the hypothetical site) followed by a transient "predictive" simulation with pre-conservation recharge at the site. The annual recharge cycle was estimated with vadose zone modeling (**Appendix I**) and resolved into monthly average flux to the water table. The difference in river discharge predicted between these base-case and predictive simulations represents the timing of subsurface return flow from the site.

The above approach uses the principal of superposition, in which transient recharge at the site is superimposed upon a steady-state representation of all other conditions within the model domain. Superposition is appropriate where the groundwater flow system exhibits relatively linear behavior. PGG assessed the (transient) calibrated model for linearity, and found that seasonal water-level variations associated with regional variations in pumping and recharge vary aquifer transmissivity (a function of saturated thickness) by less than 10% over most of the model domain. This temporal variation of transmissivity is considered to be insignificant for predictive purposes, as such small changes are within the accuracy of the model and are not expected to significantly influence predictive model results. Predicted water-levels under the 2009 steady-state condition were similar to the calibrated (1986) values, thus suggesting that the model had approached quasi-steady state towards the end of the calibration period and that changes between 1986 and 2009 are minor. All of these observations support PGG's approach of superimposing transient recharge at the site(s) over a steady-state representation of the "background" flow system.

The steady-state base-case simulation simulates irrigation field recharge in the SCBID blocks and the Greenbelt based on 2009 annual average values of deep percolation (**Appendix A**)[4]. Recharge values in the FCID and Pasco High Density irrigation zones were simulated at their 1986 calibrated values. (Note that the model is fairly insensitive to such small variations in field recharge.) Annual average pumping rates in the Pasco Greenbelt were also updated using 2009 estimates of total application (**Appendix A**). Irrigation recharge from the hypothetical sites were also simulated based on average estimated 2009 irrigation recharge for the two blocks (**Appendix I**).

The transient model of the hypothetical site was run repeatedly with final heads from one year serving as initial heads for the next year until a cyclic steady-state condition was achieved. A minimum of 25 years of transient simulation was performed, although longer periods were sometimes required to achieve cyclic steady state. A cyclic steady-state solution predicts groundwater heads and model fluxes that change from month to month, but are consistent from one year to the next.

The transient recharge flux applied to the hypothetical site was less than 0.1 percent of the total flux through the model and therefore there was potential for mass balance errors in the numerical simulation to affect the predictive results. In order to increase the predictive "signal-to-noise ratio", the transient recharge flux was increased by a factor of 10 prior to running the simulations, and model results were scaled back by a factor of ten. The use of a 10x multiplier has insignificant effect on model predictions as increased groundwater levels were less than 0.5-ft and model linearity was therefore maintained.

Current (pre-conservation) subsurface return flow to the river was evaluated by calculating the *change* in simulated fluxes to the river between the steady-state base-case model and the transient predictive model. Fluxes to the Columbia River, drain cells along the Esquatzel Coulee Wasteway, and the short reach of Snake River above its confluence with the Columbia River were all added together to obtain estimates of net return flow to all surface-water features. The Esquatzel Coulee Wasteway provides fairly rapid return-flow back to the Columbia River, and represents a small (e.g. 1%) portion of the return flow predicted from the sites. The modeled reach of the Snake River is occupied by Lake Wallula, which is ultimately controlled by reservoir levels within the Columbia River. Model simulation of post-conservation recharge from the hypothetical sites was unnecessary due to the assumption of zero recharge.

5.2 PREDICTIVE MODEL APPROACH GREENBELT

The predictive modeling approach for the Pasco Greenbelt hypothetical site involved two seasonal transient simulations; one representing pre-conservation conditions and one representing post-conservation conditions. Because the Greenbelt is groundwater sourced, the conservation benefit of a hypothetical site at this location needs to consider the change in the net effect of combined irrigation pumping and irrigation recharge under both conditions. Modeled pumping rates are based on RH2's estimates of total application, as presented in **Appendix I** for both pre-conservation and post-conservation conditions. Modeled irrigation recharge at the water table is based on vadose-zone modeling of RH2's estimated deep percolation losses, also presented in **Appendix I**.

[4] Total irrigation applications and associated deep percolation losses for 2009 were based on the WAIE method. Differences between the WAIE and MWD methods are minor relative to the accuracy of estimation.

Transient simulations at the Greenbelt site involved monthly stress periods over which annual cycles of "net recharge" (R_N = recharge minus pumping) were simulated. Monthly values of R_N can be negative when pumping exceeds irrigation recharge to the water table. Whereas the pre-conservation R_N values are based on combined values of monthly pumping and monthly recharge to the water table, the post-conservation R_N values are based purely on monthly pumping (as field recharge is assumed to be zero under conservation conditions).

Both transient models were run repeatedly with final heads from one year serving as initial heads for the next year until a cyclic steady-state condition was achieved. A minimum of 25 years was simulated. As with the other two sites, the transient recharge flux applied to the hypothetical site was less than 0.1 percent of the total flux through the model and therefore the net recharge flux (R_N) was increased by a factor of ten to filter out potential numerical noise and results were scaled back by a factor of ten.

River impacts associated with each transient simulation were evaluated by calculating the difference in predicted river fluxes between the steady-state base-case simulation and the transient predictive simulation. As with the other two sites, changes to river fluxes were evaluated at both river boundary conditions and drains boundary conditions. Conservation benefits associated with the Greenbelt site could then calculated as the change in "River Impact" between the pre- and post-conservation conditions.

5.3 PREDICTIVE RESULTS

Predictive results for the hypothetical field sites in Block 1 and Block 17 suggest that subsurface return flows from both sites to the receiving surface-water bodies are highly damped (**Figure**s **J-25** and **J-26**). Higher and lower values of aquifer diffusivity did not significantly change the damping affect.

Predictive results for the hypothetical field site in the Greenbelt show that the river impacts are reduced under post-conservation conditions relative to pre-conservation conditions (**Figure**s **J-27** and **J-28**). The change in river impact between pre and post-conservation conditions is used to estimate the conservation benefit.

Conservation benefits estimated based on the predictive results discussed above are addressed in Section 4.4.3 of the main report.

Aquifer Storage Zone	Specific Storage (Ss)	Specific Yied (Sy)	Hydraulic Conductivity Zone	Kh (ft/day)	Kz (ft/day)
1	0.0001	0.30	1	6000	600
2	0.0001	0.30	2	1000	100
3	0.0001	0.30	3	6000	600
4	0.0001	0.30	4	4000	400
5	0.0001	0.25	5	1000	100
6	0.0001	0.30	6	6000	600
7	0.0001	0.20	7	400	4
8	0.0001	0.30	8	4000	400
9	0.0001	0.25	9	1000	100
10	0.0001	0.30	10	6000	600
11	0.0001	0.20	11	1000	10
12	0.0001	0.15	12	2000	200
13	0.0001	0.15	13	5000	500

Canals and Wasteways	Type	Width (ft)	Leakage Rate (ft/day)	Total Length	Volumetric Flux (cfd)	Volumetric Flux (ac-ft/yr)
Eltopia Branch	Canal	38	0.7	34,384	914,614	7,669
Esquatzel Coulee Diversion	Canal	40	0.4	54,447	871,152	7,304
Block 1 PPL1	Lateral	5	0.4	47,971	95,942	804
Laterals	Lateral	6	0.7	245,246	1,030,033	8,637
Esquatzel Coulee	Wasteway	40	3	43,367	5,204,040	43,634
Smith Canyon	Wasteway	40	6	20,439	4,905,360	41,130
Wasteways	Wasteway	30	2	57,187	3,431,220	28,770
Wasteways, Main	Wasteway	40	2	59,418	4,753,440	39,856

Table J-1
SFC: Final MODFLOW Model Calibration Parameter Values

Franklin Conservation District
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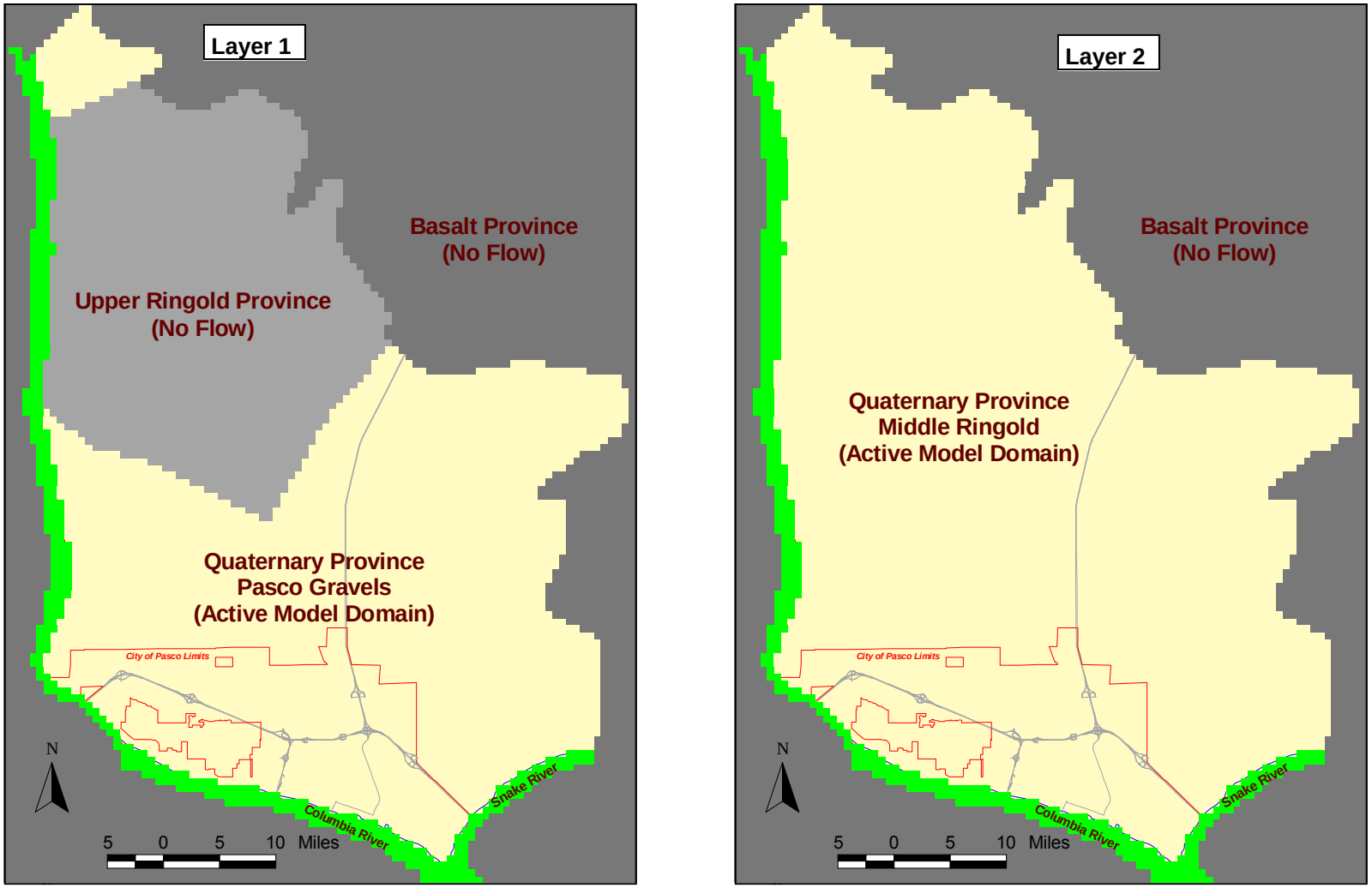

Figure J-1
SFC: Modeled Domain and Hydrogeologic Provinces

Franklin Conservation District
Retiming Benefits Analysis

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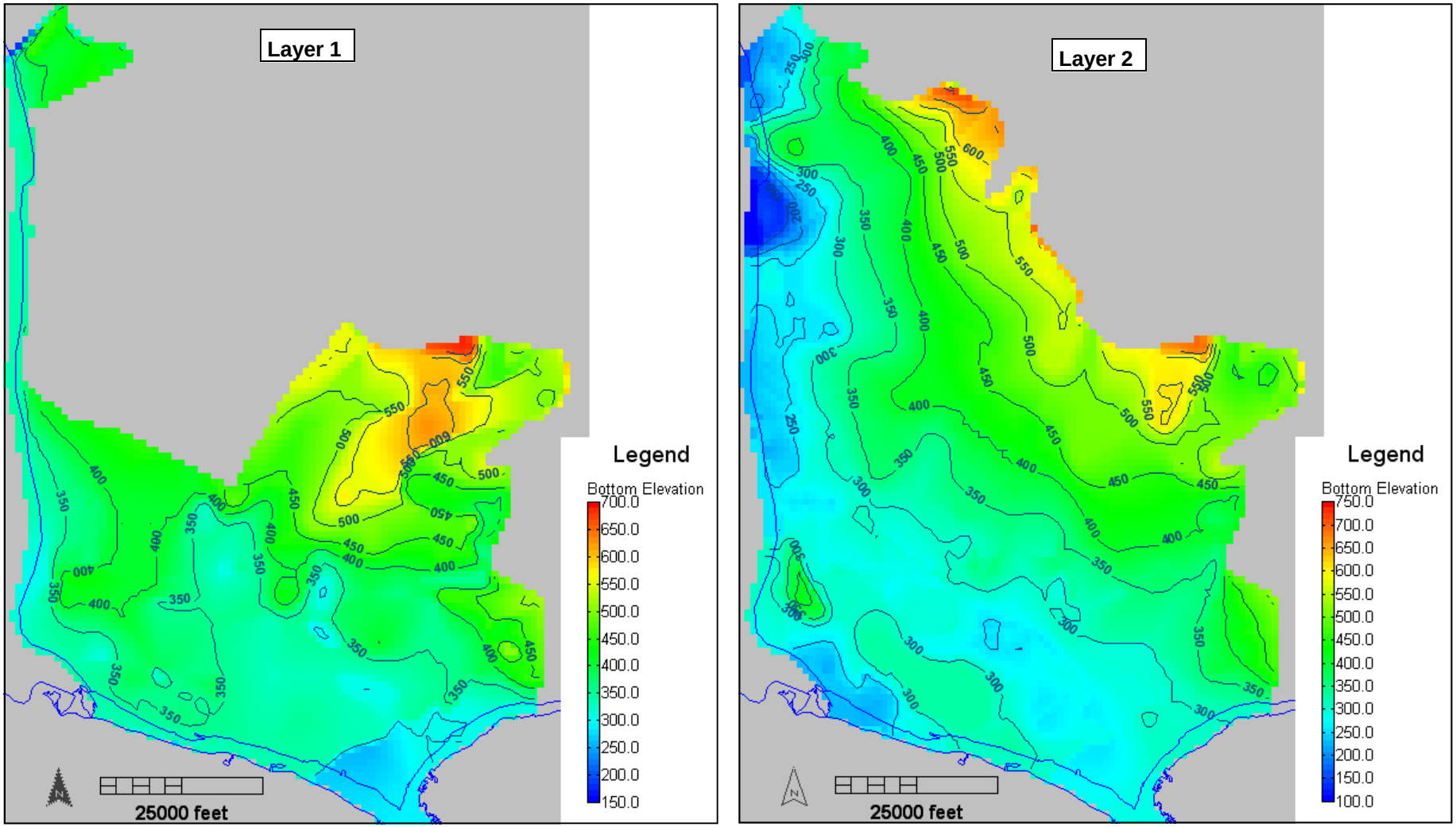

Figure J- 2
SFC: Model Bottom Elevations

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Retiming Benefits Analysis

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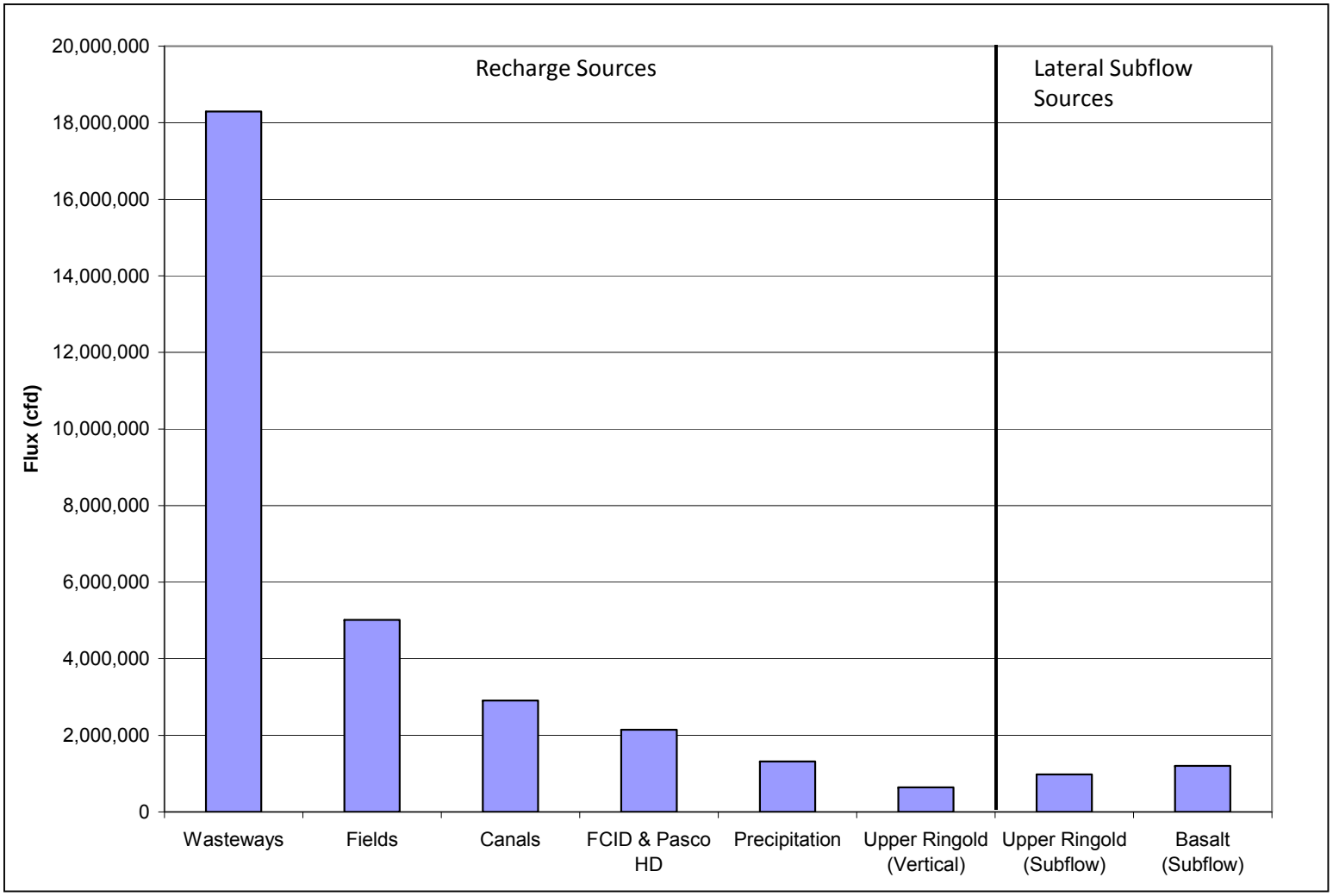

Figure J-3
SFC: Model Inflow Sources (1985 Annual Average)

Franklin Conservation District
Retiming Benefits Analysis

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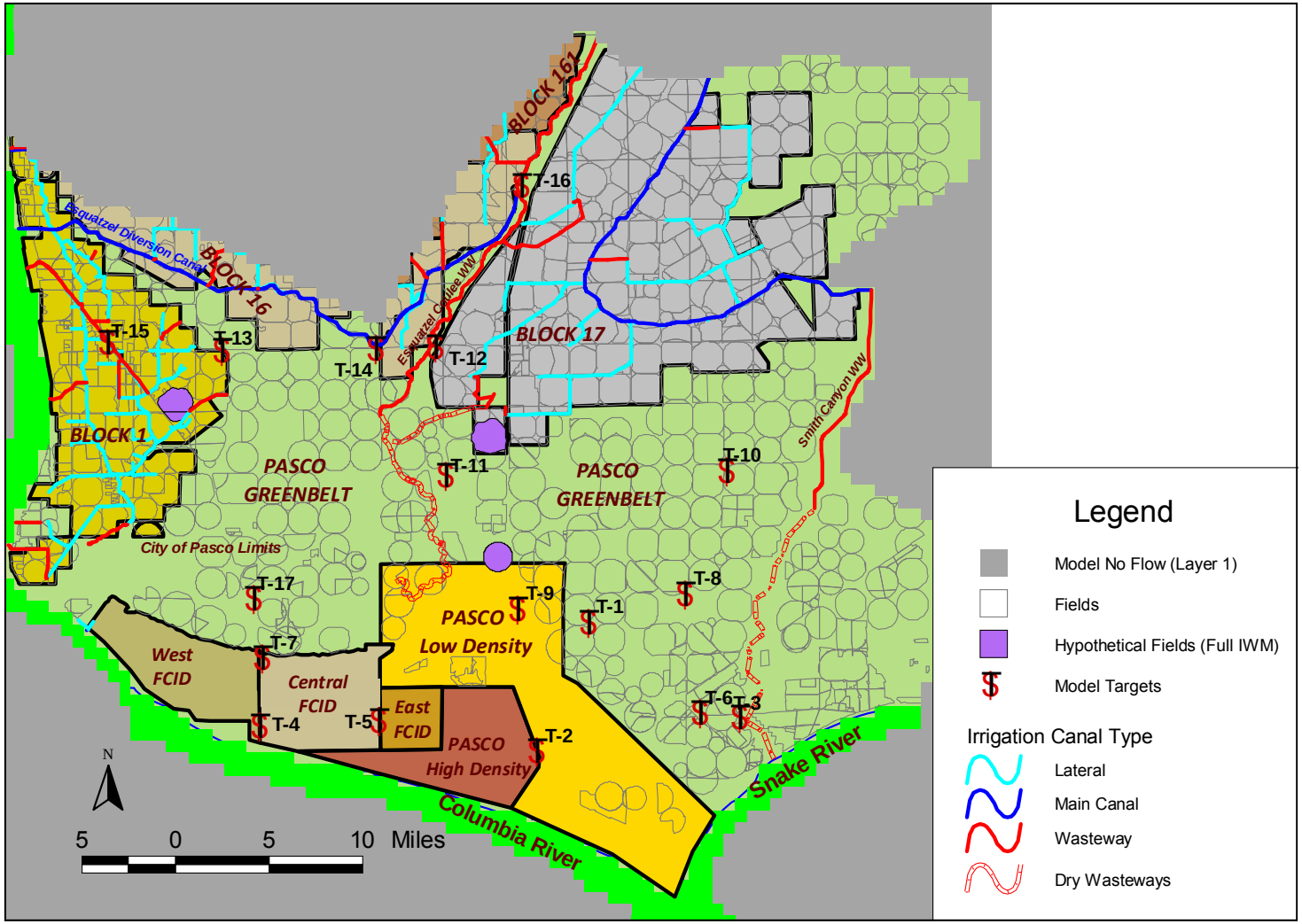

Figure J-4
SFC: Modeled Irrigation Zones and Features

Franklin Conservation District
Retiming Benefits Analysis

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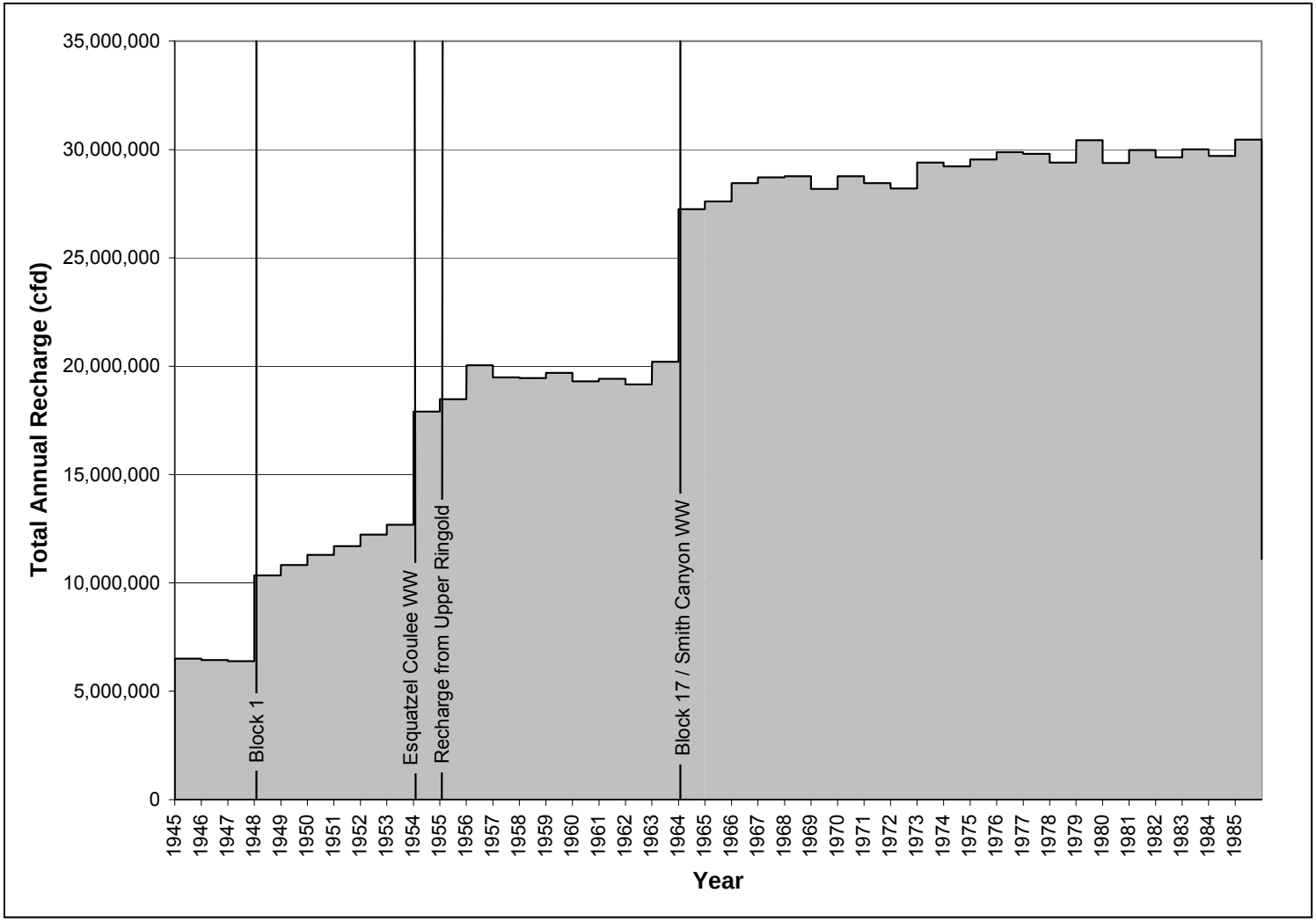

Figure J-5
SFC: Total Annual Recharge Applied to Model (ft^3/day)

Franklin Conservation District
Retiming Benefits Analysis

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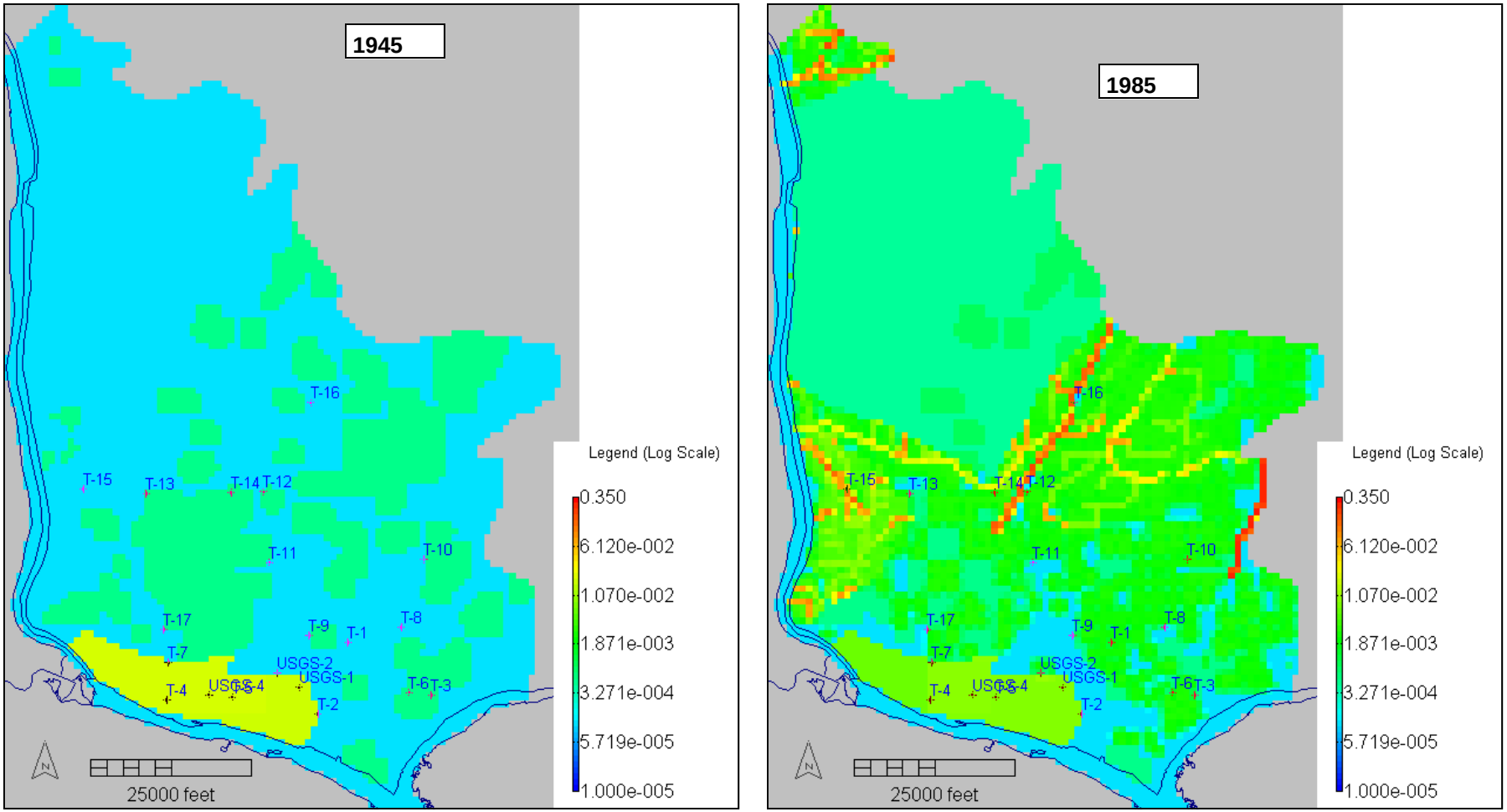

Figure J-6
SFC: Model Annual Recharge Rates (ft/day)

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Retiming Benefits Analysis

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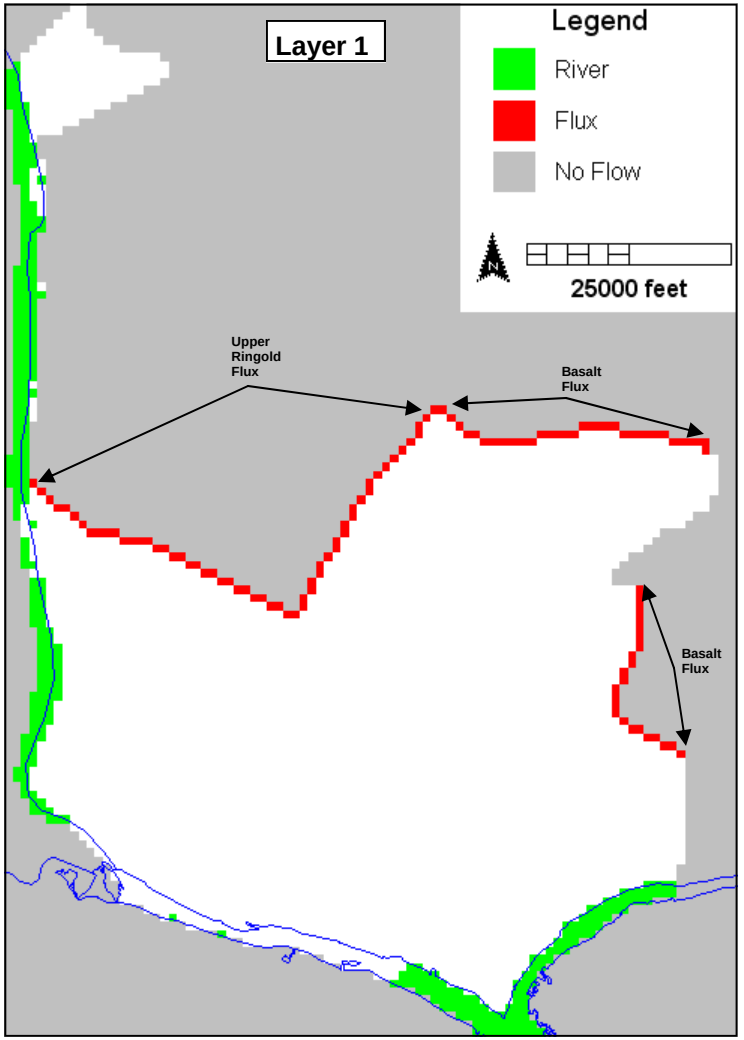

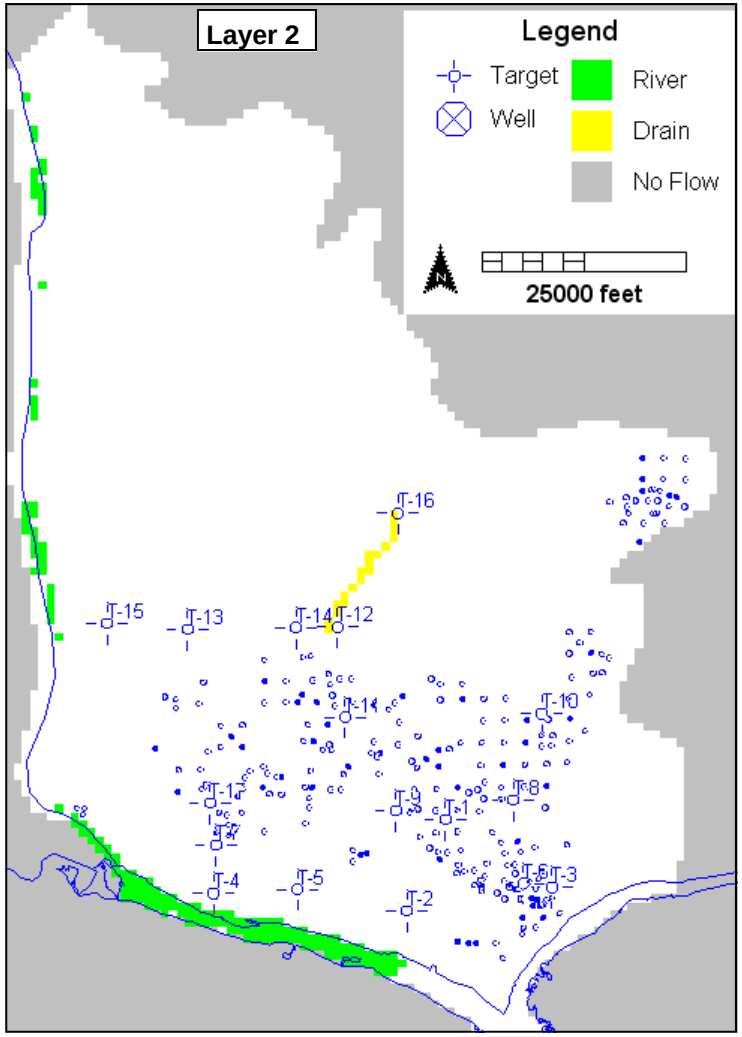

Figure J-7
SFC: Model Boundary Conditions and Head Targets

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Retiming Benefits Analysis

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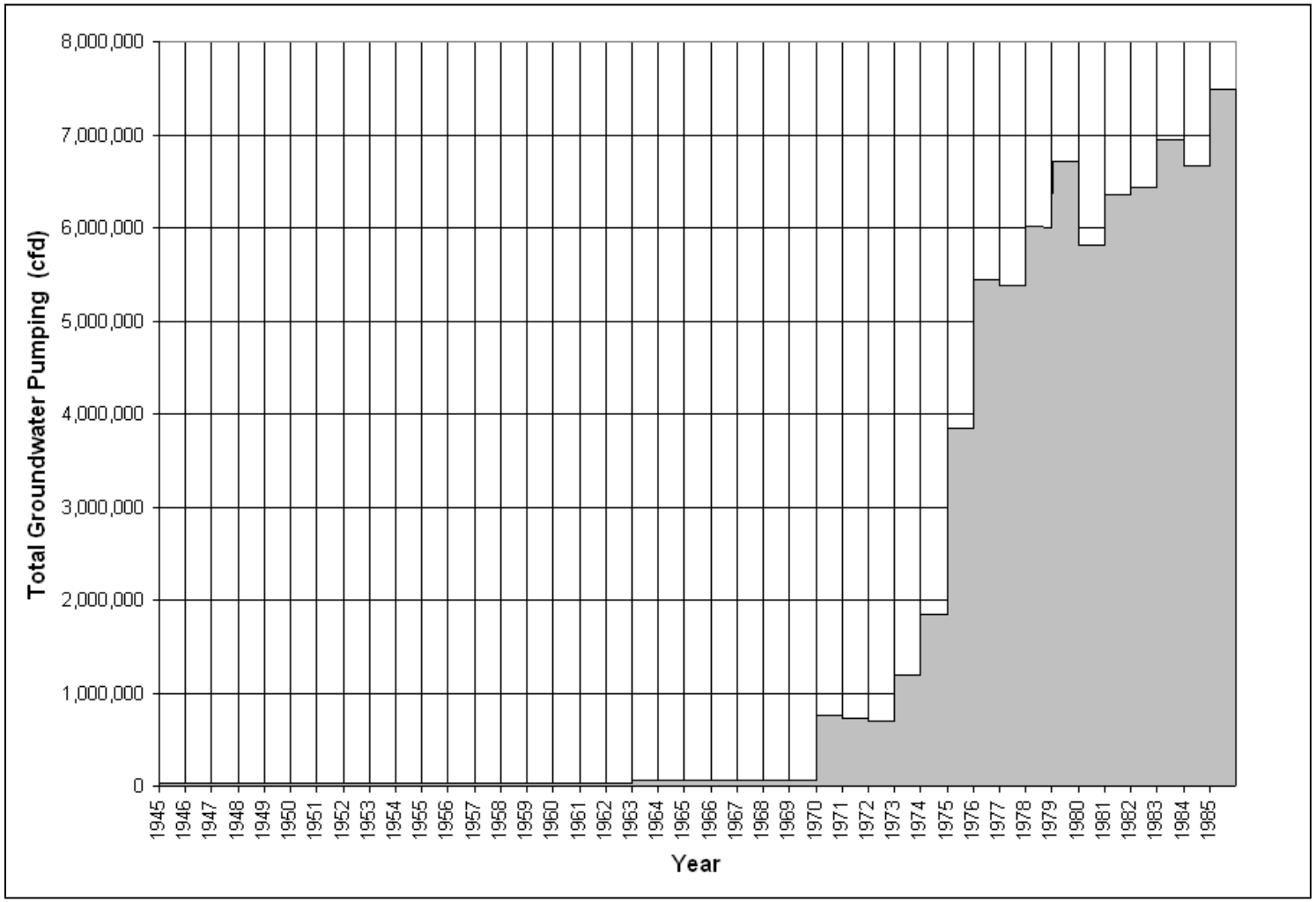

Figure J-8
SFC: Simulated Groundwater Pumping from the Greenbelt Zone

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Retiming Benefits Analysis

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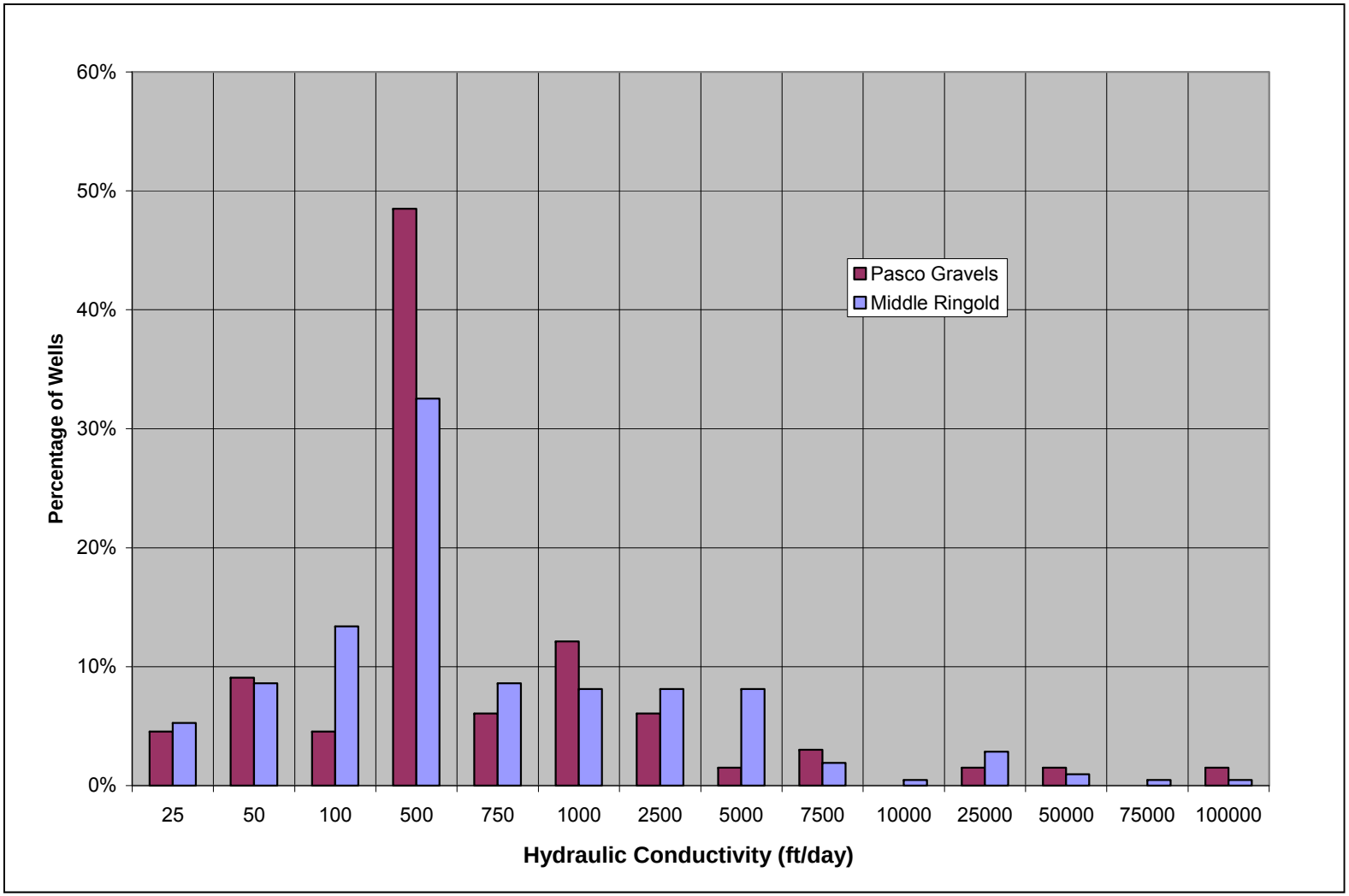

Figure J-9
SFC: Hydraulic Conductivity Distribution from Specific Capacity Data

Franklin Conservation District
Retiming Benefits Analysis

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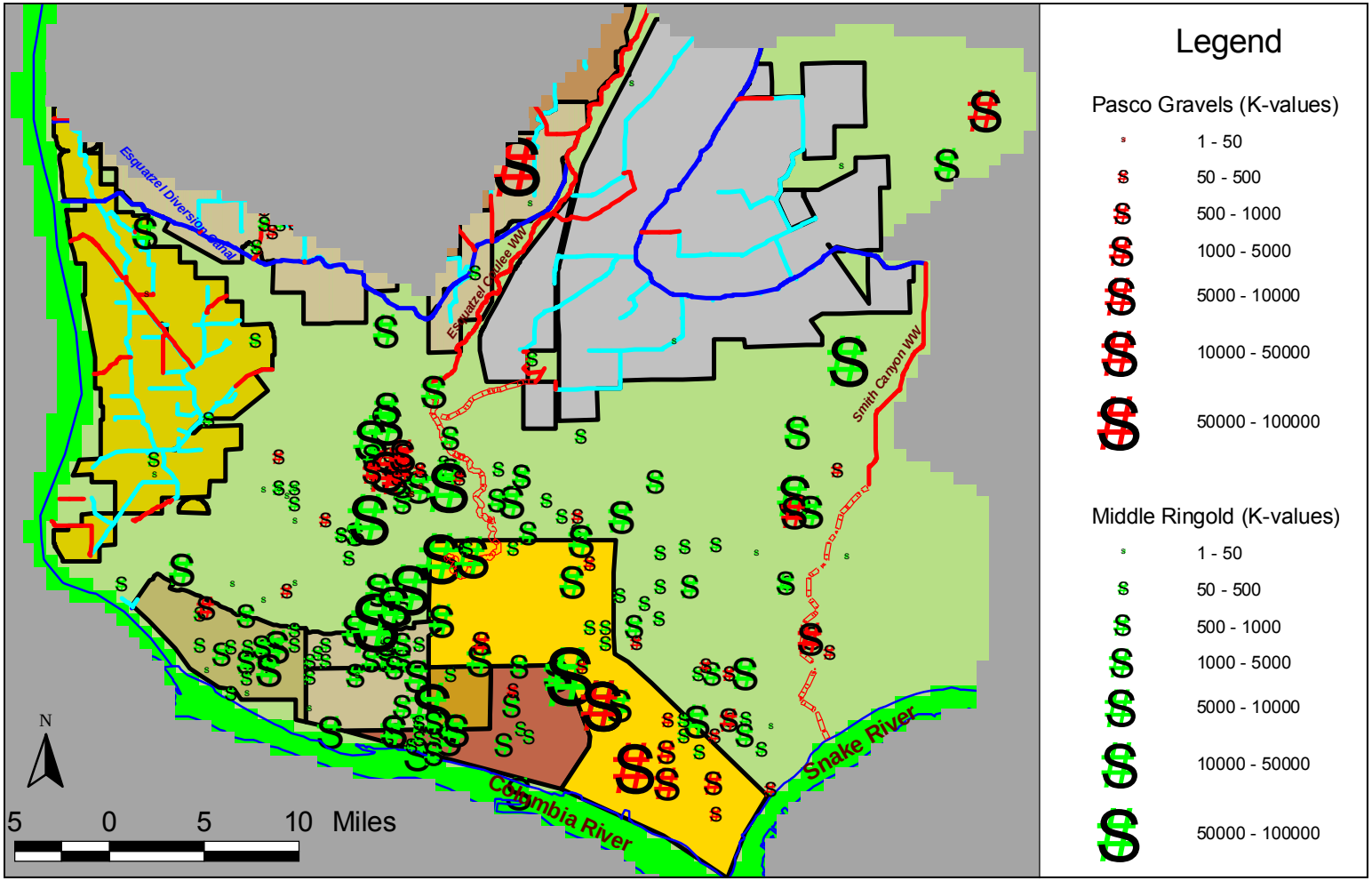

Figure J-10
SFC: Hydraulic Conductivity Map (ft/day) from Specific Capacity Data

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Retiming Benefits Analysis

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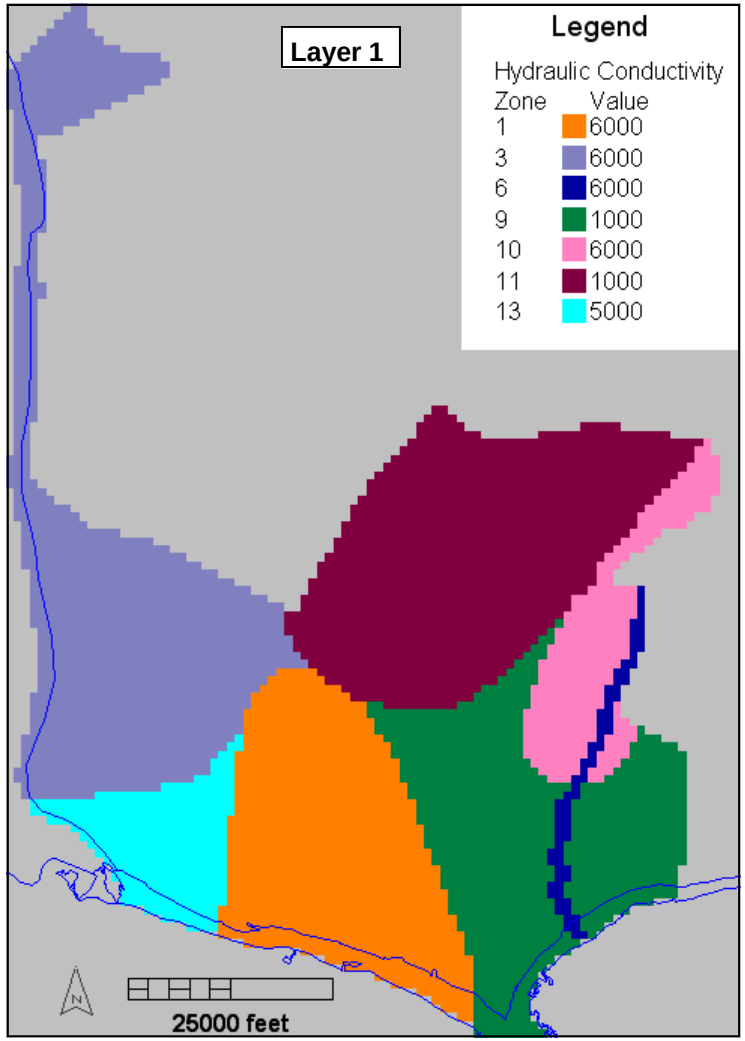

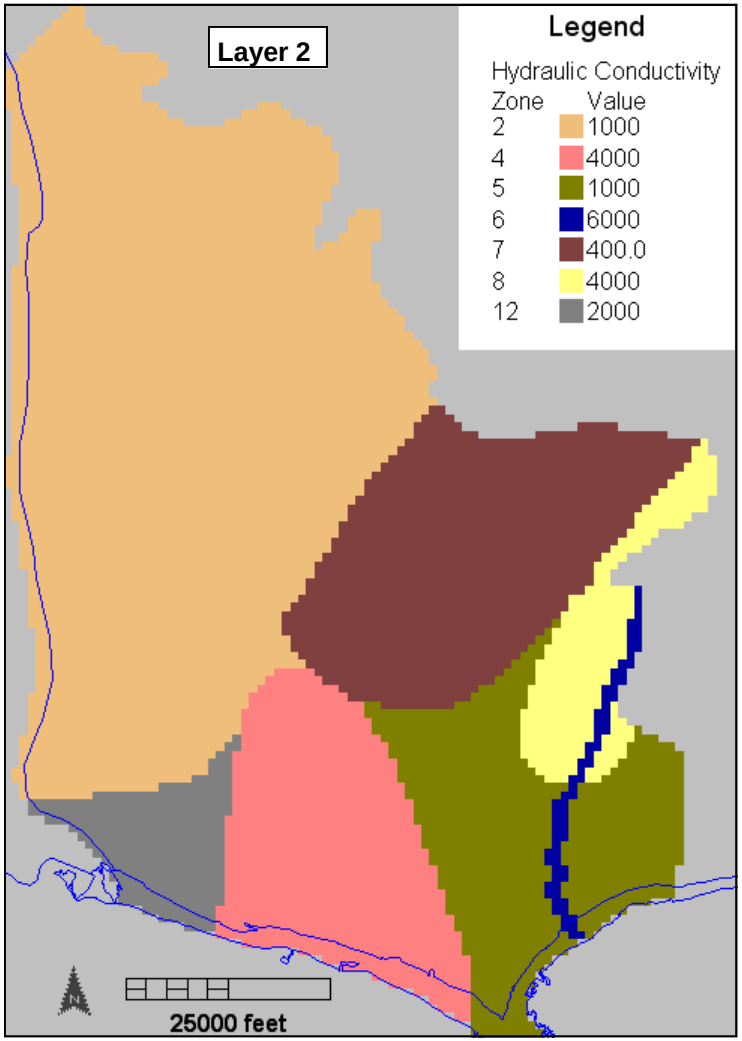

Figure J-11
SFC: Model Hydraulic Conductivity

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Retiming Benefits Analysis

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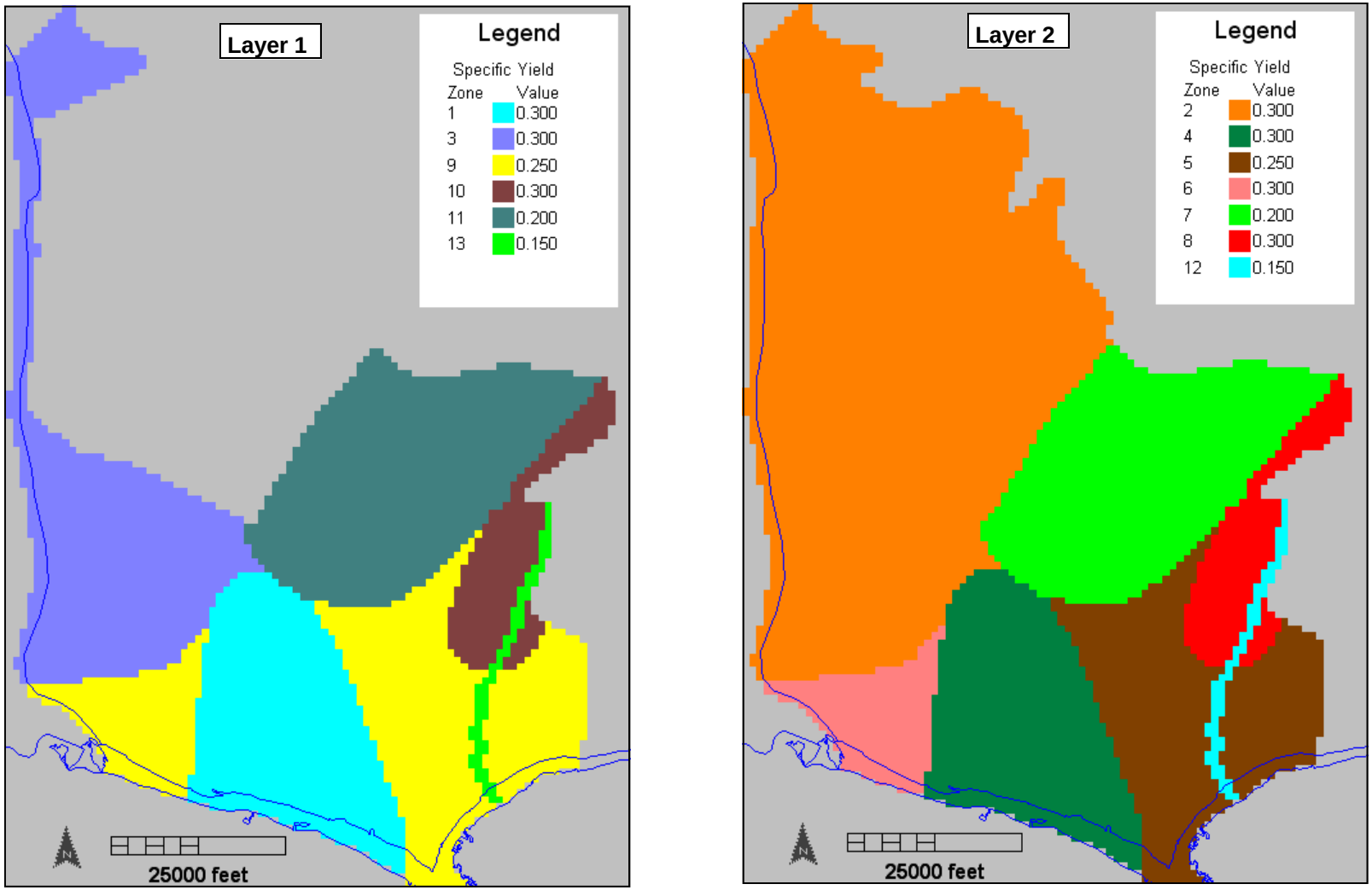

Figure J-12
SFC: Model Specific Yield

Franklin Conservation District
Retiming Benefits Analysis

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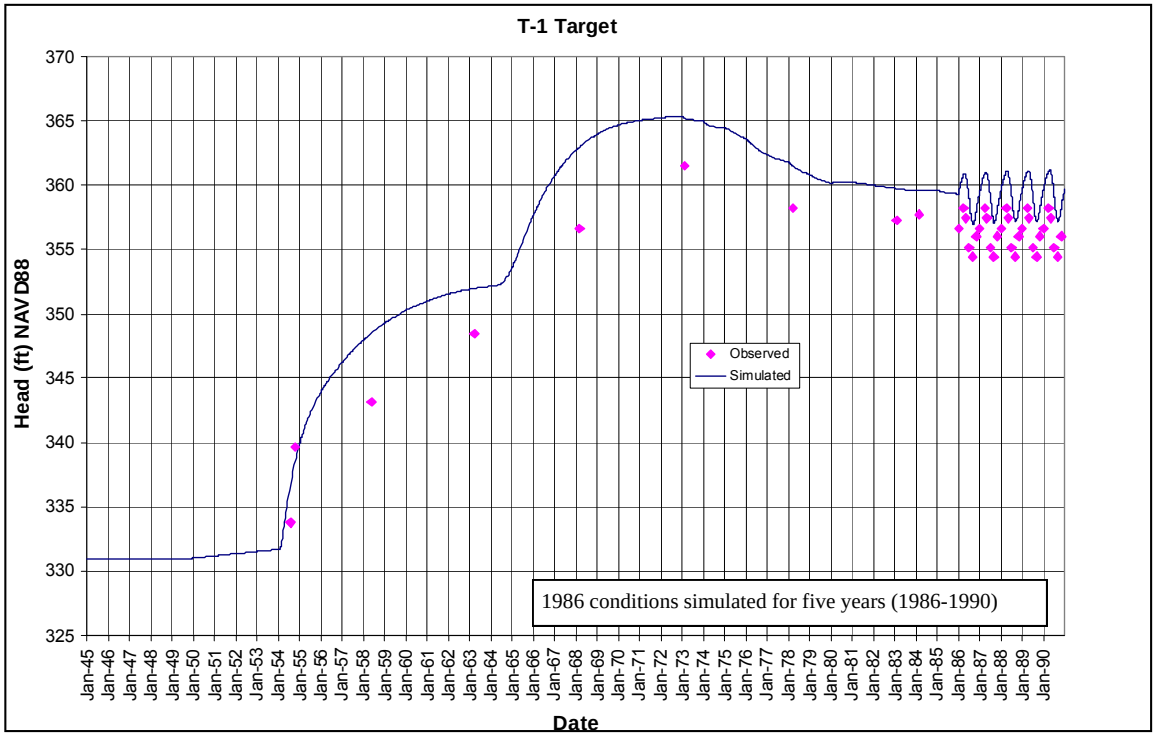


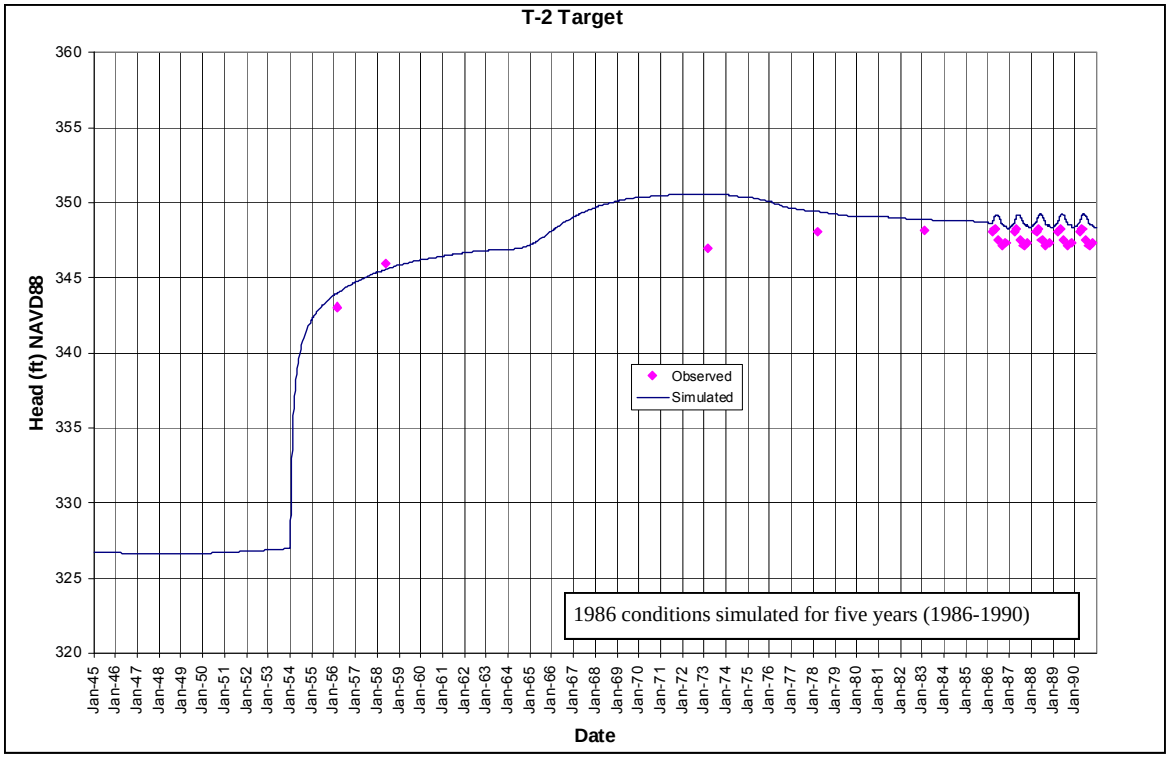
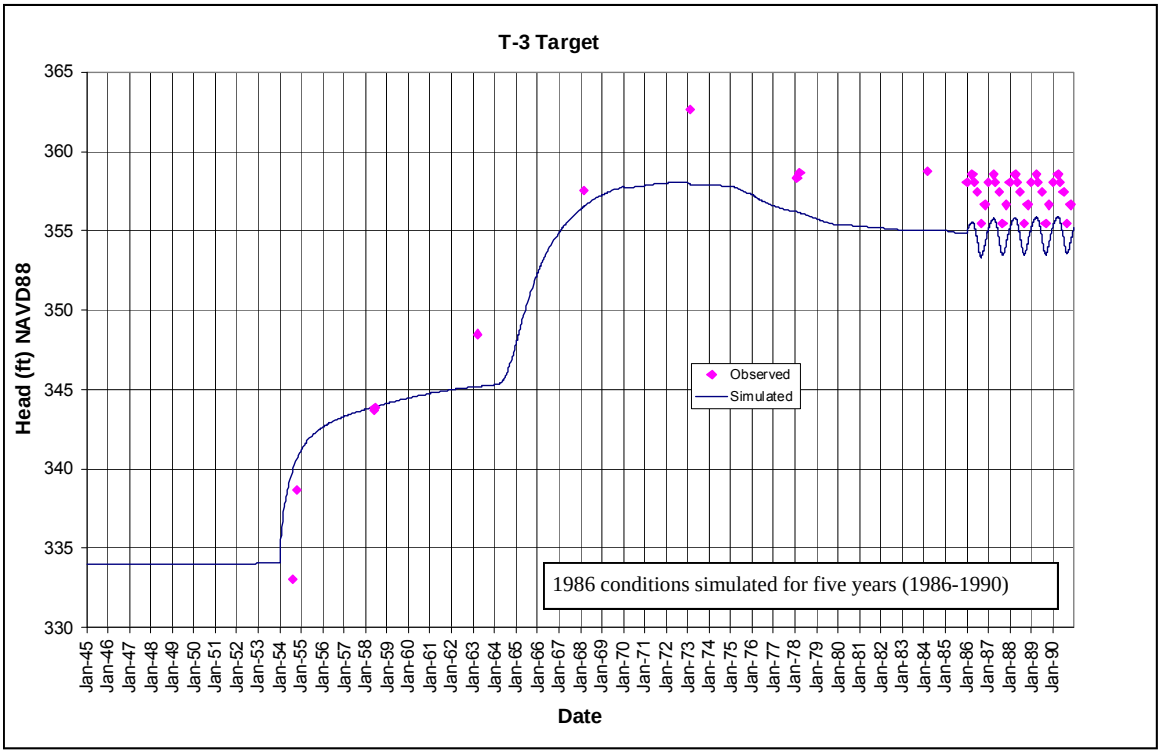


Figure J-13
SFC: Calibration Results (Targets T-1 and T-2)

Franklin Conservation District
Retiming Benefits Analysis



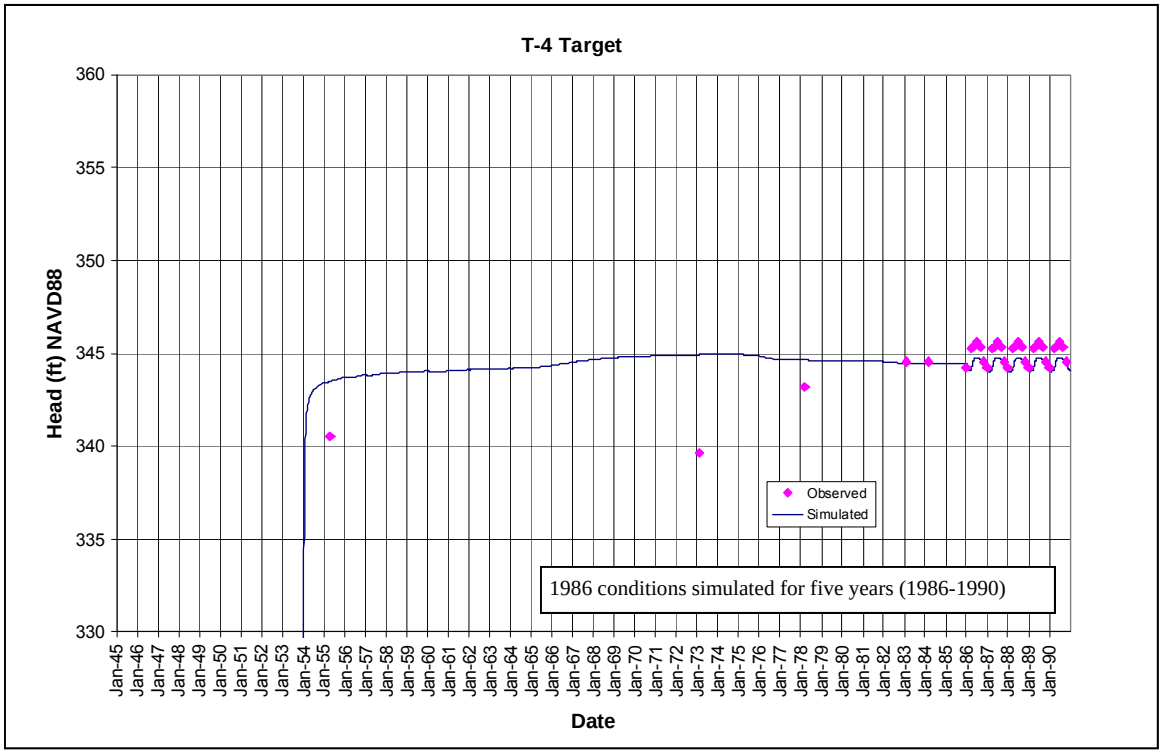
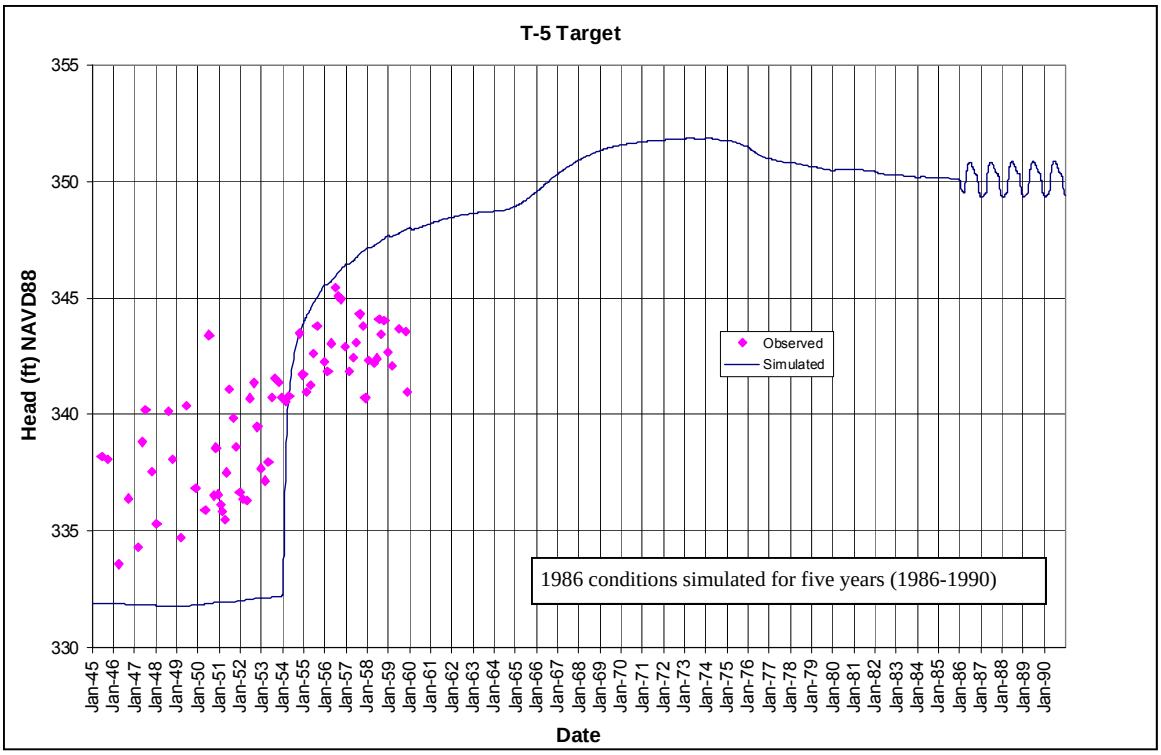


Figure J-14
SFC: Calibration Results (Targets T-3 and T-4)

Franklin Conservation District
Retiming Benefits Analysis



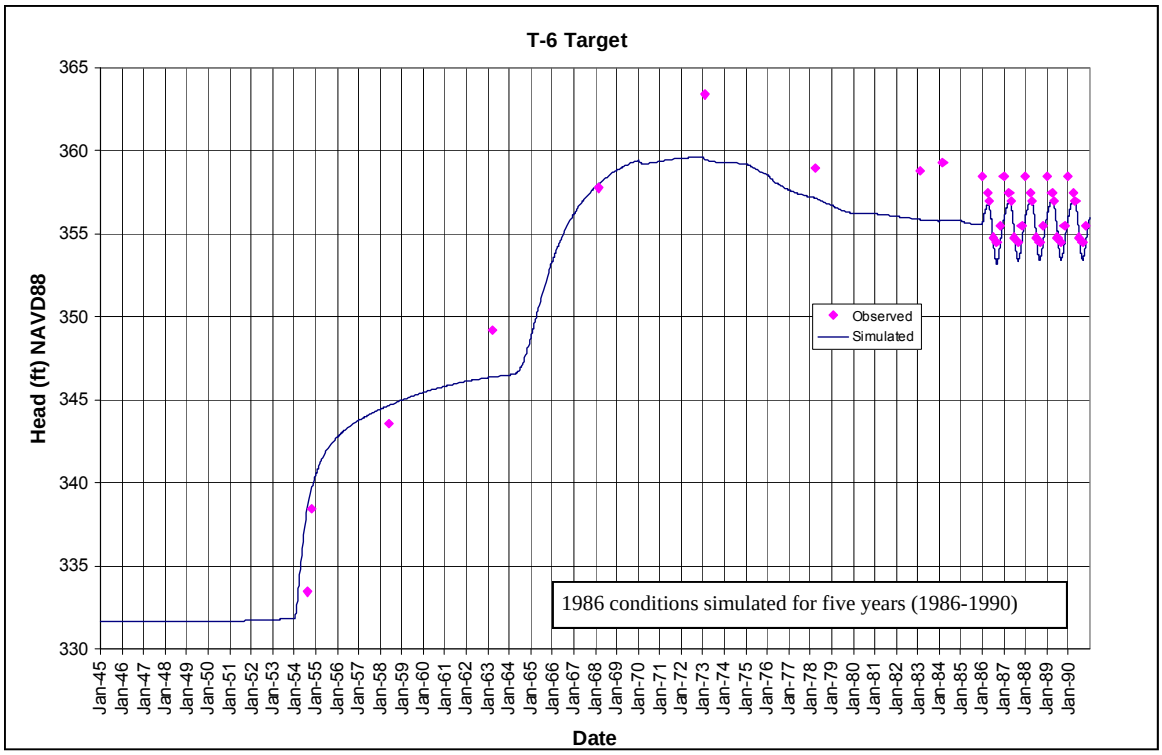
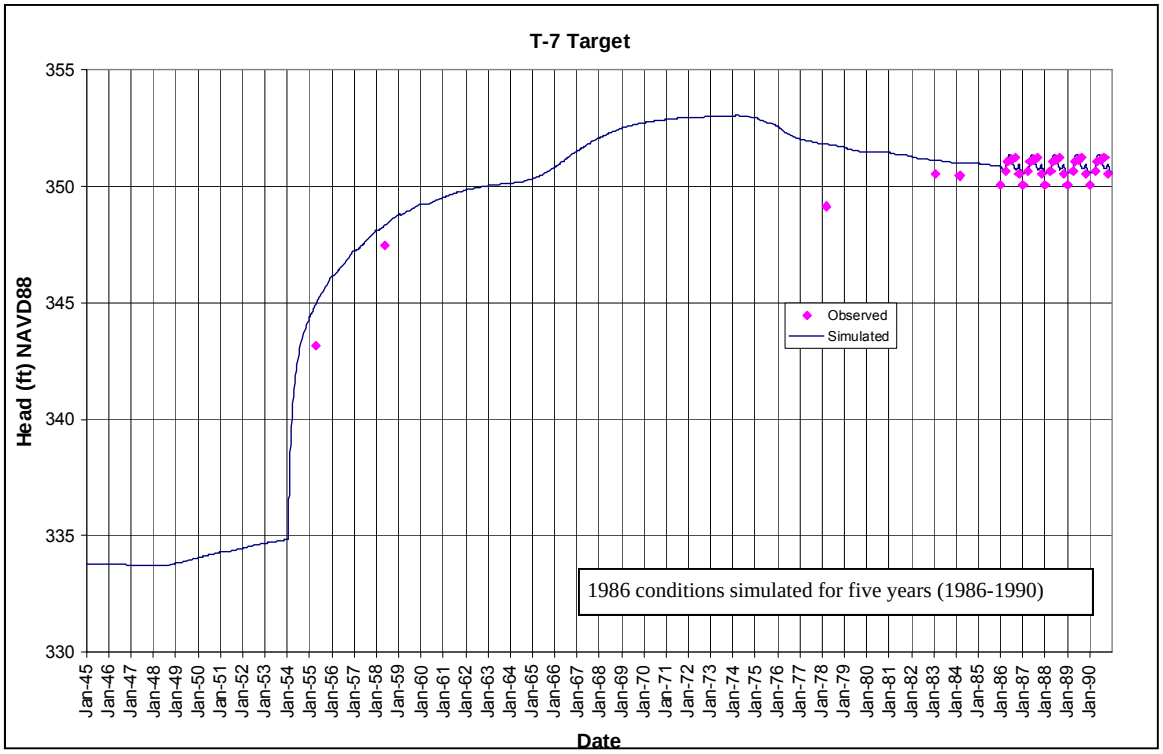


Figure J-15
SFC: Calibration Results (Targets T-5 and T-6)

Franklin Conservation District
Retiming Benefits Analysis



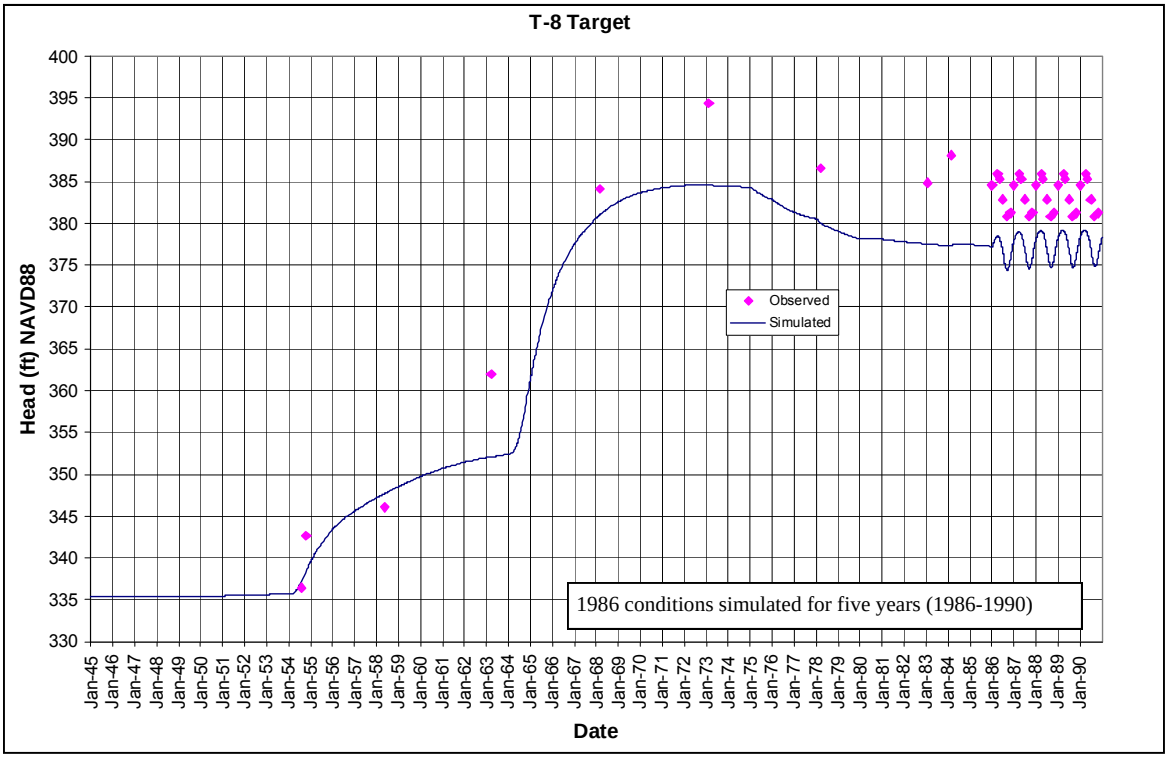
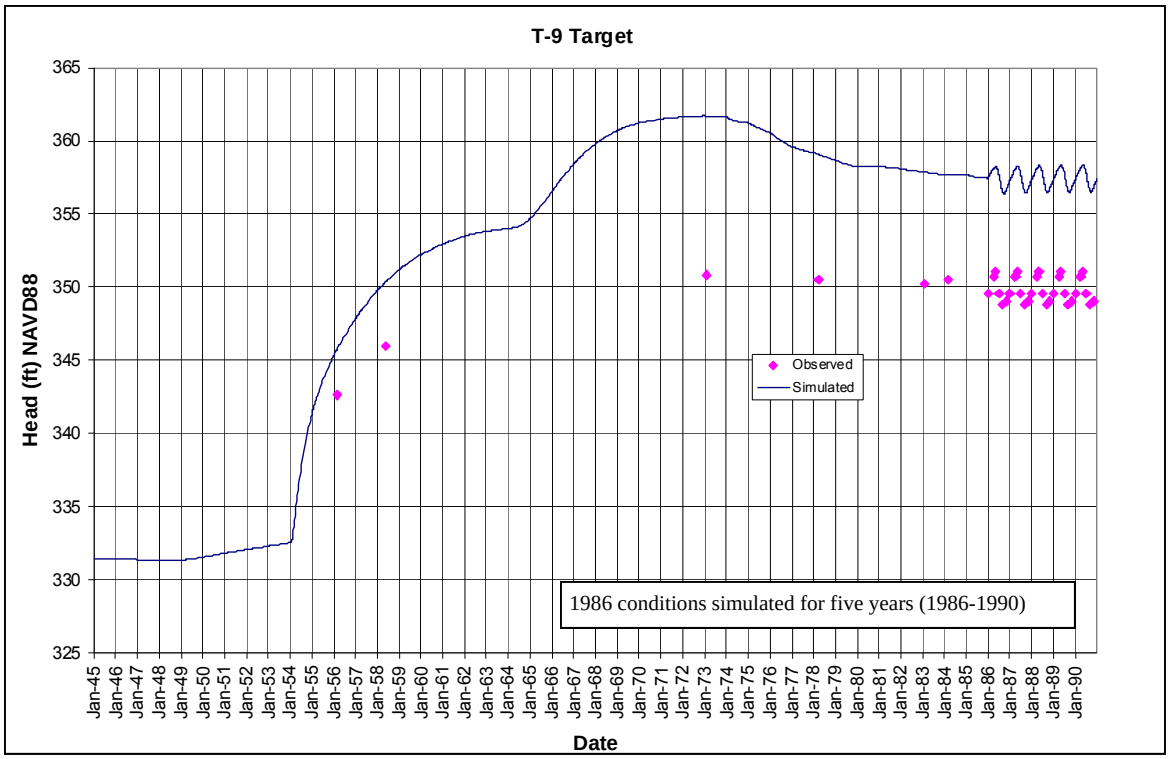


Figure J-16
SFC: Calibration Results (Targets T-7 and T-8)

Franklin Conservation District
Retiming Benefits Analysis



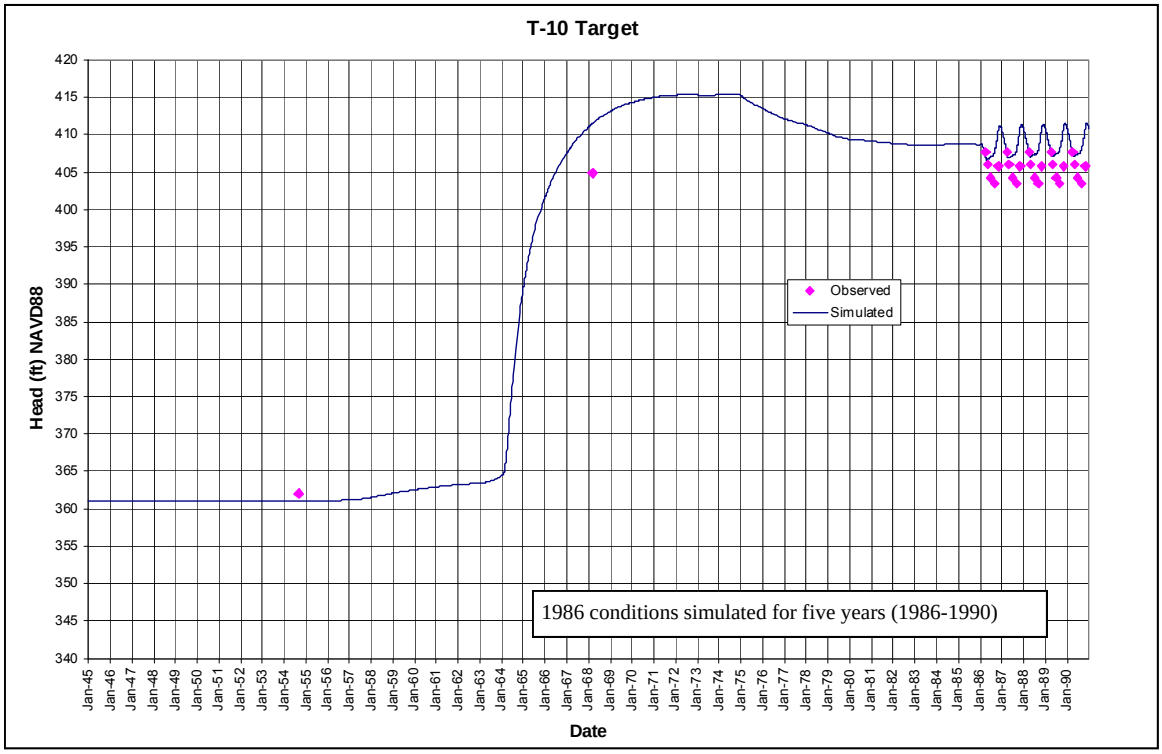
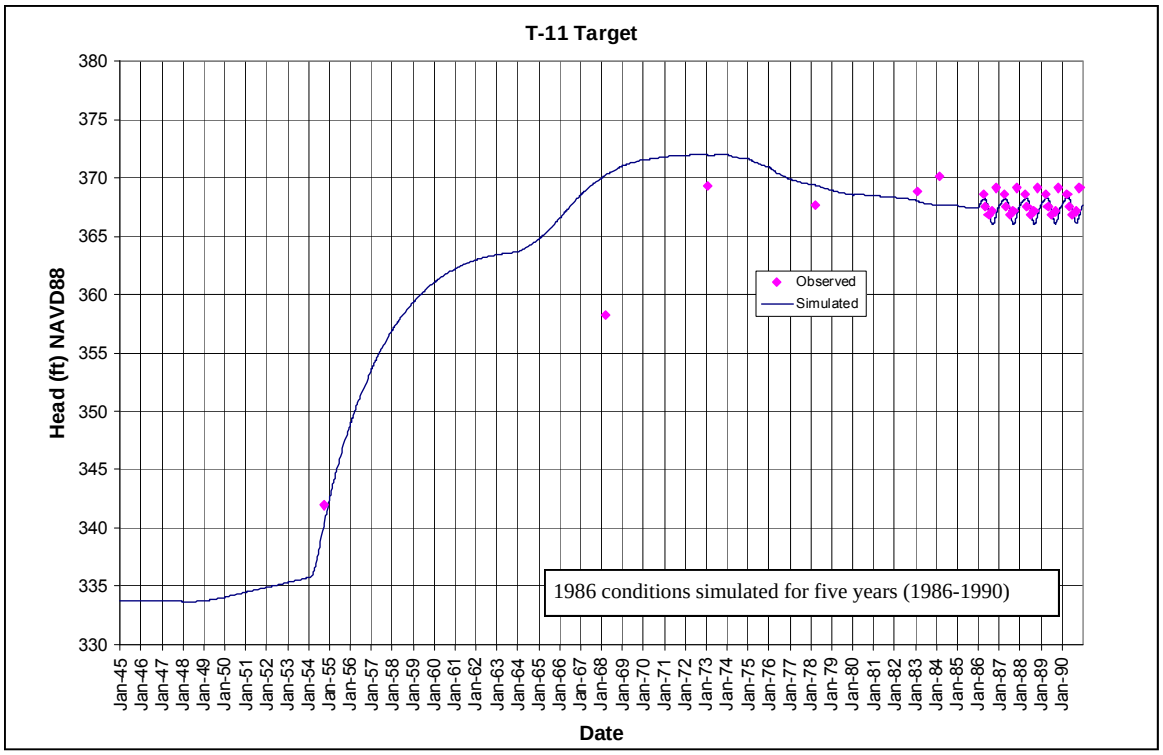


Figure J-17
SFC: Calibration Results (Targets T-9 and T-10)

Franklin Conservation District
Retiming Benefits Analysis



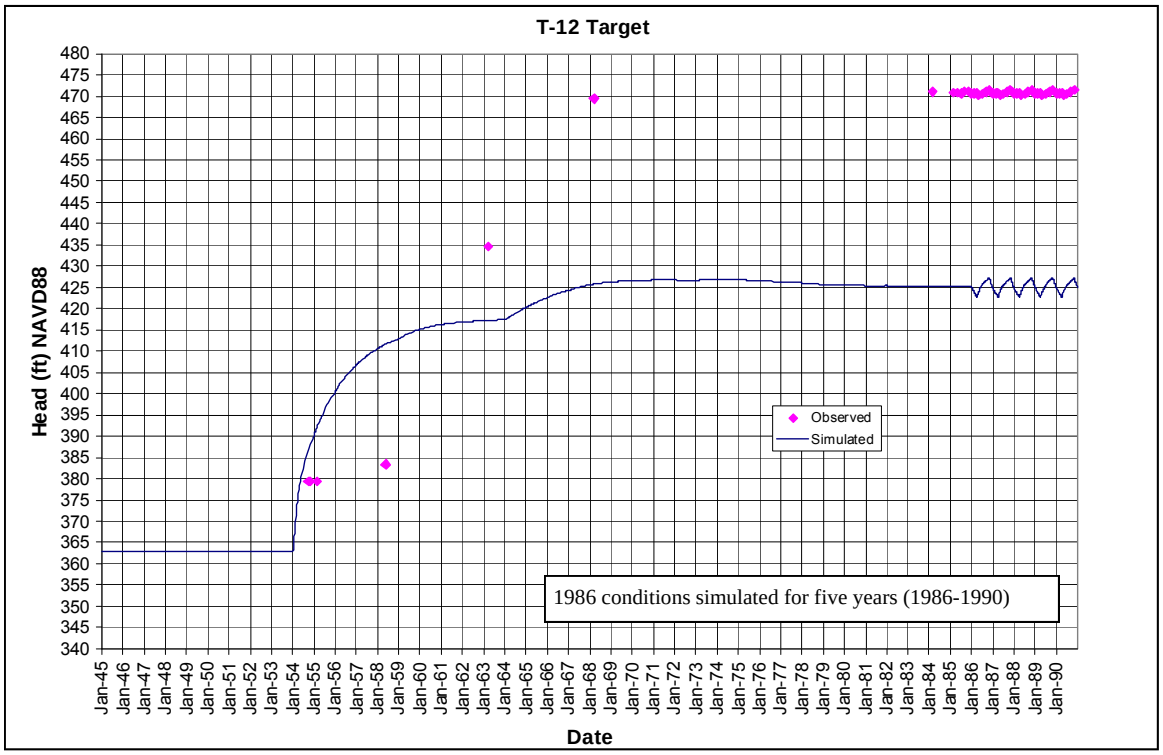
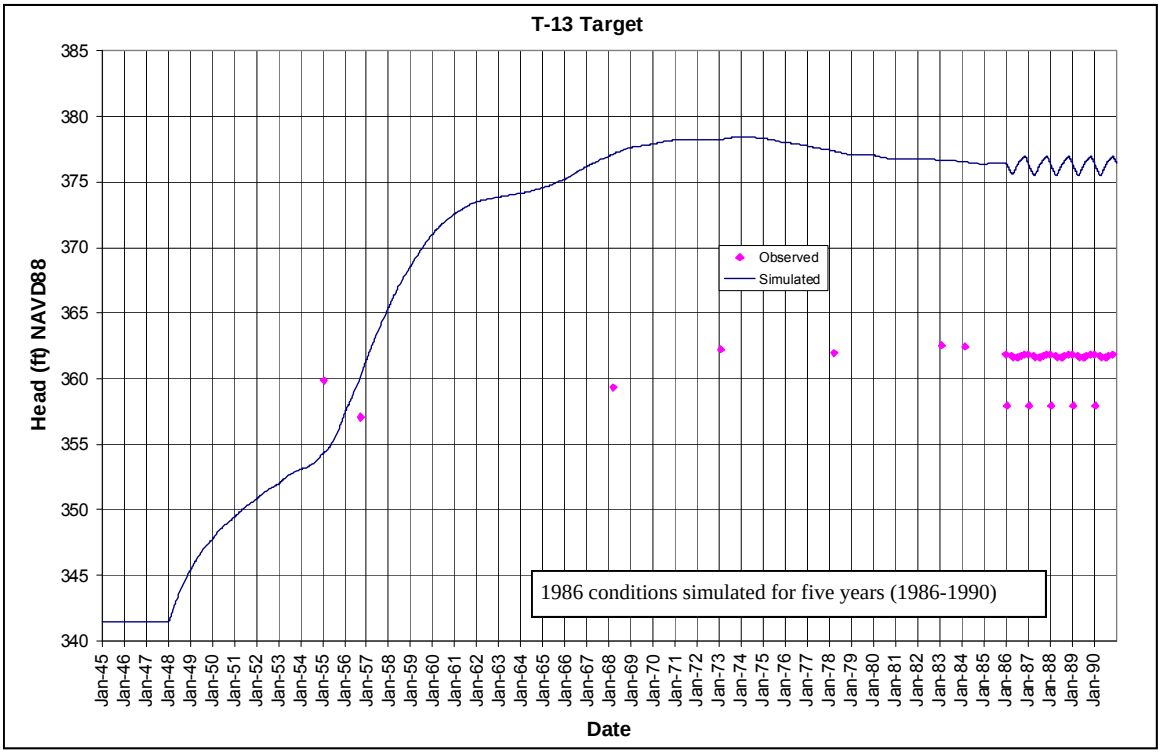


Figure J-18
SFC: Calibration Results (Targets T-11 and T-12)

Franklin Conservation District
Retiming Benefits Analysis



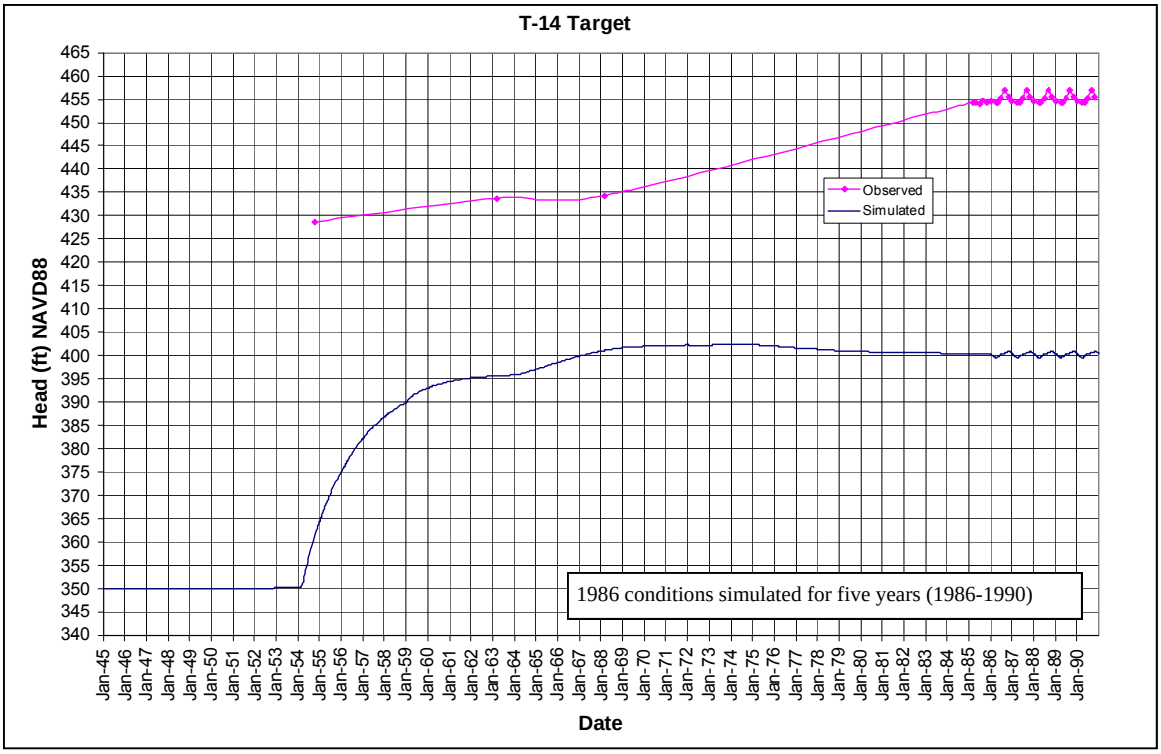
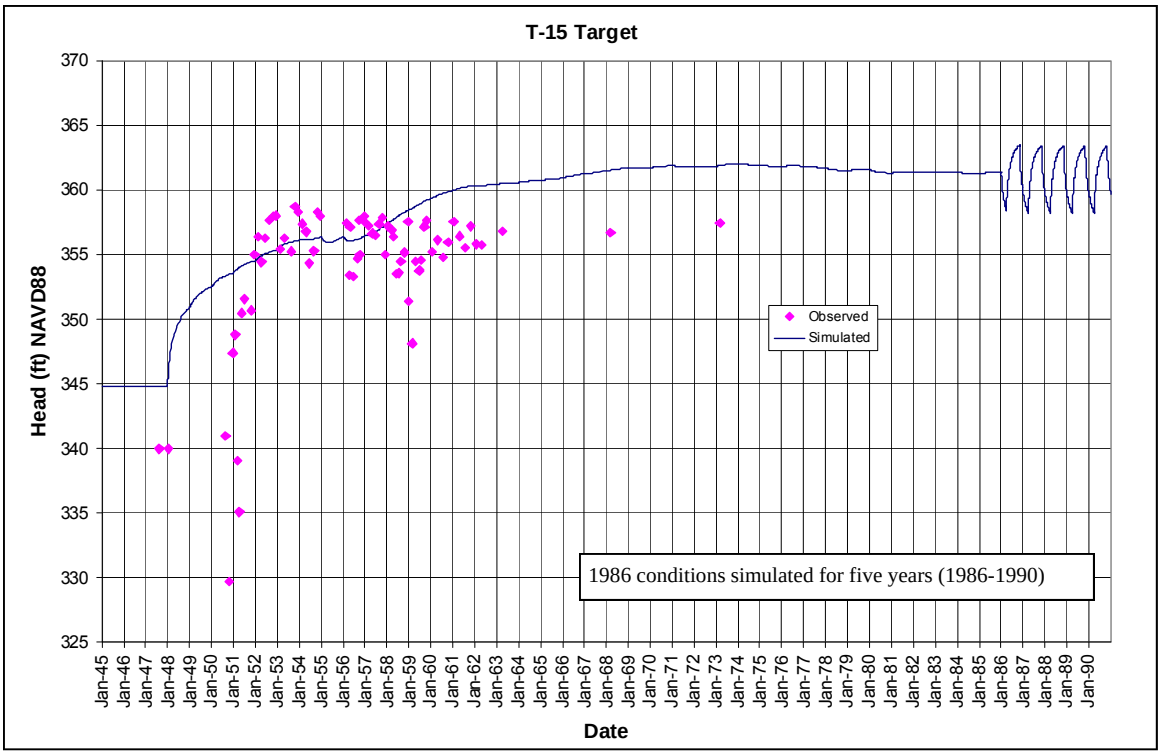


Figure J-19
SFC: Calibration Results (Targets T-13 and T-14)

Franklin Conservation District
Retiming Benefits Analysis



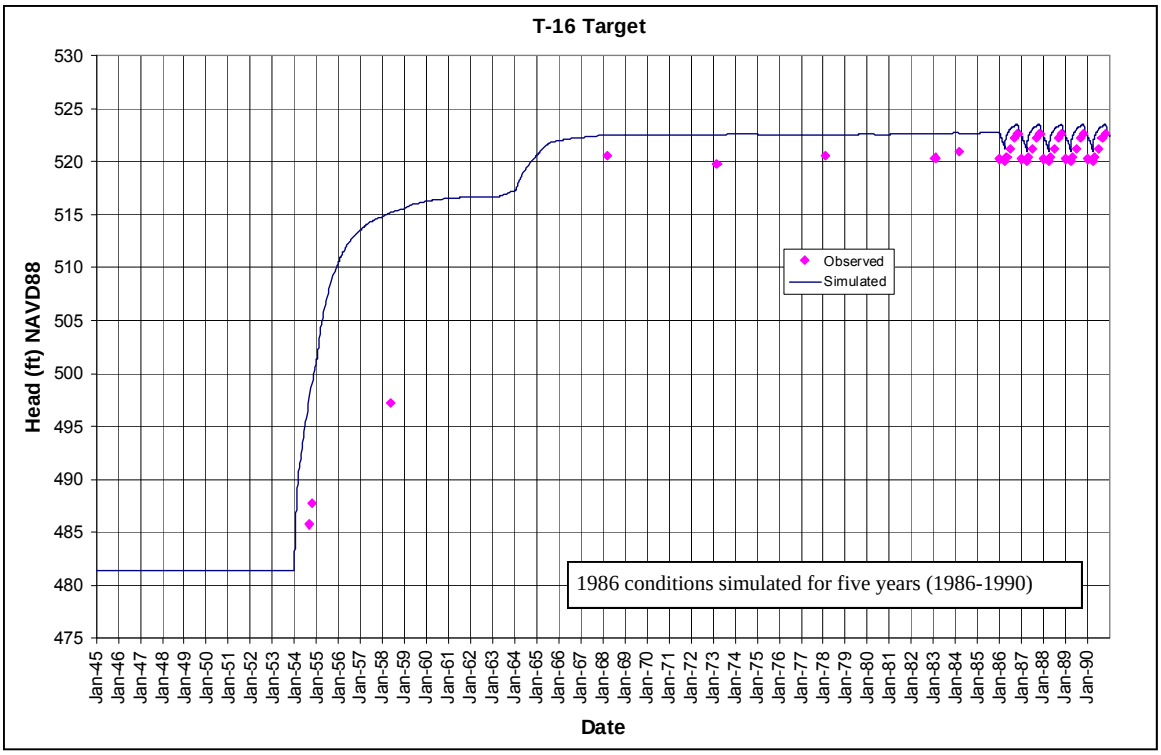


Figure J-20
SFC: Calibration Results (Targets T-15 and T-16)

Franklin Conservation District
Retiming Benefits Analysis

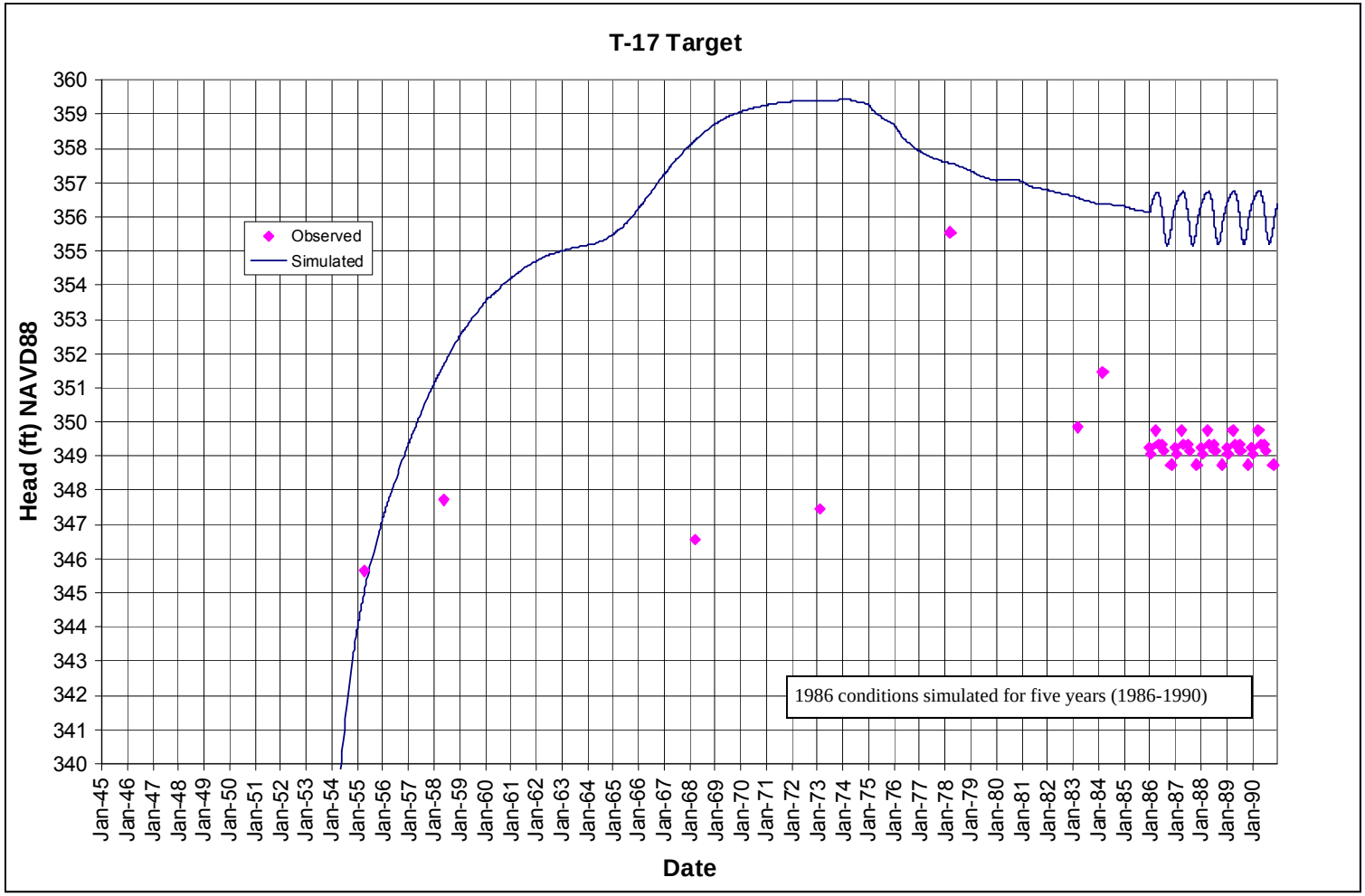
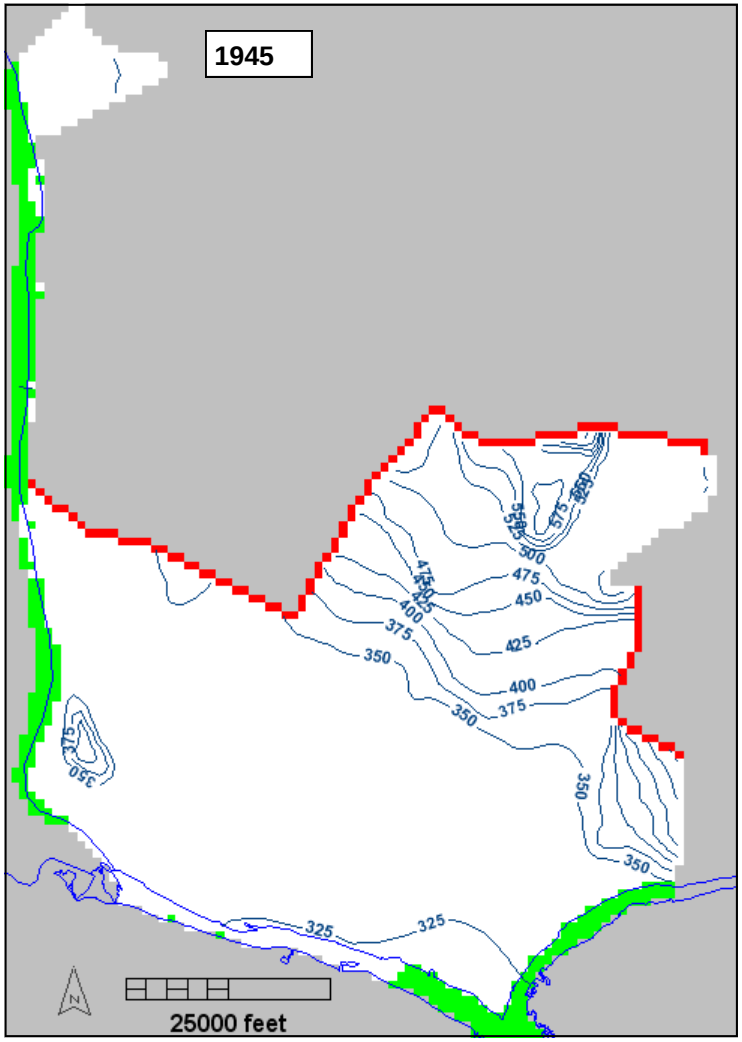


Figure J-21
SFC: Calibration Results (Target T-17)

Franklin Conservation District
Retiming Benefits Analysis

PgG



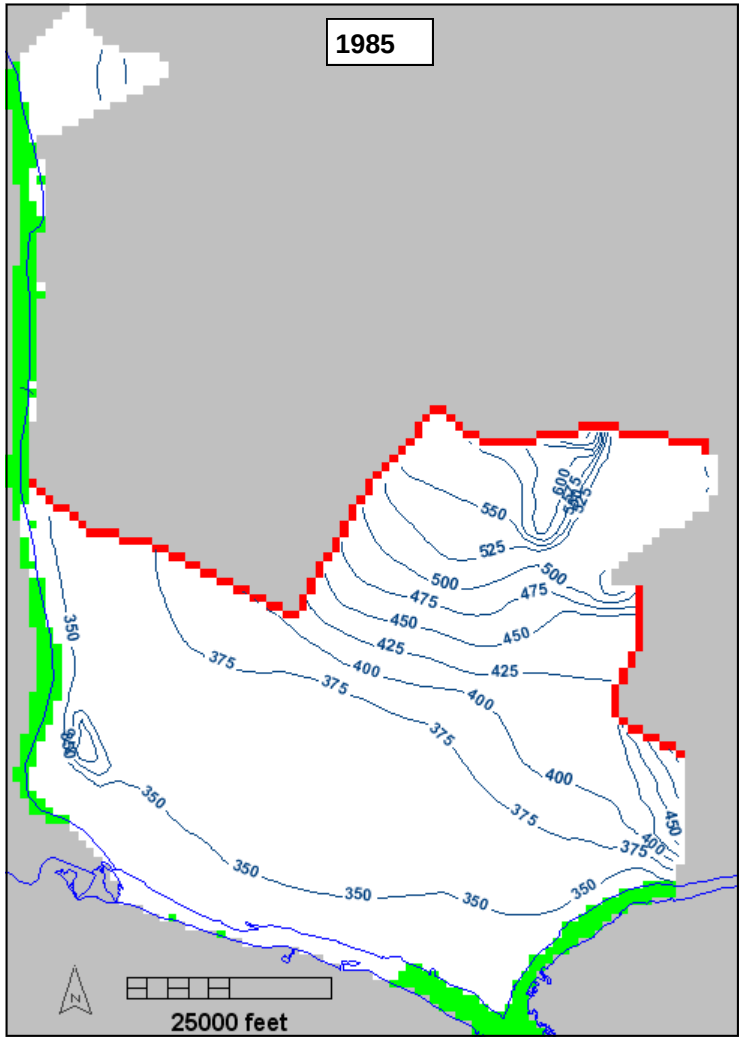


Figure J-22
SFC: Modeled Groundwater Elevations (1945 and 1985)

Franklin Conservation District
Retiming Benefits Analysis

PgG

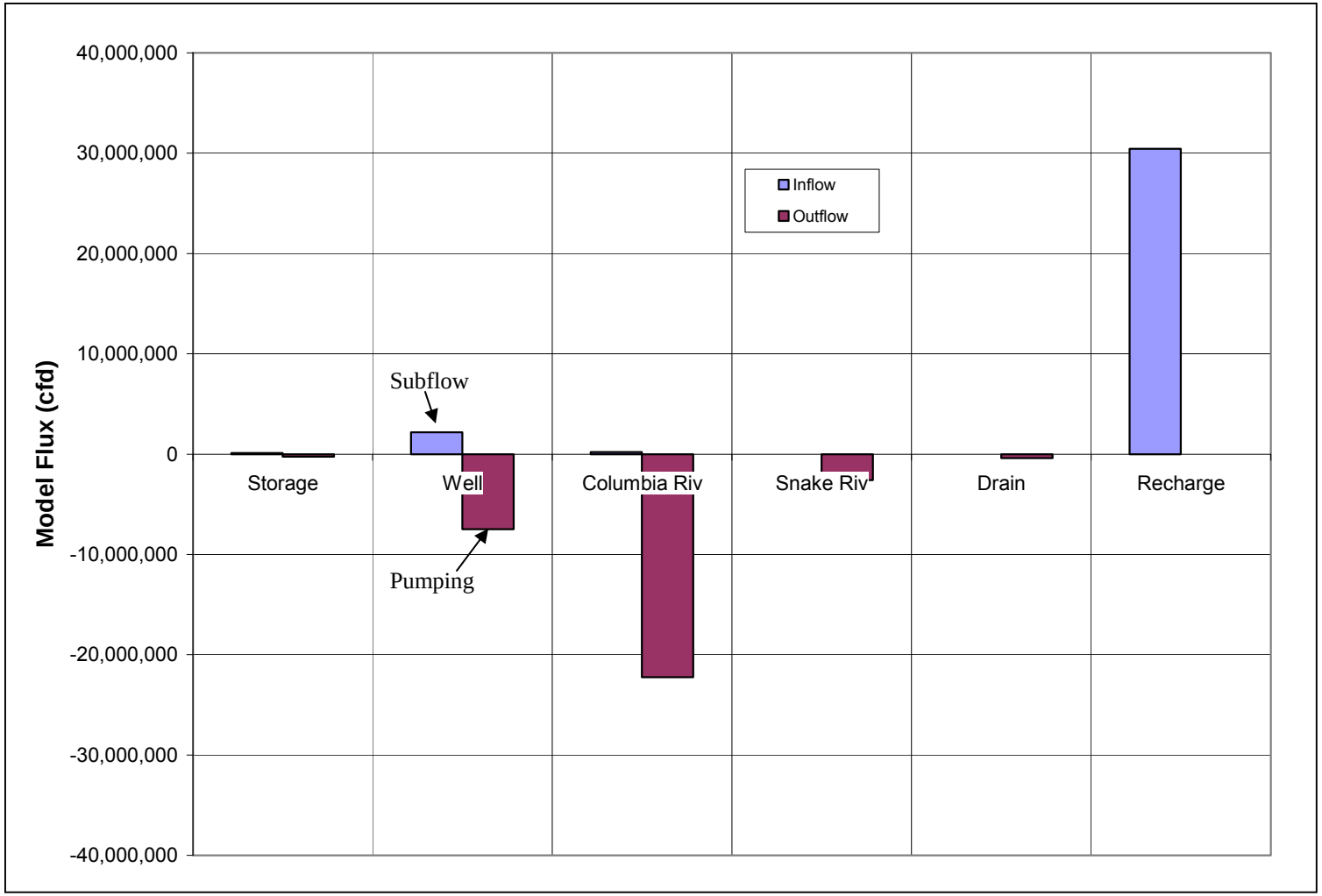


Figure J-23
SFC: Model Mass Balance (1985)

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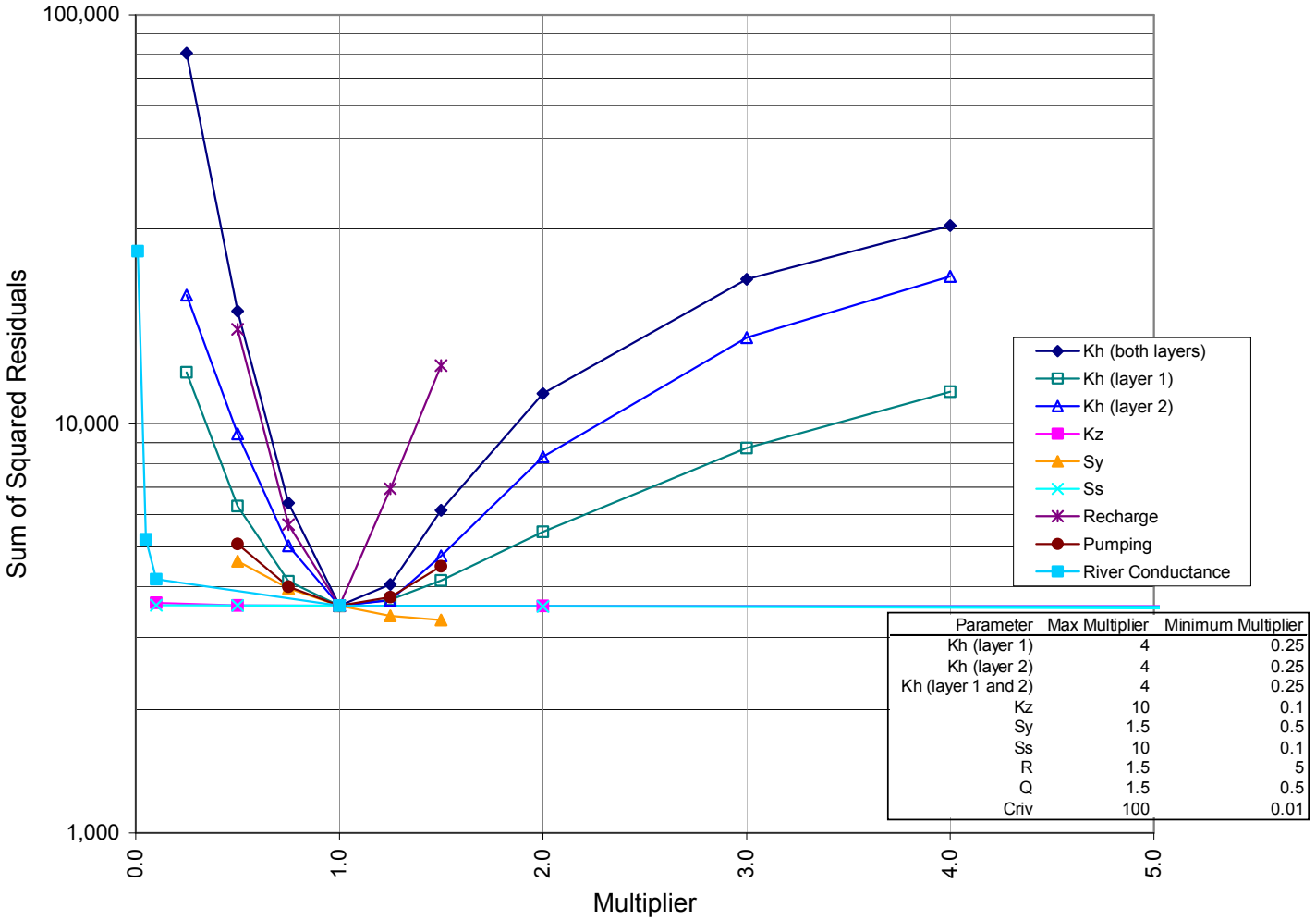
PgG



Parameter	Max Multiplier	Minimum Multiplier
Kh (layer 1)	4	0.25
Kh (layer 2)	4	0.25
Kh (layer 1 and 2)	4	0.25
Kz	10	0.1
Sy	1.5	0.5
Ss	10	0.1
R	1.5	5
Q	1.5	0.5
Criv	100	0.01

Figure J-24
SFC: Model Sensitivity

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PgG

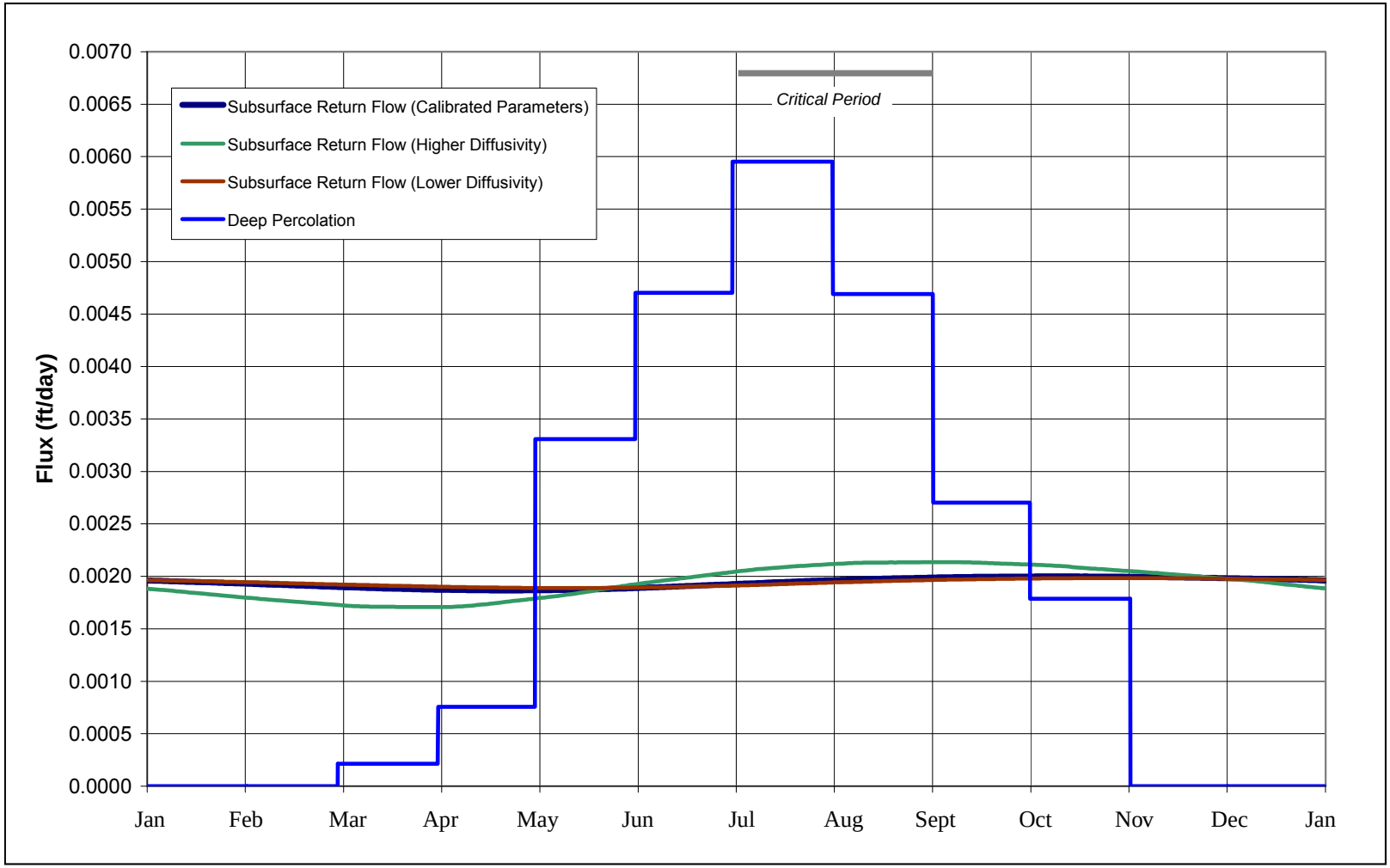

Figure J-25
SFC: Predicted Subsurface Return Flow (Block 1- Hypothetical Field)

Franklin Conservation District
Retiming Benefits Analysis

PgG

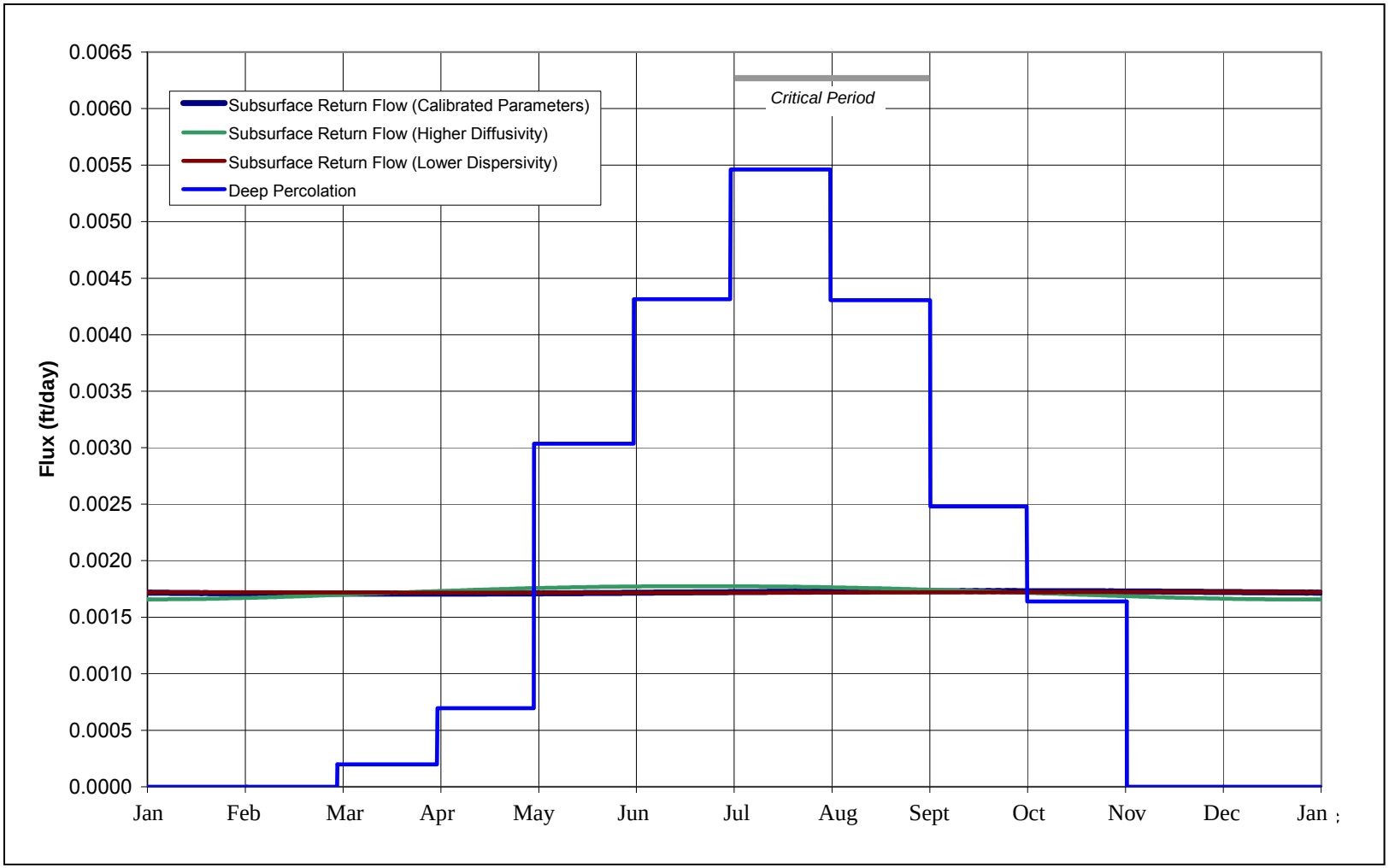

Figure J-26
SFC: Predicted Subsurface Return Flow (Block 17 - Hypothetical Conservation Site)

Franklin Conservation District
Retiming Benefits Analysis

PgG

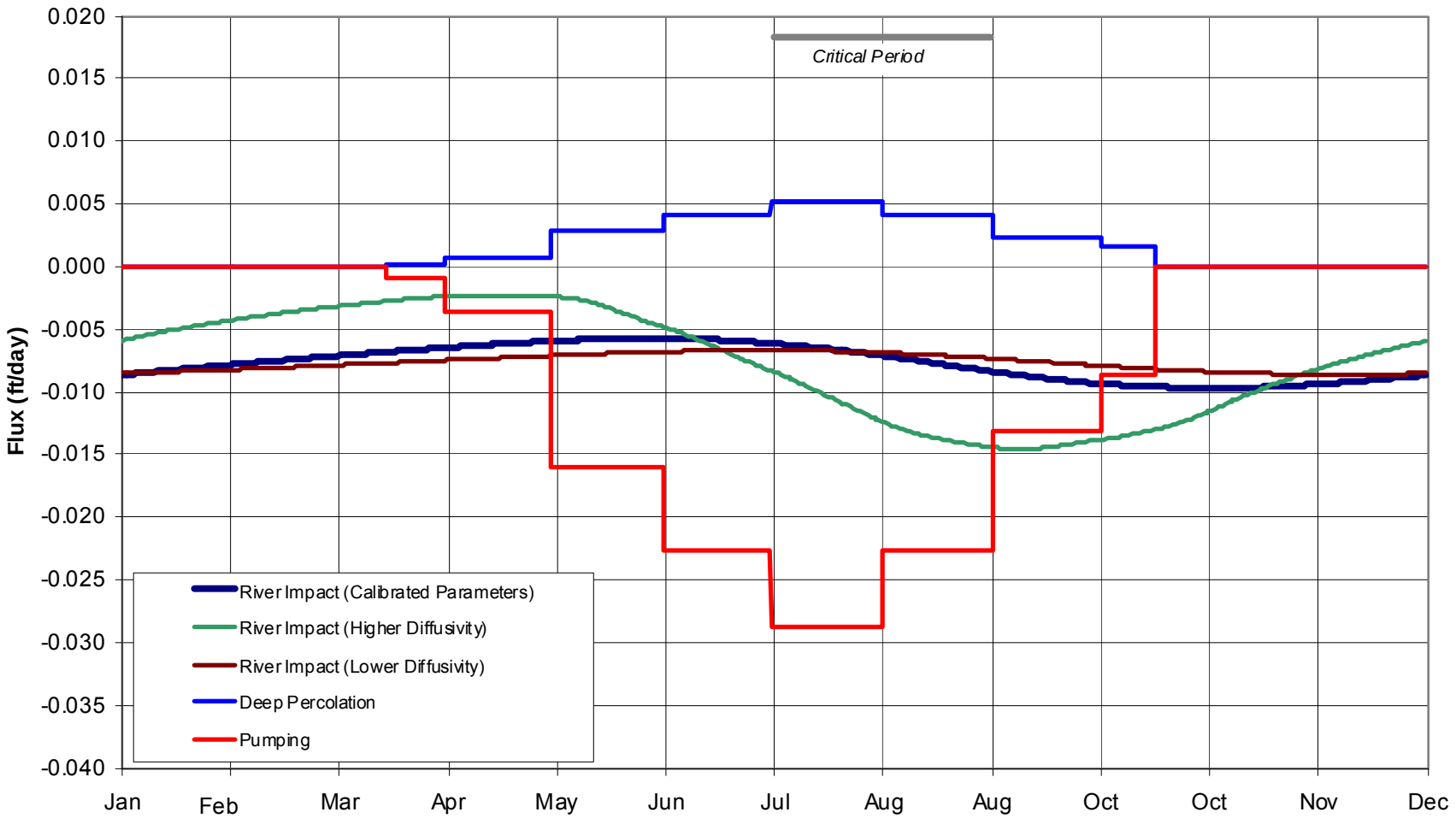

Figure J-27
SFC: Pre-Conservation River Impact (Greenbelt - Hypothetical Conservation Site)

Franklin Conservation District
Retiming Benefits Analysis

PgG

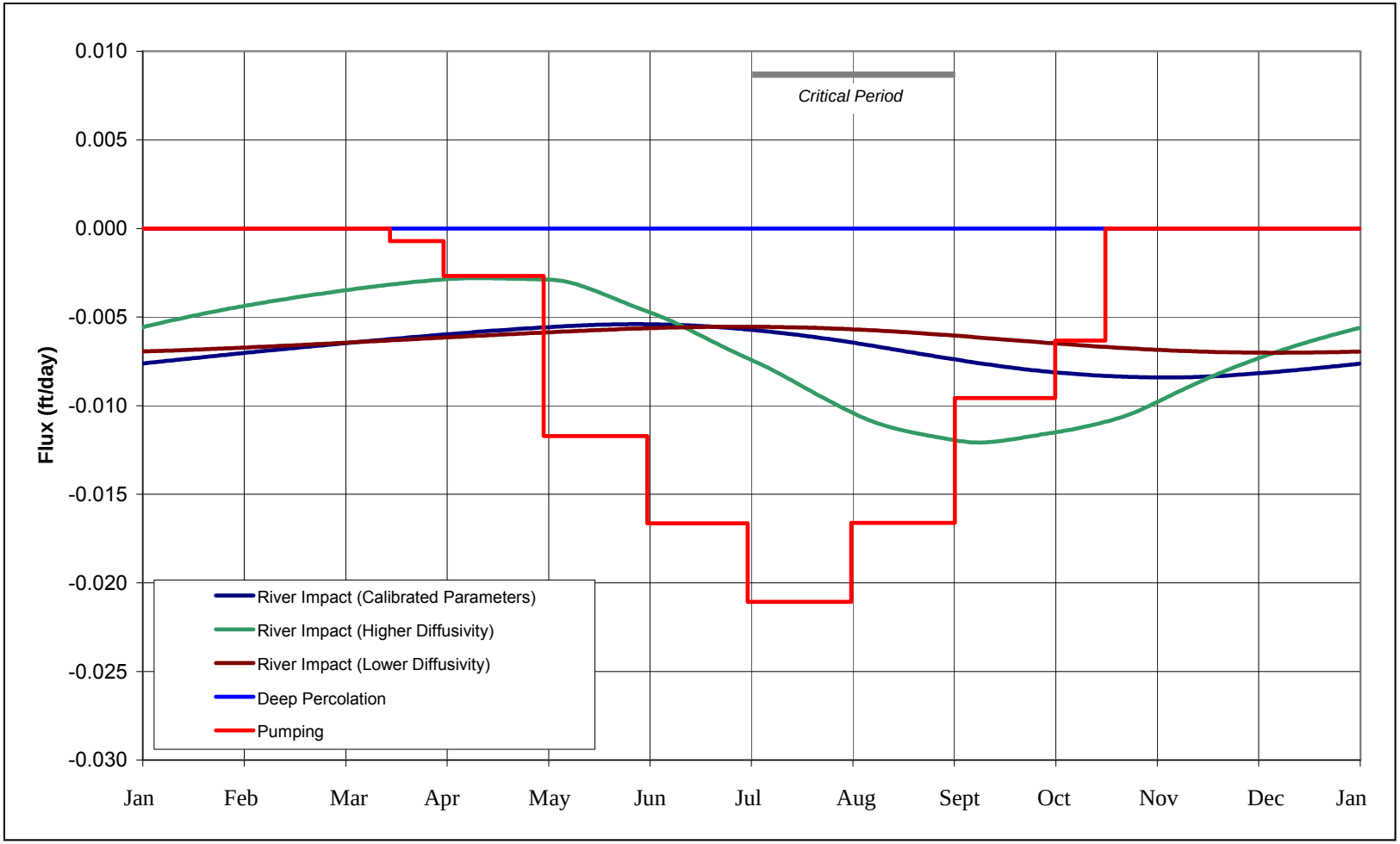

Figure J-28
SFC: Post-Conservation River Impact (Greenbelt - Hypothetical Conservation Site)

Franklin Conservation District
Retiming Benefits Analysis

PgG

APPENDIX K
DOCUMENTATION OF MODELING ANALYSES FOR WALLA WALLA STUDY AREA

February 2012

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 IRRIGATION RECHARGE 1

3.0 VADOSE ZONE MODELING 1

3.1 VADOSE ZONE HYDRAULIC PROPERTIES 2
3.2 HYDRUS MODEL SETUP 3
3.3 HYDRUS MODEL RESULTS AND INTERPRETATION 4

4.0 GROUNDWATER FLOW MODELING 4

4.1 DOMAIN AND DISCRETIZATION 5
4.2 AQUIFER PROPERTIES 6
4.3 BOUNDARY CONDITIONS 7
4.3.1 External Boundaries (Constant Head/Flux) 7
4.3.2 Pumping and Recharge 7
4.3.3 Rivers 8
4.4 CALIBRATION AND SENSITIVITY ANALYSIS 9
4.5 PREDICTIVE SIMULATIONS AND UNCERTAINTY ANALYSIS 10

1.0 INTRODUCTION

This appendix describes the approaches used to model the timing of the seasonal irrigation "recharge pulse" from the root zone (field applications) through the vadose zone (between the root zone and the water table) to the saturated zone (groundwater flow system). The analysis employs a water budget approach to estimate irrigation recharge and numerical models to evaluate flow in both the vadose zone and the saturated zone.

2.0 IRRIGATION RECHARGE

RH2 Engineering estimated irrigation losses (evaporation, runoff and deep percolation) for current and post-conservation conditions within the Walla Walla study area. RH2's evaluation is documented in Section 5.1.5 of the main report and in Appendices A and B. Irrigation losses for current conditions, estimated monthly over an assumed 7-month season are summarized below:

(all values in ft)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
SW Runoff	0.000	0.000	0.000	0.003	0.014	0.021	0.024	0.017	0.010	0.002	0.000	0.000	0.091
Evaporation	0.000	0.000	0.001	0.012	0.050	0.074	0.083	0.058	0.035	0.005	0.000	0.000	0.319
Deep Percolation	0.000	0.000	0.002	0.028	0.118	0.176	0.198	0.139	0.084	0.012	0.000	0.000	0.758
Total Losses	0.000	0.000	0.003	0.044	0.182	0.271	0.305	0.214	0.129	0.019	0.000	0.000	1.168

These irrigation losses are for the basin-wide average of irrigation methods, which are estimated to have a weighted average irrigation efficiency (WAIE) of 75.8 percent (Appendix A). The proposed site is largely irrigated with hand line, which has a very similar efficiency of 75%. As losses for the proposed site and the basin average are nearly the same, it is considered reasonable to use the basin average for PGG's calculations.

It should be noted that the irrigation season associated with these estimates is assumed to extend over seven months, from March 15th through October 15th. When used as input for the vadose-zone model, the deep percolation terms for March and October were applied to the last and first half of these months, respectively.

For post-conservation conditions, RH2 assumed that the most efficient irrigation methods are applied (center pivot with LEPA and IWM) and estimated zero deep percolation losses. This represents a *theoretical* maximum conservation condition; however, in actuality, a small amount of deep percolation will occur (and is required in order to prevent the salt buildup in the soil). In this analysis, the zero deep percolation assumption is used to estimate retiming benefit.

3.0 VADOSE ZONE MODELING

PGG used the variably saturated, finite-element model "Hydrus-1D" (Simunek et al, 2008) to simulate movement of the irrigation recharge pulse through the vadose zone. The thickness and texture of the vadose zone in the site vicinity is discussed in Section 5.2.3 of the main report, and for the purposes of modeling is represented as about 33 feet (10 meters) of Touchet Beds overlying another 10 meters of gravelly, mixed-texture deposits. (Note that Hydrus-1D requires that all calculations are performed in the metric system, so that this discussion employs units of centime-

ters and meters.) Initially, the majority of "retiming" of the irrigation recharge pulse was assumed to occur within the Touchet Beds, and most of the emphasis of Hydrus modeling was focused on water movement within the Touchet Beds. However, additional simulations of flow through the underlying gravelly sediments established that "retiming" is also influenced by this portion of the vadose-zone. Greater variability of texture within the gravelly sediments leads to more uncertainty as to the role of these sediments in vadose zone flow. PGG employed a relatively simple representation of the gravelly sediments to illustrate their role, and employed additional interpretation to provide a conservative basis for describing the degree of retiming likely to occur in the vadose zone.

3.1 VADOSE ZONE HYDRAULIC PROPERTIES

Hydraulic properties for vadose zone textures were represented using the methods of van Genuchten (1980) and Mualem (1976). Van Genuchten's method employs a variety of "fitting parameters" (e.g. θr, θr, α, n, m[1]) to represent the soil moisture characteristic curve. Mualin's method scales the unsaturated hydraulic conductivity to the saturated hydraulic conductivity (Ksat) and the shape of the soil moisture characteristic curve.

The hydraulic properties of the Touchet Beds were estimated based on grain-size evaluation of the textural sequence of a typical rhythmite bed performed by Spencer (1989). Spencer evaluated the mean and standard deviation grain size for sediments over a number or rhythmites, and showed that a typical sequence varied from fine sand at the bottom to silt at the top. Grain size averages and standard deviations for the samples used in Spencer's analysis are summarized below, with PGG's addition of USDA soil textural classification for each mean grain size:

Sample ID	Mean Grain Size (phi)	Mean Grain Size (mm)	Standard Deviation (phi)	USDA Soil Textural Classification
11	2.7	0.15	1	fine sand
10	4.2	0.05	0.8	silt (coarse)
9	3.2	0.11	0.8	fine sand
8	4.7	0.04	2.2	silt
7	3.3	0.10	1	very fine-fine sand
6	2.8	0.14	0.8	fine sand
5	4.4	0.05	2.7	silt (coarse)
4	3.4	0.09	1	Very fine sand
3	4.3	0.05	0.8	silt (coarse)
2	3	0.13	0.6	fine sand
1	2.8	0.14	0.7	fine sand

Note: phi units are the negative log base 2 of the grain diameter (mm). The phi values of standard deviation (SD) can be used to calculate a multiplier for the single standard deviation grain size relative to the mean, as 2^{SD}.

PGG used the range of USDA textural classifications defined for the rhymites to estimate an associated range of hydraulic parameters. PGG obtained grain-size distributions for 96 undisturbed soil samples from the USDA UNSODA database (Nemes et al, 1999) and identified 12 samples

[1] The parameters θr and θs represented residual and saturated water content. The parameters α, n, m are shape fitting parameters for the soil moisture retention curves.

with grain-size distributions similar to the mean and standard deviation "fine sand" texture measured by Spencer. The UNSODA database also contains reliable soil moisture retention measurements (soil tension vs. moisture content) and Ksat estimates for these samples. PGG used the USDA program RETC (van Genuchten et al, 1991) to fit the measured soil moisture retention measurements to van Genuchten parameters, ultimately fitting *all* the data to a single representative set of van Genuchten parameters. These parameters, along with the associated log-average value of Ksat for the 12 samples, were used to define the "fine sand" end member (bottom of the Touchet Bed rhythmite).

The fine-grained, "silty" end member (top of rhythmite) was defined by interpolating mid-point hydraulic parameters between the "fine sand" end member and hydraulic parameters defined for silt in the USDA ROSETTA "neural network" database (Schaap et al, 1998). PGG used the mid-point between fine sand and silt as our "silty" end member because Spencer's standard deviation phi values for the finer-grained end member (shown above) suggests more of a "sandy silt" texture. Personal communication with Spencer indicates that this standard deviation is influenced by the presence of sand but not the presence of clay (Spencer, 2011). van Genuchten parameters for the "fine sand" and "silty" end members were used to interpolate parameters for two intermediate parameter sets for intermediate soil textures, as shown on **Table K-1**. A synthetic, 60-centimeter (2-foot) rhythmite sequence was then defined with the four soils shown on **Table K-1** repeating in 0.15 meter layers, the "fine sand" end-member on the bottom grading to the "silty" end member on the top.

In order to simulate the gravelly sediments beneath the Touchet Beds, PGG assumed a 50/50 mixture of gravel clasts and two different matrix materials: fine sand and sandy silt (i.e. the two end members described above). This representation seemed reasonable, given that matrix materials described in drillers' logs near the site ranged from silt to sand, and in some cases drillers simply noted "gravel".

3.2 HYDRUS MODEL SETUP

Hydrus-1D was used to simulate a 10- and 20-meter thick, free draining vadose zone. Two different soil profiles were simulated: 10 meters of Touchet Beds and 10 meters of the underlying gravelly sediments. Flux input at the top of the Hydrus model included RH2's current-condition (pre-conservation) monthly deep percolation estimates (above), and Hydrus output from the Touchet Bed simulations was averaged into 2-week timesteps for input to simulation of the underlying gravelly sediments. Hydrus was not run for the post-conservation condition, based on the assumption of zero deep percolation loss. The 10-meter model domain was discretized into 1-cm elements and the annual recharge cycle was run 50 times back-to-back, to ensure that the Hydrus model was in equilibrium with the irrigation recharge from year to year (a condition PGG refers to as "cyclic steady-state"). Hydrus automatically selects time-step discretization to maintain model stability and accuracy.

As noted above, the Touchet Beds were simulated by repeating a 60-cm 4-layered rhythmite over the 10-m profile. In order to assess variability and uncertainty as a function of the range of texture observed in the Touchet Beds, simulation using the "Fine Sand" and "Silty" end members were also performed. The original "layered" simulation, however, is interpreted as the best representation of irrigation recharge flow through the Touchet Bed sediments because it captures the range of textures and the layered nature of the actual Touchet Bed rhythmites.

Output from the Hydrus layered Touchet Bed model was used as input to the "gravelly zone" model. As noted above, two textures were simulated: one with a matrix of fine sand and the other with a matrix of sandy silt. The method of Bower-Rice (1984) was used to correct the simulation for gravel content, with the clasts represented as impermeable barriers to unsaturated flow through the matrix materials. Gravel clasts were assumed to represent 50 percent of the soil volume.

3.3 HYDRUS MODEL RESULTS AND INTERPRETATION

Hydrus-1D results for 10 meters of layered Touchet Beds under current (pre-conservation) conditions are shown on **Figure K-1** at 1-meter depth spacings. The Hydrus predictions show increased lagging of the timing of the recharge pulse moving through the vadose zone as a function of depth, as well as increased damping with depth. PGG defined "damping" as "1-R", where R is the ratio of the flux range predicted at depth in the vadose zone to the flux range specified for irrigation recharge (e.g. 100 percent damping indicates a constant flux with no seasonal variation). At a depth of 10 meters, the peak of the predicted recharge pulse is lagged by 198 days and the pulse is 68 percent damped.

A comparison of 10-meter Hydrus pre-conservation results for the layered Touchet-Bed representation and the fine-sand and sandy-silt end members are shown on **Figure K-2**. Simulation of the two end members illustrates how texture affects predicted lagging and damping. If the Touchet Beds had been represented as purely fine sand, Hydrus predicts reduced lagging and damping of the recharge pulse. Conversely, if the Touchet Beds had been represented as purely sandy silt, Hydrus predicts increased lagging and damping of the recharge pulse. The layered configuration of the Touchet Beds is considered to be the best representation of vadose-zone processes. Uncertainty and variation in the actual texture of Touchet-Bed layering would cause a departure from PGG's synthetic Touchet-Bed representation; however, these variations are not expected to show nearly the range as defined by the two end-member model results.

Figure K-2 also shows predictions for a 20-meter vadose zone under current (pre-conservation) conditions where 10 meters of the layered Touchet Beds are underlain by 10 meters of gravelly materials with either fine-sand or sandy-silt matrix. Relative to vadose-zone flux at a depth of 10 meters within the layered Touchet Beds (thick blue curve), Hydrus predictions of flux after passing through an additional 10 meters of gravelly materials (reddish curves) shows additional damping and increased lag, such that maximum fluxes within the vadose zone occur near the "critical period" defined for the Columbia River (the months of July and August). This was not the case with only the single 10 meter layered Touchet Bed representation. Differences in Hydrus predictions for the two gravelly matrix textures are notable but not considerable. Because consideration of the gravelly portion of the vadose zone places the maximum flux rates (i.e. recharge to the underlying water table) within the critical period, both these predictions and those of the Touchet Beds alone were used as input to the saturated flow model, described below.

4.0 GROUNDWATER FLOW MODELING

PGG developed a groundwater flow model of the downstream sub-region of the Walla Walla Basin. This sub-region contains most of the Gardena Bench and the two pilot sites originally selected for the Walla Walla study area. The model domain is shown on **Figure 5-2** of the main report. Section 5.2.2 of the main report describes the hydrostratigraphic units in the Walla Walla Basin. The model represents the key suprabasalt hydrostratigraphic units (MPC, QC and QF),

with the bottom of the active groundwater flow system assumed to be the MPF unit (groundwater flow within this unit is largely limited by it's the fine-grained texture). The model also simulates recharge, pumping and groundwater/surface-water interactions within this subregion. A range of model hydraulic parameter values was defined based on previous calibration of models developed by Barker & Mac Nish (1976) and Petrides (in press). Calibration of PGG's model was largely limited by sparse groundwater elevation data in this sub-region; however, limited calibration activities achieved a reasonably good match to existing groundwater levels, and a sensitivity analysis identified key parameters for model calibration.

In order to predict retiming of irrigation recharge, PGG simulated irrigation recharge to the water table at the proposed site using output from the Hydrus model under both current and post-conservation conditions (see Section 2, above). PGG's predictive analysis addressed hydrogeologic uncertainty by running the predictive simulations over a variety of model "realizations" covering a reasonable range of key aquifer parameter values. These simulations generated a family of predictions for the timing under which irrigation recharge returns to the Walla Walla River (and other smaller streams), from which retiming benefits were estimated.

Modeling was performed using the USGS numerical code MODFLOW 2005 employing the MODFLOW NWT package (Niswonger et al, 2011); and with Groundwater Vistas (ESI, 2011) as the graphical user's interface. The following sections describe the model design, calibration, sensitivity analysis, and family of predictive simulations.

4.1 DOMAIN AND DISCRETIZATION

The 125-square-mile model domain covers a portion of the areal extent of the MPC aquifer – with the west, north and south boundaries defined by definition of MPC extent in the stratigraphic model prepared by WWBWC and GSI (Baker, 2009) and the eastern boundary defined by a north-south line located just downstream of the Mill Creek confluence with the Walla Walla River (main report, **Figure 5-2**). The location of the eastern boundary was selected to be far enough away from the proposed conservation site such that it is unlikely to introduce boundary artifacts to the predictive simulations.

The model includes three layers which, from top to bottom represent the QF (layer 1), QC (layer 2) and MPC (layer 3) units. Bottom elevations of the MPC, QC and QF units were defined based on GSI's definitions of the top elevations of the MPF, MPC and QC (respectively)[2]. Similarly, PGG's model honored GSI's interpretations of where MPC, QC and QF units were absent. Where units were absent, a layer thickness of 1 foot was assigned. See WWBWC's stratigraphic report (Baker, 2009) for maps of unit structure contours (elevations) and occurrence.

The horizontal coordinate reference system employed in this model is Washington State Plane, South Zone, North American Datum of 1983 (NAD83), US Survey Feet. Elevation values are in feet referenced to the North American Vertical Datum of 1988 (NAVD 88).

[2] In areas where the MPC extended farther out than GSI's definition of the top of the MPF, PGG used GSI's definition of the top of the Columbia River Basalts as the bottom of the MPC.

4.2 AQUIFER PROPERTIES

Aquifer properties include hydraulic conductivity (K) and storage parameters (referred to in this appendix as "S" – comprising values of specific yield (S_Y) and specific storage (S_S)). Existing assessments of aquifer properties coincident with the model domain are largely limited to existing model evaluations performed by Barker and Mac Nish (1978) and Petrides (in press). Due to differences between these two model interpretations, two separate models were made with differing spatial distribution of aquifer properties:

- In the "BMN" model, PGG reproduced the K and S_Y values and zonation employed by Barker and Mac Nish (1978) in their calibrated flow model. The authors based their K distribution on analysis of specific capacities measured in wells, and made some adjustments towards the end of calibration. They did not differentiate between the MPC and the QC units in their definition of the "gravel aquifer", therefore PGG assigned their K distribution to layers 2 and 3. They did not explicitly model the QF; therefore, PGG assigned the same singular, uniform K values to the QF unit as the "AP" model described below.
- In the "AP" model, PGG employed uniform values of K, S_Y, and S_S for each hydrostratigraphic unit based on average values estimated by Petrides during his model calibration (Petrides, pers. comm., 2011). Cells where the MPC unit was missing were defined as inactive. Cells where the QC and QF units were missing were assigned the aquifer properties of the underlying units (MPC and QC, respectively).

Although PGG's BMN and AP models directly employed aquifer property values used by the respective model authors, PGG performed a sensitivity analysis to evaluate model sensitivities to varying these parameters (Section 3.4).

Figure K-3 shows the K and S zonations for the gravel aquifer (combined MPC and QC – Layers 2 and 3) in the BMN model. Note that the S zonations shown on **Figure K-3** were assigned to all three model layers. **Figure K-4** shows the K zonation for the top layer of both models (predominantly QF, but QC where QF is absent along the Walla Walla River). **Figure K-5** shows the K zonation for layers 2 and 3 of the AP model. Aquifer property values employed in previous models and in PGG's models are summarized in the table below:

Model / Unit	PGG K Value (ft/d)	Model K Range (ft/d)	PGG Sy Value	Model Sy Range
BMN / Gravel Aquifer (MPC+QC)	10, 40, 100	<13, 13- 64, 64 – 133[3]	0.12, 0.2	0.1 – 0.15, 0.16 – 0.25
BMN / QF	8	not modeled	0.12 0.2	not modeled
AP / MPC	125	90 - 200 (avg 125)	0.1 0.25	0.1 – 0.25
AP / QC	360	200 - 500 (avg 360)	0.1 0.25	0.1 – 0.25
AP - QF	8	5 - 15 (average 8)	0.1 0.25	0.1 – 0.25

Note: commas above indicate that multiple values were used within the same unit. Multiple values listed without commas indicate that two simulations were performed by PGG (one for each value).

[3] The Barker and Mac Nish model employed a fourth K zone (133 – 215 ft/d); however, this zone occurs upvalley and outside PGG's model domain

Two versions of the AP model were ultimately developed, both using the same average K values derived by Petrides but differing in S values. Specifically, the "AP-High-S" model employed an S_S/S_Y of 0.0001/0.25 and the "AP-Low-S" model employed an S_S/S_Y of 0.0001/0.1 (S_Y has much more influence on predictive simulations than S_S). It should be noted that the BMN model used a similar range of S_Y values to the AP models; however, the BMN model used lower values of K for the "gravel aquifer" (see table above), leading to lower values of aquifer diffusivity. Diffusivity (D) is defined as aquifer transmissivity ("T" = K * aquifer saturated thickness) divided by effective storage coefficient (D = T/S). Lower D values tend to produce more lagging and damping of a recharge stress on the timing of associated groundwater discharge to a hydraulically coupled river.

It should be noted that while the Barker and Mac Nish estimates of aquifer K were largely based on well specific capacity distributions (with some adjustments during calibration), the Petrides K values employed by PGG were based on calibration of a model that emphasized areas upgradient of PGG's model study area. Petrides notes that the spatial distribution of calibration targets leads to a more comprehensive calibration in the middle and upper portions of the Walla Walla Valley, with about 30% of the targets located around existing infiltrating basins, and calibration focusing on artificial aquifer recharge events (Petrides, pers. comm.., 2011). Because aquifer permeability near the recharge basins estimated by Petrides is expected to be higher than K values in PGG's downvalley study area, the K values used in the AP models are likely to be somewhat overestimated, possibly leading to higher values of D and under-prediction of lagging and damping associated with the seasonal irrigation recharge pulse.

4.3 BOUNDARY CONDITIONS

Boundary conditions employed in the model include constant head and constant flux cells on the external model boundaries, pumping, recharge, and rivers.

4.3.1 External Boundaries (Constant Head/Flux)

Constant head (CH) cells were placed around the north, east and south model boundaries to represent groundwater inflows from upgradient loess, gravel aquifer and basalt aquifers (respectively). CH values were initially set based on a 3-year (2007-2009) average head distribution generated by Petrides based on WWBWC monthly/quarterly water-level monitoring over this period. Petrides provided PGG with a contour map of average groundwater elevations, and the contours were used to interpolate head values for each CH cell. CH cells were only assigned to model layer 3 (MPC), and are shown on **Figure K-6**. During calibration, PGG "optimized" the model by allowing CH cells to vary by a maximum of 20 feet, which is likely commensurate with the accuracy of the defined water-level map and associated averaging. During predictive simulations, the CH cells were converted to constant flux (CF) cells based on the fluxes in these cells calculated by the calibrated model. This conversion ensured that prediction of the change in irrigation recharge at the proposed site did not have any effect on upgradient inflows from areas adjacent to the model domain.

4.3.2 Pumping and Recharge

As part of model preparation, Petrides (in press) defined a number of pumping/recharge subregions in which irrigation pumping and areally distributed recharge (from precipitation and from irrigated fields) was estimated. Both pumping and recharge were estimated in a geographic in-

formation system (GIS) with relatively high resolution; however, both were averaged uniformly across each sub-region for the purpose of modeling.

Petrides estimated pumping based on: a review of well logs; estimation of areally distributed irrigation requirements; consideration of water rights and the availability of surface-water vs. groundwater; and surveying farmers regarding their irrigation practices (surface-water vs. groundwater) and sources of groundwater pumping (gravel vs. basalt aquifer, and how choices are made if a farmer has wells in both aquifers). Although Petrides estimated groundwater pumping for individual farms, he averaged pumping withdrawals for each of his model subregions.

Petrides estimated recharge based on the California Department of Water Resources "Integrated Water Flow Model" (IWFM), which includes detailed water budget functions for estimating recharge from both precipitation and irrigation activities. Irrigation recharge is based on factors such as crop requirement, irrigation efficiency and soil type.

Although Petrides' estimates of areal recharge and pumping were done in daily time increments over his 2007-2009 calibration period, PGG required average annual values for our model calibration. Petrides provided PGG with average annual calibration values from his GIS coverage over four sub-regions which comprised PGG's model domain. Recharge and pumping were summed together to obtain "net recharge" values (all values were positive, indicating that recharge is greater than pumping withdrawals). Because Petrides' model did not extend significantly north of the Walla Walla River, PGG employed an average value of Petrides' four sub-regions for this area. **Figure K-7** shows the resulting five pumping/recharge sub-regions and **Table K-2a** shows the associated net recharge values.

Within the pumping/recharge sub-regions shown on **Figure K-7**, PGG added recharge from leaky ditches, also estimated by Petrides over his 2007-2009 study period. Petrides' provided estimates of ditch leakage for each ditch within PGG's model boundaries (**Table K-2b**) along with polylines defining the course of each ditch. All model cells crossed by a polyline were attributed to a given ditch, and the estimated average annual ditch recharge was distributed evenly across the referenced model cells. Supplemental recharge associated with leaky ditches can be seen on **Figure K-7** as linear features with colors contrasting to the background sub-region.

4.3.3 Rivers

Petrides' model handled all major surface-water bodies (ditches, streams, rivers) explicitly, allowing them to lose or gain water based on the hydrologic conditions predicted by his IWFM model. The leaky ditches discussed above were surface-water bodies that showed predominant losses to the groundwater system. For PGG's model, surface-water features that showed gains from groundwater, or were known to be major rivers (e.g. Walla Walla, Touchet) were represented with MODFLOW's "river" package. The river package requires length and width dimensions for the river in each associated model cells, along with estimates of stream stage, streambed thickness, and streambed hydraulic conductivity. PGG assigned stream stages of 1 and 2 feet to minor and major surface-water features respectively; and used the model cell dimension (250 feet) for stream length. PGG used Petrides' estimates of stream width, streambed thickness (assumed to be 1 meter), and streambed K (estimated during Petrides' model calibration).

River cell parameters for each surface-water body represented are shown on **Table K-2c**. **Figure K-6** shows the distribution of river cells within the model domain. Almost all river cells occur in model layer 1; however, a small number of cells occur in layer 2 where the top layer is notably

thin. PGG evaluated the role of the river parameter assumptions during calibration and sensitivity analysis (discussed below).

4.4 CALIBRATION AND SENSITIVITY ANALYSIS

Model calibration efforts were limited by relatively sparse available groundwater level data. As noted in the main body of this report, long-term groundwater level data are generally unavailable for the model area. This makes it difficult to determine whether the groundwater flow system is in a state of change or is currently at (or near) a state of equilibrium. For the purpose of calibration, PGG assumed that the system is near equilibrium ("quasi-equilibrium") and ran the model in steady-state mode (constant values of annual average recharge, pumping, and non-varying constant heads). Calibration targets were 2007-2009 average groundwater elevations from WWBWC monitoring wells (the same time period as model estimates of pumping and recharge, discussed above). PGG obtained groundwater elevations and monitoring well locations from the WWBWC database (available on www.wwbwc.org), well completion depths from WWBWC, and compared well completion depths to the WWBWC stratigraphic model to assign calibration targets to model layers. Model calibration targets are summarized in **Table K-3**.

PGG's limited calibration can concurrently be viewed as a sensitivity analysis, as key model parameters were varied and the effects on calibration statistics were noted. Prior to the sensitivity analysis, PGG allowed Groundwater Vistas to adjust the constant head values along the model perimeter by defining several CH cell "reaches" and allowing Vistas to optimize the CH values to best fit the model targets (an adjustment range of ±20 feet was permitted relative to a groundwater level range of 350 feet across the model domain). Then, using the model parameters developed by Petrides ("AP" model) as a base case, PGG varied the following parameters: aquifer K, aquifer anisotropy (ratio of horizontal to vertical K), riverbed K, and recharge. In addition, PGG ran the model using parameter estimates derived from the Barker – Mac Nish ("BMN") model.

Table K-4a summarizes the parameters varied in the calibration / sensitivity analysis runs, **Table K-4b** presents the residuals[4] for the model calibration targets for each run along with the associated calibration statistics, and **Figure K-8** shows the predicted heads and target residuals for the basecase (AP) model. The model showed low sensitivity to increasing anisotropy, increasing riverbed K and reducing recharge (**Table K-4a**). Slightly more sensitivity was observed from changing aquifer K, increasing recharge, and use of the full range of BMN model parameters (rather than the AP parameters). The model showed the greatest sensitivity to decreasing the riverbed K; however, this change led to a poorer fit to calibration targets. The best fit was achieved using the BMN model parameters, which improved the "sum of squared residuals" (SSR) statistic by 2.6 percent relative to the AP basecase.

The significance of low sensitivity parameters (such as aquifer K), is that calibration does not significantly reduce the uncertainty in parameter values. Without constraint of uncertainty via calibration, uncertainty in model predictions can only be constrained by other means of estimation (e.g. interpretation of aquifer tests and specific capacity measurements).

Overall, PGG's calibration / sensitivity analysis suggested that model-predicted heads are largely controlled by surface-water features, and that the dominant means of changing model predicted heads is to change the modeled hydraulic connection between groundwater and surface-water

[4] "Residuals" are defined as observed minus model-predicted groundwater elevations. Negative residuals mean that the model is predicting too high heads.

features. Across the range of AP-based model sensitivity runs, lowering the riverbed K reduced the quality of the calibration and increasing the riverbed K had little effect. Therefore, Petrides' original estimates of riverbed K were considered adequate for the calibrated model. Comparing **Tables K-2c** and **K-4a** shows that Petrides and Barker / Mac Nish derived similar values of riverbed K during their model calibrations[5].

4.5 PREDICTIVE SIMULATIONS AND UNCERTAINTY ANALYSIS

Given the low model sensitivity to aquifer K and the fact that steady-state calibration does not facilitate estimation of aquifer specific yield (Sy), PGG performed model predictive analysis of retiming benefits from conservation at the proposed site over ranges of these parameters. PGG identified aquifer K and Sy as key parameters likely to control prediction of retiming benefits, and ran the model over a set of "realizations" (combinations of possible K and Sy values) to address model uncertainty for these parameters. The range of K was defined by the AP parameters (high-end) and the BMN parameters (low-end), as discussed in Section 3.2. The range of Sy was defined as 0.10 to 0.25 (for the AP model) and the mapped distribution of BMN Sy values for the BMN realizations. In addition, to include consideration of uncertainty of predicted recharge timing in the vadose zone, PGG input the groundwater flow model realizations with output from a range of Hydrus simulations. **Table K-5** lists the realizations used for predictive analysis. The relative diffusivity (aquifer transmissivity divided by storage coefficient) is listed for each realization based on consideration of aquifer K and Sy. More lagging and damping of the recharge pulse will occur with lower relative diffusivity.

The model was run in transient mode with all boundary conditions held constant at the annual average condition except for the irrigation recharge from the site. Irrigation recharge from the Hydrus modeling was resolved into 2-week stress periods for model input. The model was typically run for greater than 20 years, until a repeated cycle emerged in predicted annual variations of groundwater discharge to surface-water receptors ("cyclic steady state"). This approach assumes that the groundwater flow system behaves in a relatively linear fashion throughout the year and before/after conservation at the proposed site. This assumption appears to be reasonable, since review of groundwater level monitoring data suggests that annual water-level variations are ≤5 feet in most wells, which is small compared to the total saturated thickness of the gravel aquifer (main report, Section 5.2.7).

Irrigation recharge input to the groundwater model realizations was run for pre-conservation conditions only, as post-conservation recharge was assumed to be zero (or near zero). Hydrus predictions of vadose zone flux (in feet per day) were generalized to biweekly averages and multiplied by the conservation area for the proposed site (80 acres) to estimate associated irrigation recharge to the water table. Three schedules of irrigation recharge were input to the groundwater flow model realizations:

1. Vadose zone flux at the bottom of 33 feet of Touchet Beds, represented as layered fine-sand to sandy-silt rhythmites;
2. Vadose zone flux at the bottom of 33 feet of pure fine sand, interpreted as a high diffusivity end-member representation of the Touchet Beds; and,
3. Vadose zone flux at the bottom of 33 feet of Touchet Beds followed by 33 feet of gravel and fine sand.

[5] Note that Table 4a indicates that Barker & Mac Nish used a model riverbed K of 1.33 ft/d.

The second recharge schedule is likely to under-estimate lagging and damping of the irrigation recharge pulse, as representing the Touchet Beds purely as fine sand ignores the lower hydraulic conductivity and higher storage of the silty component of the rhythmites. The most realistic representation of irrigation recharge to the water table is likely to be the third representation, as Touchet Bed rhythmites are underlain by gravelly materials.

Figure K-9 shows the predicted timing of groundwater discharge to model river cells associated with irrigation recharge under current conditions. The irrigation recharge begins at the land surface at the proposed site (as estimated by RH2), travels through the vadose zone to reach the water table (as predicted by Hydrus), and travels through the groundwater flow system to discharge to surface-water features (as predicted by MODFLOW). The family of discharge curves on each figure demonstrates the range of uncertainty associated with the model predictions.

As shown on **Figure K-9**, the most damping of river discharge from the recharge pulse (almost 100 percent damped) is predicted for the "layered" representation of the Touchet Beds combined with the BMN model configuration (slightly more damping would be expected if the vadose zone simulation included the gravelly sediments underlying the Touchet Beds). It should be recalled that the BMN model is more likely to represent actual local conditions than the AP model because the aquifer K values in the AP model are likely high for the downvalley location of the site. Even with the "fine sand" representation of the vadose zone, the BMN model predicts considerable damping of river discharge associated with the site recharge pulse. The most seasonal variation of river discharge is associated with the "fine sand" AP simulations – a combination expected to underpredict damping in both the vadose zone and the saturated flow system. Representing the vadose zone as "layered" Touchet Bed rhythmites (rather than pure fine sand) significantly reduces predicted seasonality of river discharge. Adding the thickness of gravelly sediments beneath the Touchet Beds also further increases predicted lagging and damping of river discharge from the irrigation recharge pulse.

Conservation re-timing benefit, at any time, can be estimated with the following formula:

$$B_{RT} = \Delta_{DP} - \Delta_{RD} = (DP_{PRE} - DP_{POST}) - (RD_{PRE} - RD_{POST}) \qquad (\textit{Equation 1})$$

Where:
B_{RT} = retiming benefit (change in Columbia River flow)
Δ_{DP} = reduction in river diversion due to reduced deep percolation loss from conservation
Δ_{RD} = reduction in river discharge via subsurface return flow due to reduced deep percolation loss from conservation
DP_{PRE} = deep percolation irrigation loss before conservation
DP_{POST} = deep percolation irrigation loss after conservation
RD_{PRE} = river discharge before conservation
RD_{POST} = river discharge after conservation

As RH2's analysis of irrigation losses assumes the maximum theoretical conservation savings (i.e. zero post-conservation deep percolation losses), equation 1 above can be simplified to:

$$B_{RT} = DP_{PRE} - RD_{PRE} \qquad (\textit{Equation 2})$$

Section 5.3.4 of the main report illustrates how model predictions of pre-conservation irrigation return flow to the river (RD_{PRE}) can be subtracted from the portion of pre-conservation river diversions supporting deep percolation losses (DP_{PRE}) to estimate retiming benefit.

Table K-1
Hydraulic Properties Generated for Touchet Bed Simulation

	Fine Sand from UNSODA analysis (end member)	Sandy (interpolated)	Sandy & Silt (interpolated)	**"Silty" (end member)**	UNSODA 100% silt
Theta-S	**0.350**	0.389	0.428	**0.467**	0.583
Theta-R	**0.044**	0.044	0.044	**0.044**	0.045
Theta Range	**0.306**	0.345	0.384	**0.422**	0.539
alpha	**0.031**	0.028	0.025	**0.023**	0.014
n	**2.380**	2.253	2.125	**1.998**	1.615
m	**0.580**	0.556	0.529	**0.499**	0.381
Ksat (cm/d)	**209**	180	150	**125**	38

Note: Theta-S = saturated moisture content, Theta-R = residual moisture content.
Ksat - saturated hydraulic conductivity. Alpha, n and m are curve fitting parameters.

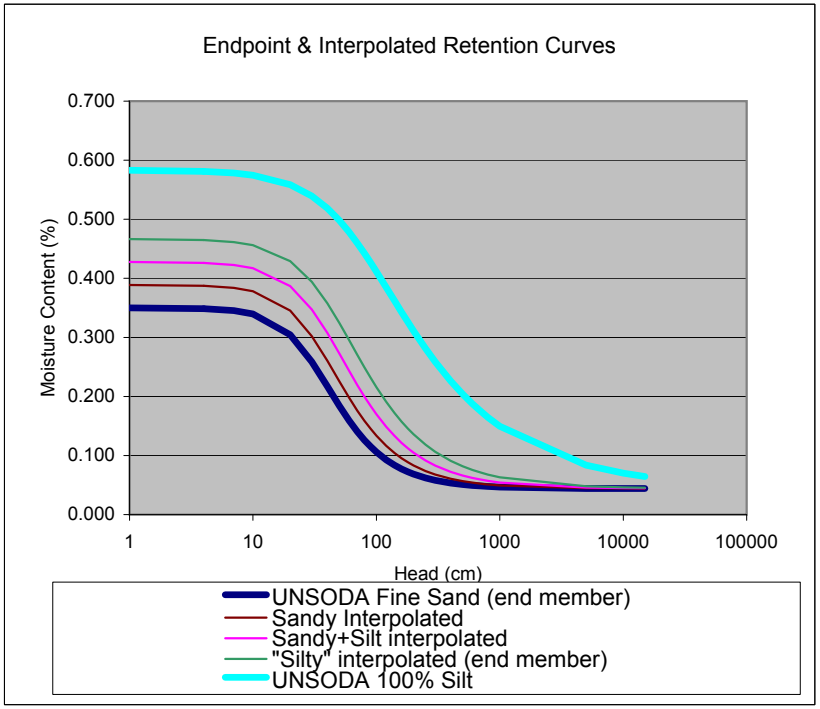

Table K-2a Pumping/Recharge Sub-Regions
2007-2009 estimates from Petrides (2011)

Zone	Rech (ft/yr)	Note
7	0.57	
6	0.80	
5	0.60	
4	0.50	
0	0.50	North of Walla Walla River (average of other sub-regions)

Table K-2b Average Annual Ditch Leakage Estimates
2007-2009 estimates from Petrides (2011)

Ditch ID	Leakage (cfs)	Ditch ID
65	0.003	North Gardena trib
66	0.153	Lower Gardena ditch
63	0.019	Gardena ditch
44	0.101	Upper White ditch
46	0.154	Richartz ditch
61	3.404	Burlingame canal

Table K-2c Definition of River Cells

Stream Segment ID	Name	Width (ft)	Stage Depth (ft)	Streambed Thick (ft)	Streambed Hydraulic Conductivity (K) (ft/d)
30	Walla Walla main stem	32.8	2	3.3	6.6
31	Mud Creek trib	49.2	1	3.3	1.3
37	Mud Creek	8.2	1	3.3	1.3
48	Little Mud creek	6.9	1	3.3	1.3
52	Upper Dugger creek	3.3	1	3.3	1.3
54	Swartz creek	4.9	1	3.3	1.3
55	Upper Pine creek 2	14.8	1	3.3	1.3
56	Lower Pine creek	16.4	1	3.3	1.3
58	Touchet River	40.0	2	3.3	1.3

Table K-3 Model Calibration Targets

Well ID	Land Surface Elevation (ft)	X Coordinate (SPS NAD83)	Y Coordinate (SPS NAD83)	Average Groundwater Elevation (ft)	Depth of Screen Top (ft)	Depth of Screen / Well Bottom (ft)	PGG Interpreted Aquifer	PGG Interpreted Model Layer
GW_106	452	2105304	258072	426	50	65	MPC	3
GW_107	523	2135062	264909	515	45	60	MPC	3
GW_108	621	2150333	259101	592	60	75	MPC	3
GW_109	515	2126784	254088	499	70	85	MPC	3
GW_110	666	2149135	249959	637	70	85	MPC	3
GW_120	566	2136437	246215	559	6	31	QF	1
GW_121	503	2125418	249397	488	10	40	QF/QC	2
GW_122	602	2147718	256804	584	15	55	QC/MPC	2
GW_123	447	2110697	258665	435	5	30	QF/QC	2
GW_124	506	2103757	250942	492	14	39	QF/QC	2
GW_125	427	2095704	258728	411	5	30	QC	2
GW_126	465	2103180	269934	442	15	55	MPC	3
GW_34	661	2147034	243822	631	n/a	50	MPC	3
GW_37	683	2150243	241011	650	n/a	90	MPC	3
GW_63	669	2147229	238822	640	285	301	??MPC??	3
GW_64	684	2148502	238050	651	n/a	55	MPC	3
GW_66	688	2149670	238296	658	n/a	70	MPC	3
GW_68	594	2133984	239383	574	n/a	211	??MPC??	3
GW_69	696	2149653	236830	675	n/a	43	MPC	3
GW_82	549	2101707	257121	451	140	220	MPC	3
GW_83	549	2101707	257121	538	0	20	QF	1
GW_86	444	2105391	261006	427	17	27	QF/QC	2
GW_92	559	2112698	248108	454	90	185	QF/QC	2
GW_93	581	2109804	254198	442	160	300	MPC	3
GW_94	496	2125068	261629	493	5	24	QF/QC	2
GW_95	496	2125068	261629	423	63	78	MPC	3
GW_96	498	2127650	261694	492	5	26	MPC	3

NOTE: n/a = not applicable (e.g. open ended casing)

Table K-4a Summary of Steady State Calibration Runs

Run ID	Model Basis	MPC Kh/Kz	QC Kh/Kz	QF Kh/Kz	Rech Mult	Rivervbed K Mult	Relative Sensitivity	Δ Sum of Squared Resid's	Description
GB-SS-6	AP	125/12	360/36	8.2/0.8	1x	1x	n/a	n/a	Best fit using Petrides K values and recharge
GB-SS-6a	AP	125/1.2	360/3.6	8.2/0.08	1x	1x	low	-0.5%	Evaluate role of anisotropy
GB-SS-6b	AP	40/4	120/12	3/0.3	1x	1x	low-mod	-1.3%	Reduce K by one third
GB-SS-6c	AP	375/37	1080/108	24/2.4	1x	1x	low-mod	0.9%	Increase K by 3x
GB-SS-6d	AP	125/12	360/36	8.2/0.8	1x	10x	low	-0.4%	Increase riverbed K by 10x
GB-SS-6e	AP	125/12	360/36	8.2/0.8	1x	0.1x	moderate	7.1%	Reduce riverbed K to 0.1x
GB-SS-6f	AP	125/12	360/36	8.2/0.8	2x	1x	low-mod	0.9%	Increase recharge by 2x
GB-SS-6g	AP	125/12	360/36	8.2/0.8	0.5x	1x	low	0.0%	Reduce recharge to 0.5x
GB-SS-6h	BMN	40/4;10/1;100/10	120/12	8.2/0.8	1x	K=1.33 ft/d	mod-low	-2.6%	Use K & stream K values from Barker & Mac Nish

Notes: Run GB-SS-6 represents the "base-case" to which other runs are compared. Values in red were altered from base-case during calibration

Table K-4b Model Target Residuals and Calibration Statistics

Target ID	Layer	Observed Head (ft)	GB-SS-6 Redidual (ft)	GB-SS-6a Residual (ft)	GB-SS-6b Residual (ft)	GB-SS-6c Residual (ft)	GB-SS-6d Residual (ft)	GB-SS-6e Residual (ft)	GB-SS-6f Residual (ft)	GB-SS-6g Residual (ft)	GB-SS-6h Residual (ft)	GB-SS-6h Residual (ft)
GW_106	3	426.0	-5.0	-6.6	-7.9	-5.3	-4.3	-10.4	-6.1	-4.5	-5.9	-5.9
GW_107	3	515.0	1.2	0.2	1.4	-0.9	3.2	-9.0	0.5	1.5	-0.5	-0.5
GW_108	3	591.6	1.7	1.8	0.7	2.1	1.2	1.3	1.1	1.9	-0.6	-0.6
GW_109	3	498.8	-11.6	-13.6	-16.4	-11.0	-8.4	-19.8	-15.6	-9.5	-15.3	-15.3
GW_110	3	636.5	17.1	16.8	14.2	18.1	15.4	16.7	15.7	17.8	11.6	11.6
GW_120	1	559.3	-7.3	-8.6	-10.6	-6.4	-6.4	-11.1	-9.8	-6.1	-12.2	-12.2
GW_121	2	487.8	-20.1	-22.6	-19.4	-21.4	-15.6	-29.2	-22.7	-18.8	-19.5	-19.5
GW_122	2	584.2	-8.0	-8.1	-11.4	-6.4	-10.4	-8.8	-9.6	-7.1	-10.1	-10.1
GW_123	2	435.0	-4.0	-5.8	-4.5	-5.4	-2.0	-13.2	-5.2	-3.4	-2.1	-2.1
GW_124	2	491.7	55.6	54.6	48.6	57.1	56.5	52.0	52.1	57.4	42.7	42.7
GW_125	2	411.2	-1.8	-1.7	-2.2	-1.8	-1.3	-4.1	-2.3	-1.5	-3.4	-3.4
GW_126	3	441.7	21.0	20.9	20.6	21.3	20.8	21.3	21.0	21.1	20.4	20.4
GW_131	3	441.4	-2.2	-3.0	-3.4	-2.6	-1.9	-7.8	-2.8	-1.9	-4.7	-4.7
GW_34	3	631.1	6.7	6.2	2.9	8.0	3.6	6.0	4.9	7.6	2.8	2.8
GW_37	3	649.6	2.2	2.2	1.0	2.7	0.9	2.1	1.7	2.5	-0.1	-0.1
GW_63	3	640.3	-8.1	-8.4	-11.8	-6.9	-12.5	-8.4	-9.6	-7.4	-10.9	-10.9
GW_64	3	651.0	-10.8	-10.9	-13.3	-10.0	-13.5	-10.9	-11.7	-10.3	-12.2	-12.2
GW_66	3	657.6	-7.0	-6.8	-8.5	-6.5	-9.2	-7.1	-7.6	-6.7	-7.9	-7.9
GW_67	3	537.3	-10.0	-11.1	-12.2	-9.5	-9.4	-13.2	-11.8	-9.1	-22.0	-22.0
GW_68	3	573.9	11.1	10.4	9.5	11.5	11.7	9.2	9.8	11.8	-1.0	-1.0
GW_69	3	674.7	-2.9	-3.4	-4.6	-2.5	-4.1	-3.0	-3.5	-2.7	-1.7	-1.7
GW_82	3	450.5	23.6	22.8	19.9	24.3	24.2	20.3	21.8	24.5	15.0	15.0
GW_83	1	538.4	111.4	109.7	107.1	112.2	112.0	108.1	109.5	112.4	102.6	102.6
GW_86	2	427.4	-3.3	-4.1	-4.6	-3.4	-3.0	-7.9	-4.0	-3.0	-5.1	-5.1
GW_92	2	454.0	-13.6	-15.8	-23.8	-11.5	-10.7	-21.2	-19.8	-10.4	-37.2	-37.2
GW_93	3	441.7	-7.4	-9.2	-14.0	-6.6	-5.3	-15.2	-11.6	-5.3	-20.3	-20.3
GW_94	2	493.0	0.3	0.0	-3.5	1.3	1.3	-6.6	-2.6	1.8	-5.5	-5.5
GW_95	3	423.4	-69.4	-70.2	-73.5	-68.4	-68.4	-76.3	-72.3	-68.0	-75.1	-75.1
GW_96	3	492.4	-9.1	-9.6	-13.2	-8.0	-8.1	-15.8	-11.9	-7.7	-13.4	-13.4
Statistics:												
Residual Mean			1.73	0.90	-1.13	2.22	1.95	-2.14	-0.08	2.65	-3.16	-3.16
Abs. Res. Mean			15.64	16.04	16.71	15.62	15.36	18.47	16.51	15.29	16.62	16.62
Res. Std. Dev.			28.21	28.19	28.06	28.30	28.14	29.17	28.40	28.15	27.71	27.71
Sum of Squared Residuals (SSR)			**23,173**	**23,067**	**22,866**	**23,374**	**23,070**	**24,809**	**23,390**	**23,184**	**22,562**	**22,562**
Change in Sum of Squares			n/a	-0.5%	-1.3%	0.9%	-0.4%	7.1%	0.9%	0.0%	-2.6%	-2.6%
RMS Error			28.27	28.20	28.08	28.39	28.20	29.25	28.40	28.27	27.89	27.89
Min. Residual			-69.42	-70.18	-73.52	-68.38	-68.36	-76.28	-72.34	-67.96	-75.11	-75.11
Max. Residual			111.42	109.68	107.05	112.18	112.00	108.07	109.52	112.39	102.58	102.58
Number of Observations			29	29	29	29	29	29	29	29	29	29
Range in Observations			263.52	263.52	263.52	263.52	263.52	263.52	263.52	263.52	263.52	263.52
Scaled Std. Dev.			10.7%	10.7%	10.6%	10.7%	10.7%	11.1%	10.8%	10.7%	10.5%	10.5%
Scaled Abs. Mean			5.9%	6.1%	6.3%	5.9%	5.8%	7.0%	6.3%	5.8%	6.3%	6.3%
Scaled RMS			10.7%	10.7%	10.7%	10.8%	10.7%	11.1%	10.8%	10.7%	10.6%	10.6%

NOTES: n/a - not applicable; AP - Petrides model parameters; BMN - Barker Mac Nish parameters; RMS = root mean squared; "scaled" = relative to observation range.

Table K-5 Predictive Model Realizations

Realization	Conser-vation Status	Vadose Zone Thickness (ft)	Vadose Zone Texture	Saturated Model	Sy	Relative Diffusivity
7d	Pre	33	layered Touchet Beds	"AP" low S	0.1	high
7c	Pre	33	fine sand	"AP" low S	0.1	high
7h	Pre	33	layered Touchet Beds	"AP" high S	0.25	medium
7g	Pre	33	fine sand	"AP" high S	0.25	medium
8d	Pre	33	layered Touchet Beds	"BMN"	per BMN[1]	low
8c	Pre	33	fine sand	"BMN"	per BMN[1]	low
11a	Pre	66	layered Touchet Beds + sandy gravel	"AP" low S	0.1	high
11c	Pre	66	fine sand + sandy gravel	"AP" low S	0.1	high
11d	Pre	66	layered Touchet Beds + sandy gravel	"AP" high S	0.1	medium

NOTES:
"AP" - Petrides model parameters; BMN - Barker Mac Nish model parameters
[1] Sy values derived from Barker Mac Nish model estimates.

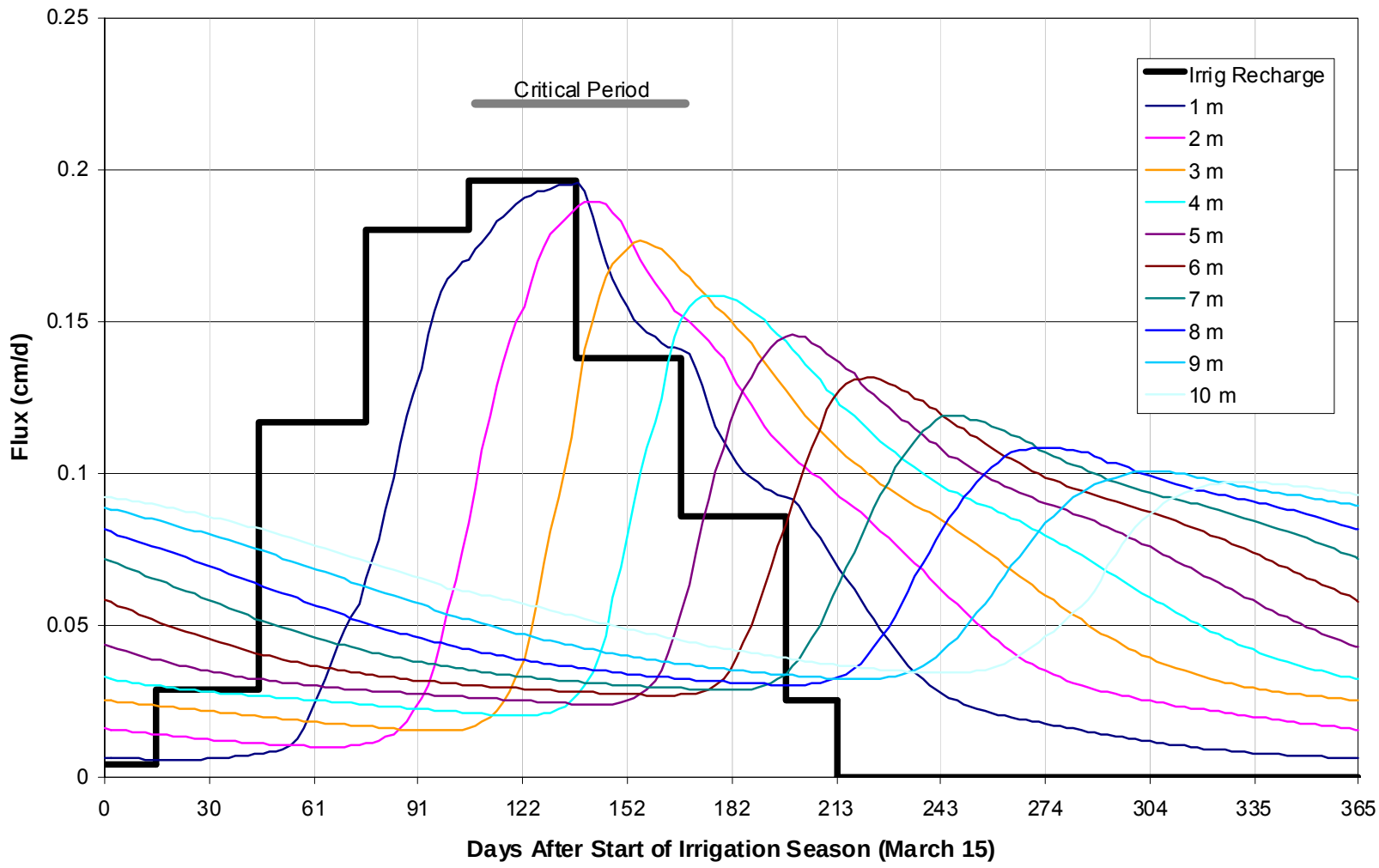

Figure K-1
Pre-Conservation Hydrus Results for 10 Meters of Layered Touchet Beds

Franklin Conservation District
Retiming Benefits Analysis

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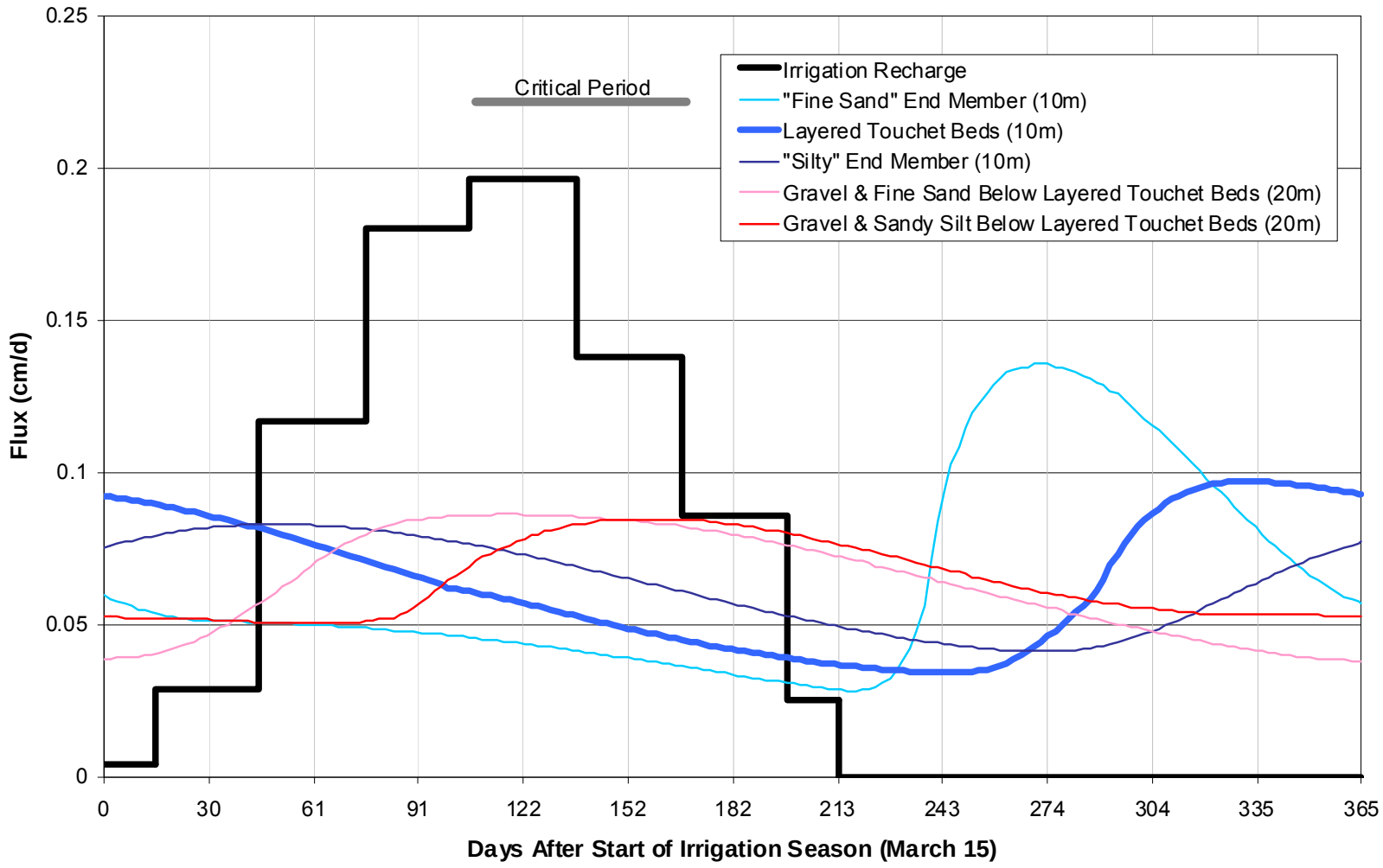

Figure K-2
Pre-Conservation Comparison of Hydrus Results for Various Vadose Zone Configurations

Franklin Conservation District
Retiming Benefits Analysis

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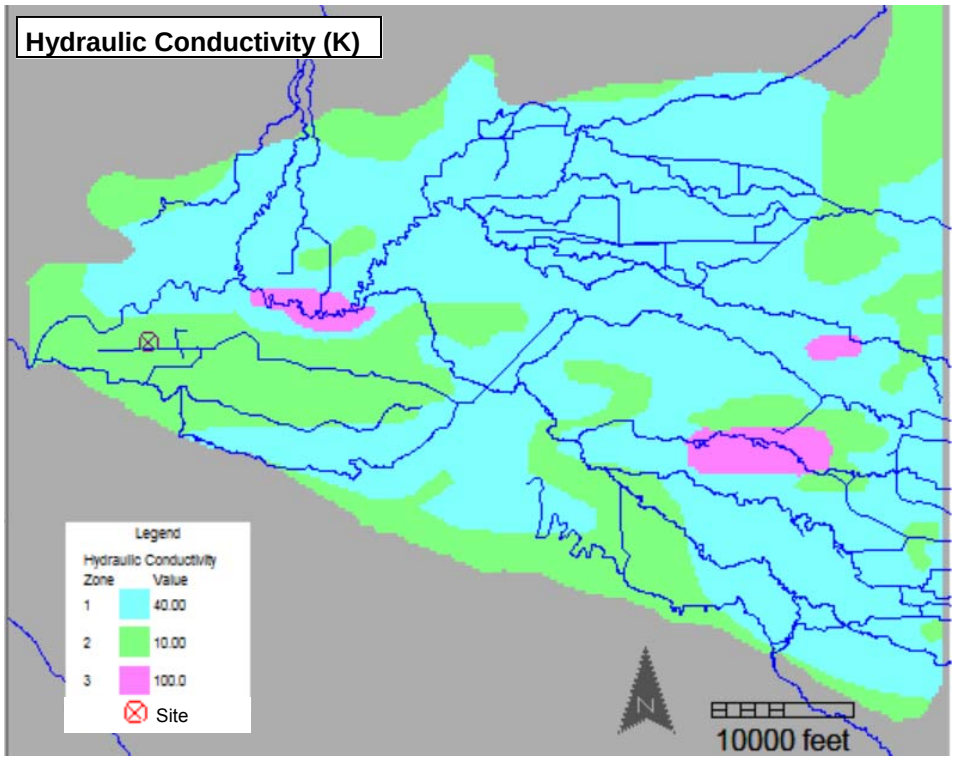

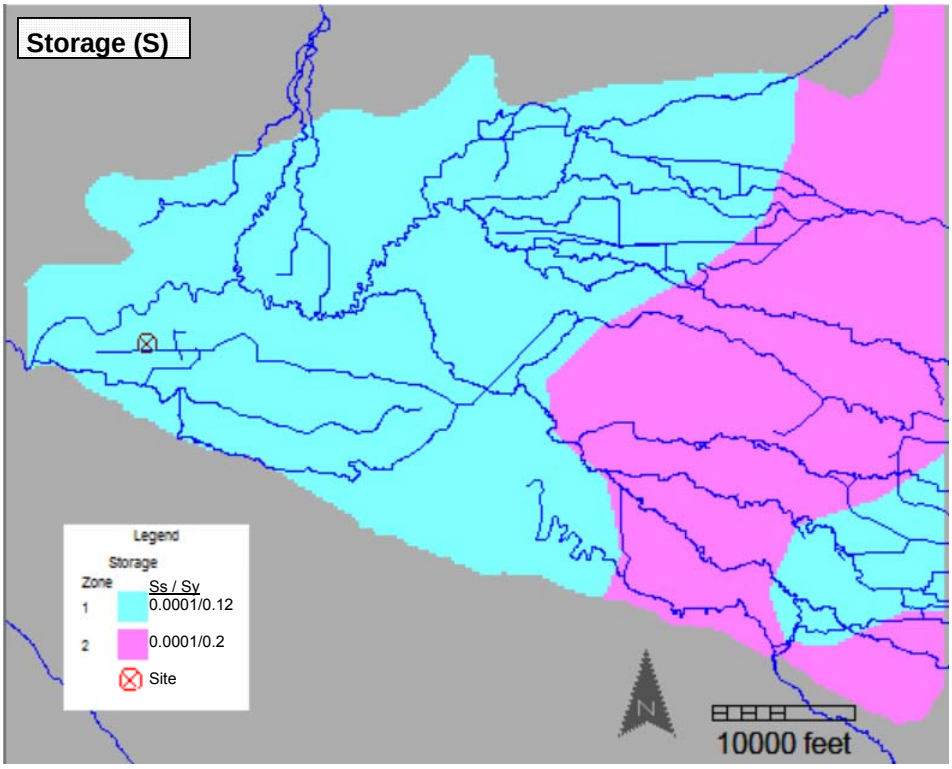

Figure K-3
BMN Model: K and S Zonations for the Gravel Aquifer (Model Layers 2&3)

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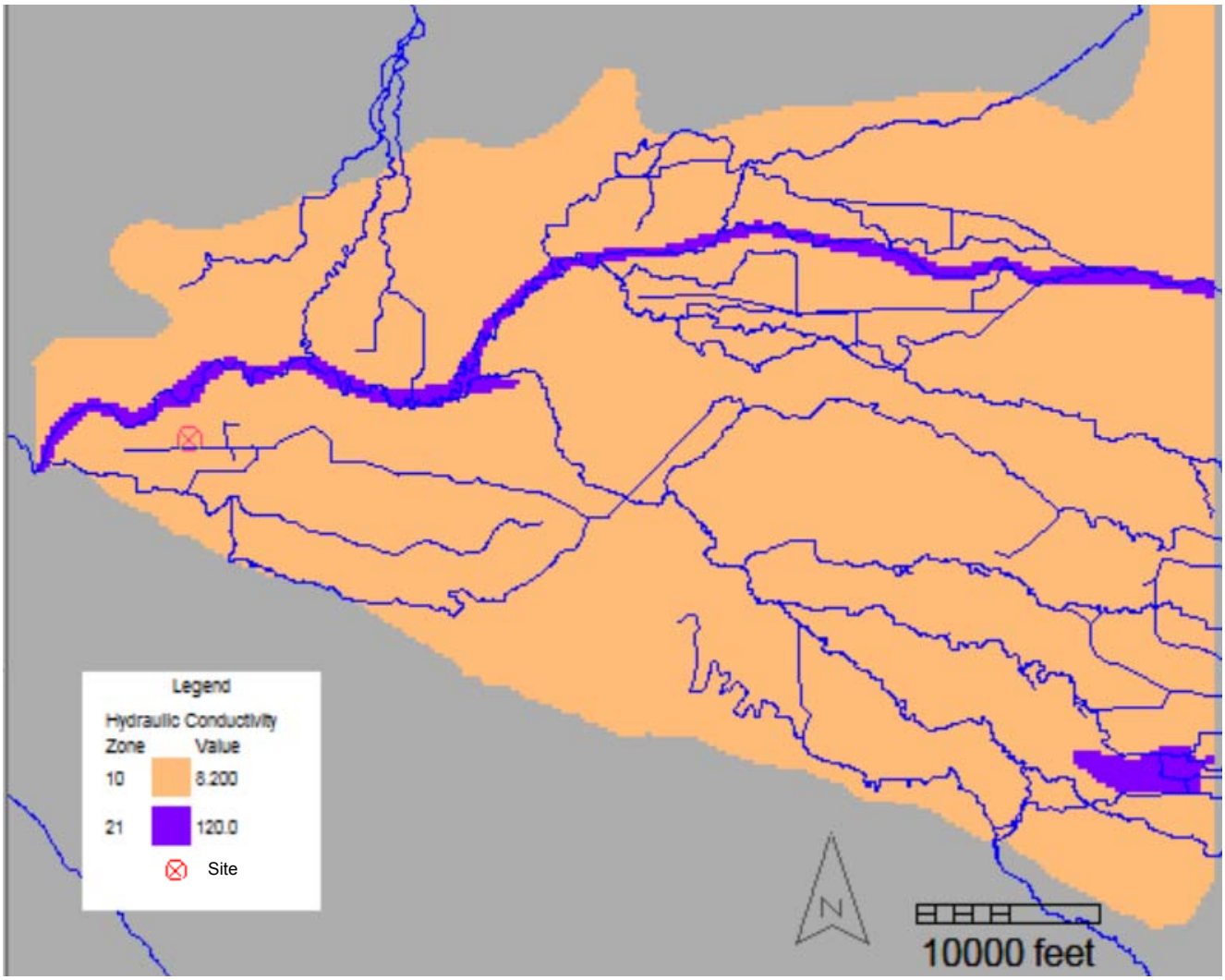

Figure K-4
K Zonations for Layer 1 of BMN and AP Models

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Retiming Benefits Analysis

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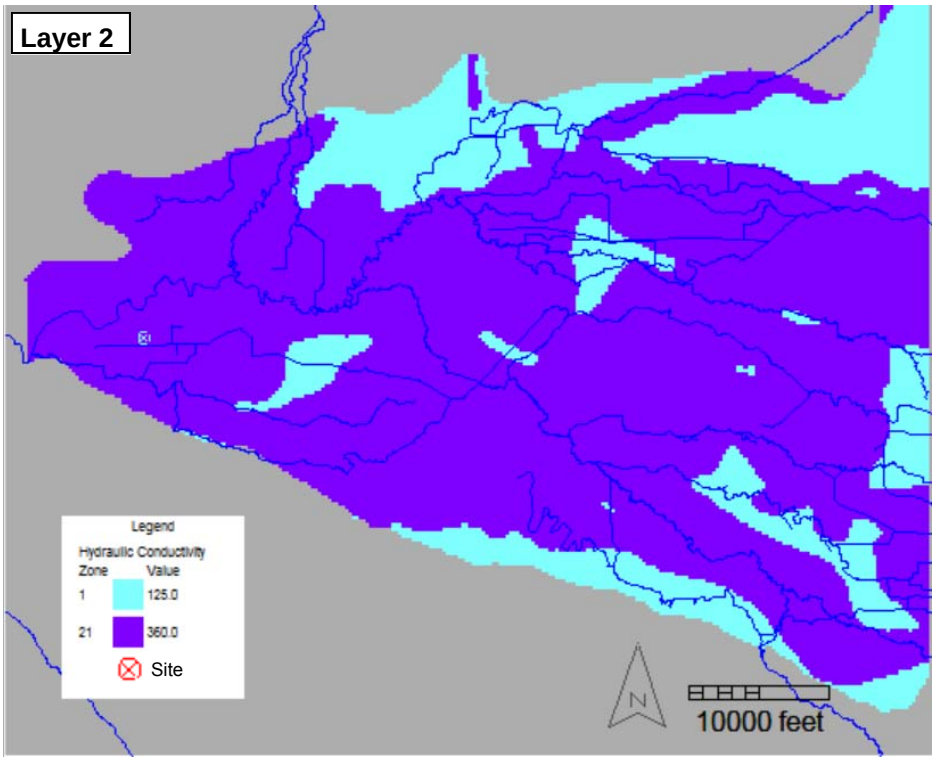

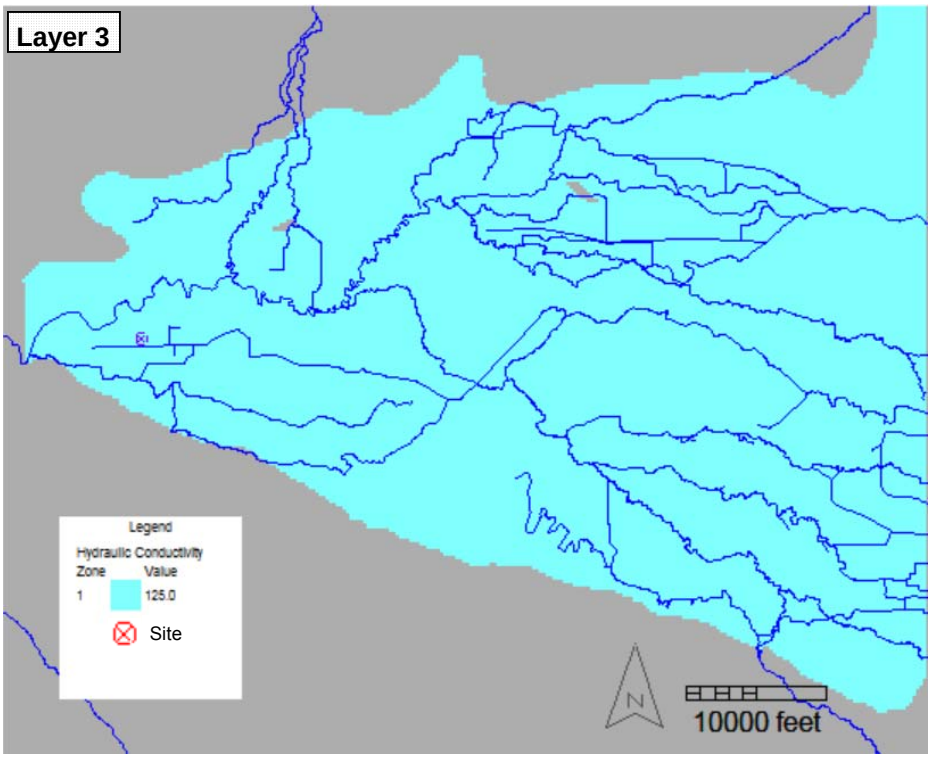

Figure K-5
AP Model: K Zonation for Layers 2 and 3

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Retiming Benefits Analysis

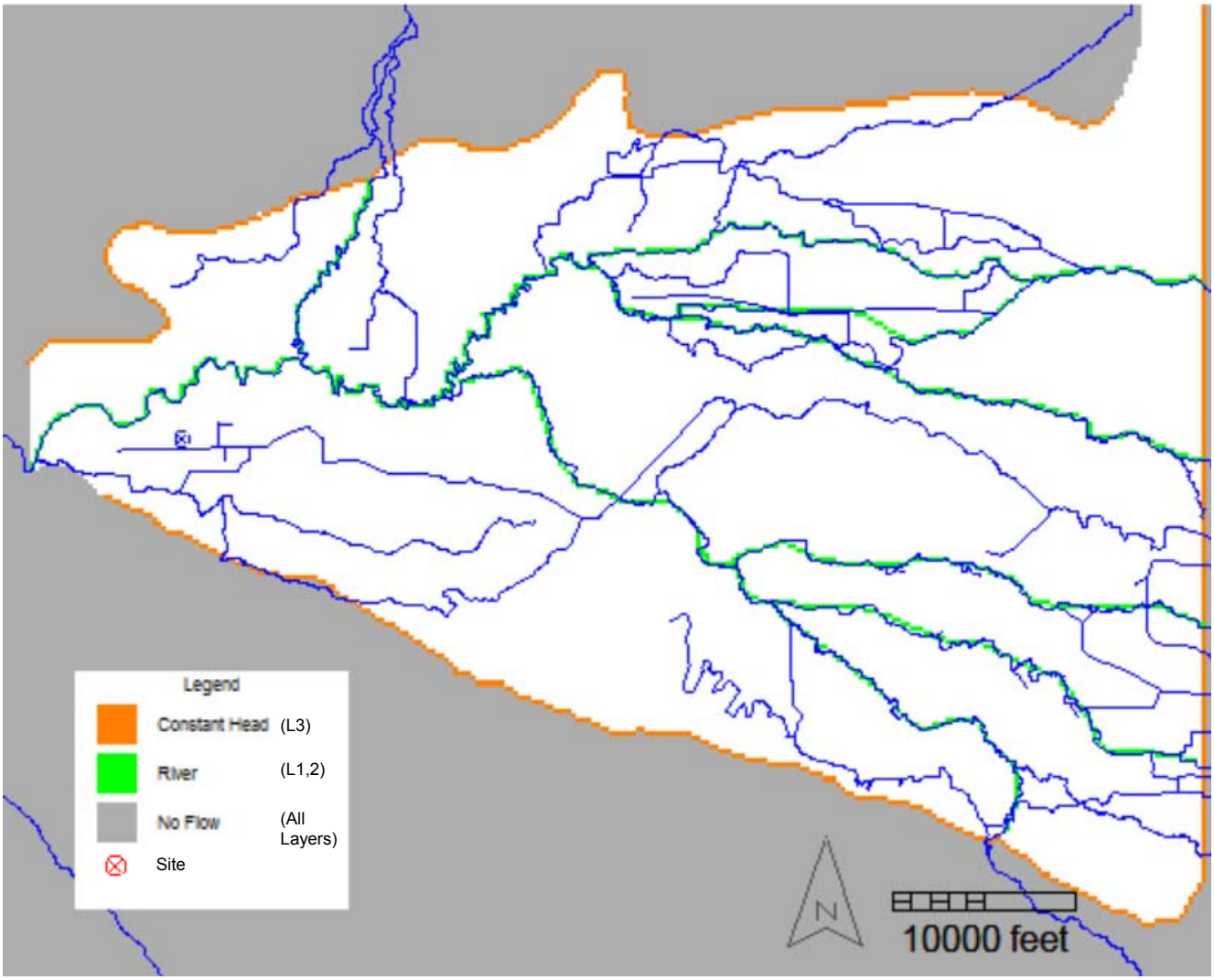

Figure K-6
Boundary Conditions in BMN and AP Models

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Retiming Benefits Analysis

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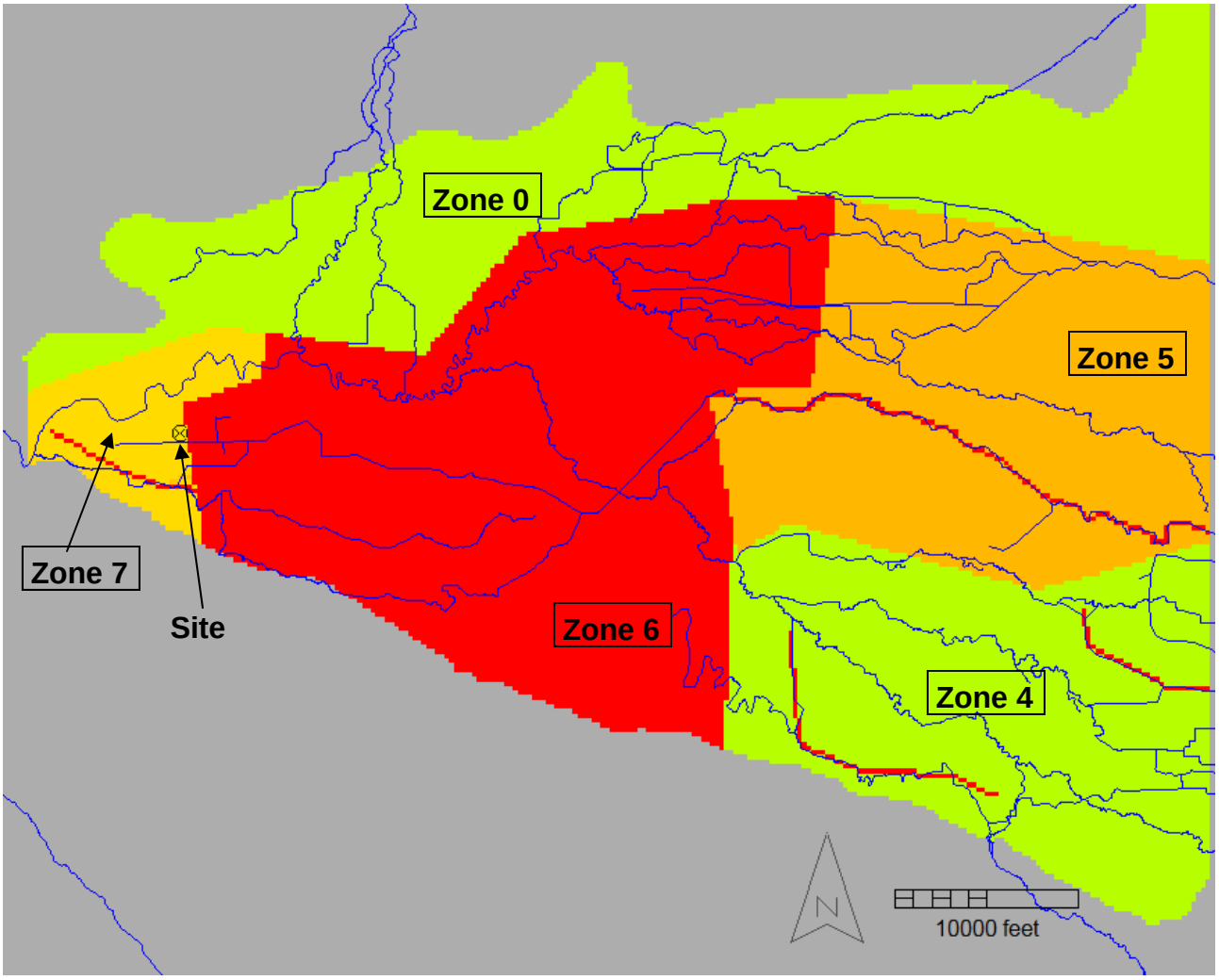

Figure K-7
Pumping/Recharge Sub-Regions in BMN and AP Models

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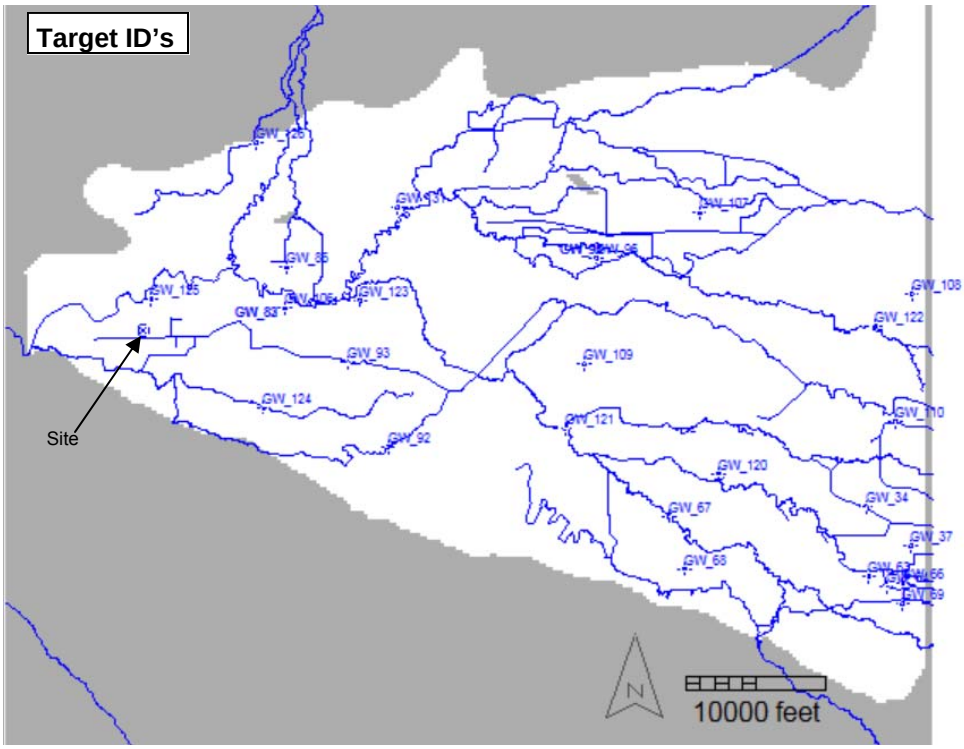

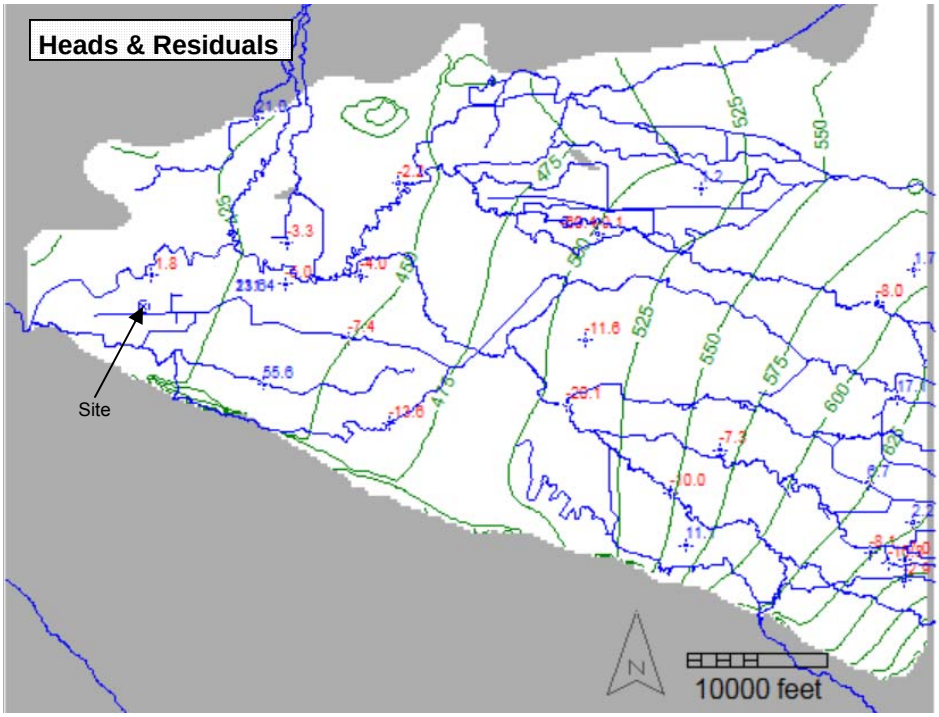

Figure K-8
AP Model Basecase: Predicted Heads and Target Residuals

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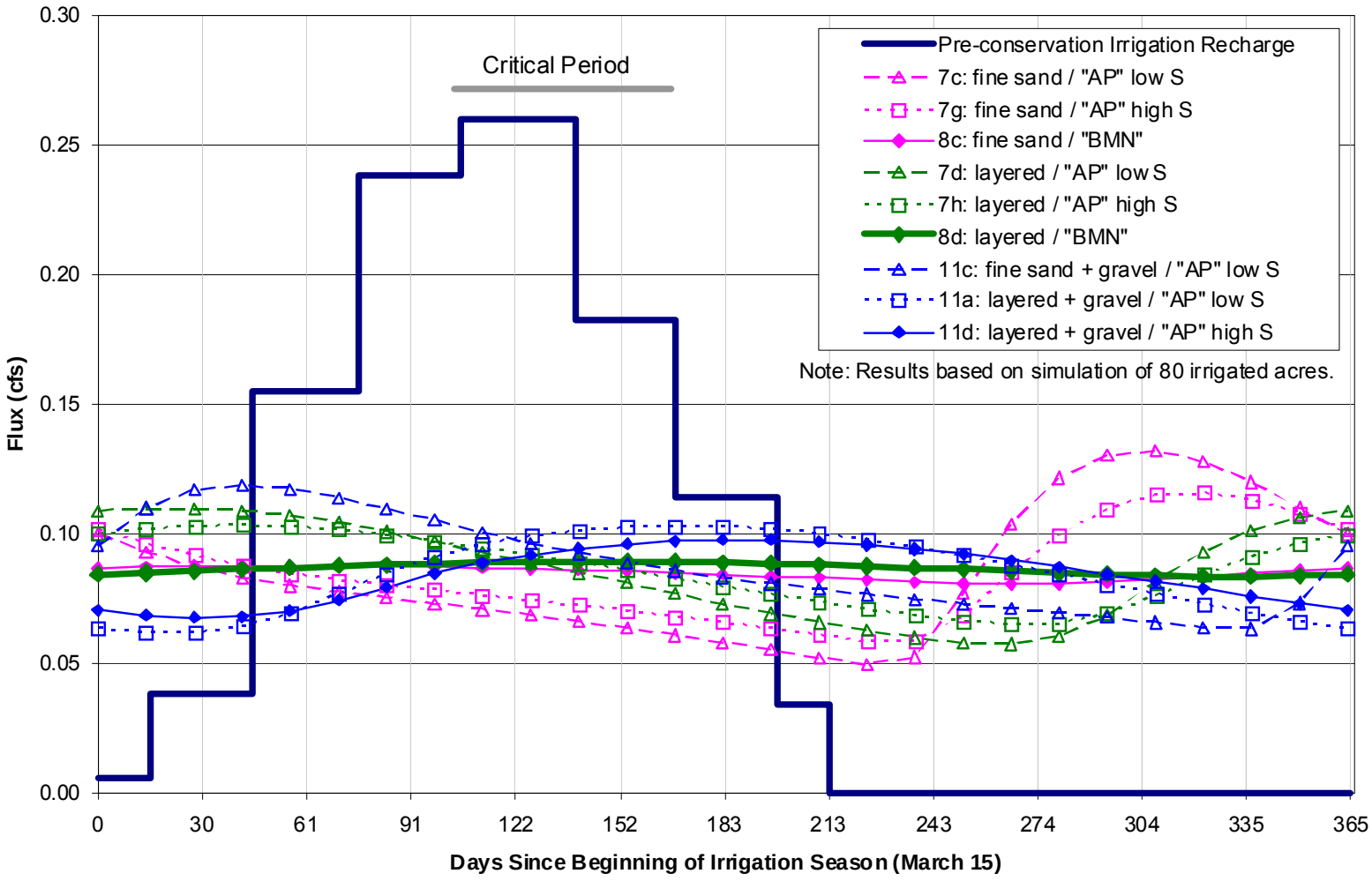

Figure K-9
Pre-Conservation Comparison of MODFLOW Model Results

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Retiming Benefits Analysis

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