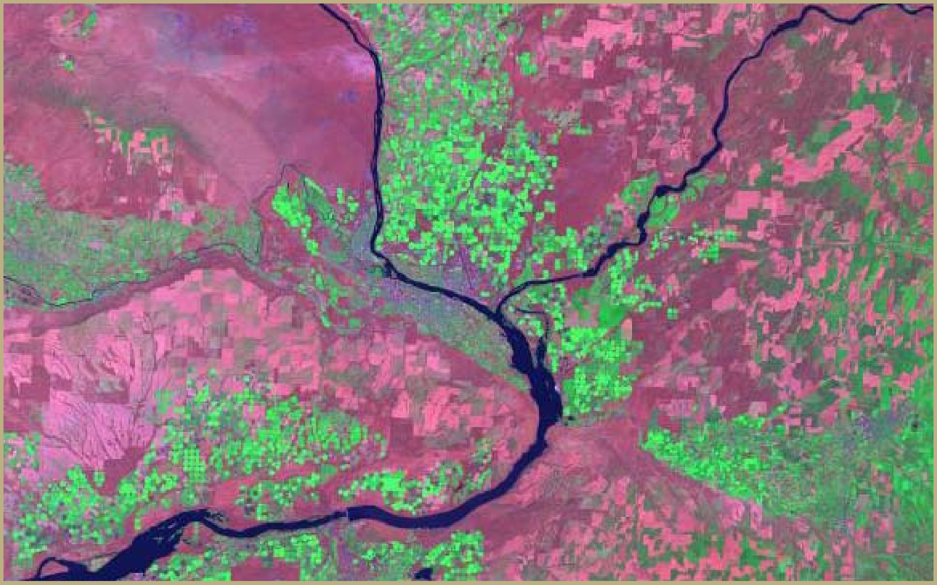
PACIFIC groundwater GROUP

RETIMING BENEFITS ANALYSIS FOR CONSERVATION IN THE WALLA WALLA, HORSE HEAVEN HILLS AND SOUTHERN FRANKLIN COUNTY STUDY AREAS



DEPARTMENT OF
ECOLOGY
State of Washington

Ecology Publication Number: 12-12-005

February 2012

RETIMING BENEFITS ANALYSIS FOR CONSERVATION IN THE WALLA WALLA, HORSE HEAVEN HILLS AND SOUTHERN FRANKLIN COUNTY STUDY AREAS

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February 27, 2012
JZ1001
Franklin Retiming Report Final.doc

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SIGNATURE

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1.0 INTRODUCTION

This report presents analysis of three study areas identified as good candidates for irrigation conservation projects. The goal of such projects would be to reduce irrigation diversions/withdrawals, thus making more water available during the critical flow periods on a given stream for additional beneficial uses without impairment to existing water rights or fisheries objectives.

In early March 2010, the consultant team of Pacific Groundwater Group (PGG) and RH2 Engineering (RH2) met with Mark Nielson of the Franklin Conservation District (FCD) and members of the Irrigation Work Group (IWG) to discuss study areas for preliminary evaluation. Nine areas were considered, of which three (Horse Heaven Hills, Southern Franklin County, and the Walla Walla Basin) appeared to meet most of the following criteria identified for an "ideal" area:

1. Currently makes significant use of low-efficiency irrigation methods (e.g. flood irrigation) and can be converted to high efficiency (e.g. center pivot irrigation with low energy precision application (LEPA[1]) and/or irrigation water management (IWM));
2. Far enough from Columbia River such that the timing of subsurface irrigation return flows is lagged and/or damped so as to deliver a significant portion of the return flow back to the river outside the critical flow period for a river or stream;
3. Irrigation practices are served by surface water diverted from the Columbia River or one of its tributaries;
4. Existing water rights should be perfected (certificated) and not part of the Columbia Basin Project. Participants in this conservation program must have the authority to transfer a portion of their existing water rights into Ecology's Trust Water Right Program;
5. Hydrogeologic conditions in the area should be relatively well understood and not overly complex, such that timing analysis of subsurface return flow is defensible and not dominated by uncertainty;
6. High potential for multiple irrigation conservation projects in the area, such that a single timing analysis can apply to multiple sites within the area.

The purpose of this report is to provide:

- A basis for assessing how key criteria from the above list apply to the selected study areas;
- Estimates of the potential for conservation and reduction in irrigation losses; and
- Defensible estimates of the "retiming" of subsurface return flow and hydrologic benefits due to conservation.

Overall, PGG and RH2's analyses suggest that each of the three study areas meet some, but not all, of the ideal criteria outlined above. The timing of subsurface return flows in all three study areas appears amenable to increasing water availability during defined critical flow periods. Along with providing "retiming benefits" through reducing deep percolation losses, proposed conservation would also create additional benefits such as reducing evaporation losses (i.e. consumptive use).

This work was performed, our findings obtained, and this report prepared, using generally accepted hydrogeologic practices used at this time and in this vicinity, for exclusive application to this study, and for the exclusive use of FCD. This is in lieu of other warranties, express or implied.

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[1] For the purpose of this report, LEPA is defined as a center pivot irrigation system with low pressure drop tubes and no end gun(s).

2.0 EXECUTIVE SUMMARY

<u>*General Comments*</u>

1) This document evaluates the potential for irrigation conservation and the benefits associated with the "retiming" of associated subsurface irrigation return flow. RH2 evaluated current crop and irrigation practices and the potential for reducing irrigation recharge (as needed for retiming). PGG evaluated hydrogeologic conditions and the pathways for subsurface return flow, and used a variety of models to estimate the timing of subsurface return flows. Dr. Thomas Harter addressed modeling of irrigation water through the vadose zone.

2) In order to maximize conservation potential within the three study areas, both mechanical upgrades and the addition of irrigation water management (IWM) to existing irrigation systems would be required. Replacing existing irrigation systems with center pivot structures with low energy precision application (LEPA) will reduce the overall amount of water needed, and will nearly eliminate surface return flows. Furthermore, adopting irrigation water management (IWM) practices will promote operation of center pivot structures at maximum efficiency while fulfilling crop water needs. In order to achieve the maximum irrigation conservation potential estimated for the three study areas, upgrades would be required over a significant irrigated acreage.

3) Conservation benefit is calculated as the reduction in surface-water diversion associated with conservation minus the subsurface return flow also eliminated by the conservation measure. Conservation benefits achieved during "critical flow periods" can potentially increase water availability for beneficial uses. Conservation reduces irrigation losses, which are distributed between evaporation, deep percolation, and surface-runoff. Conservation savings associated with reduced evaporation represent a full and (nearly) immediate benefit to streamflow, and are herein termed "E benefit". Reduced surface return flows provide no significant conservation benefit because the timing of surface return flow is similar to leaving the water in the river. Conservation savings associated with reduced deep percolation leads to retiming of water availability, which is interpreted as a benefit if more water remains in the river during critical flow periods. This critical flow increase is balanced by less water available during the non-critical flow period, hence the term "retiming benefit".

4) Early project scoping assumed that "pilot site" locations would be identified for prediction of conservation benefits. However, to date, only one pilot site location has been identified (in the Walla Walla Basin). In order to evaluate potential conservation benefits in the other study areas, PGG evaluated three hypothetical sites within the Southern Franklin County (SFC) study area and assessed conservation at various distances from the Columbia River in the Horse Heaven Hills study area. Until the Washington State Conservation Commission (WSCC) identifies additional pilot sites, PGG's analysis provides "proof of concept" of conservation benefits during critical flow periods.

5) RH2 estimated losses associated with current irrigation methods and under post-conservation conditions. Under current conditions, losses are estimated to be distributed among evaporation (27% to 36% of total loss), deep percolation (60% to 65% of total loss), and surface flow (typically a small remainder)[2]. For the purpose of this analysis, RH2 assumed that conservation achieves the maximum theoretical reduction in deep percolation loss (zero remaining deep percolation) for conversion to center pivot with LEPA and IWM. In actuality, a small amount of residual deep percolation is expected to occur, but should only have a minor impact to the calculations presented herein. While PGG's

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[2] These estimates are compiled based on the study area analyses presented within this report.

evaluations provide "proof of concept" of conservation benefits, residual deep percolation can be included in future calculations once pilot sites are identified.

6) The critical flow period defined for the Columbia River is July-August, whereas the critical flow period for the Snake River is April-August. For the purpose of this project, all estimates of conservation benefit were assessed relative to a July-August critical period. Both the Horse Heaven Hills and Walla Walla study areas discharge only to the Columbia River, and although the SFC study area also discharges to a short reach of the Snake River, this reach is occupied by Lake Wallula which is an expression of reservoir levels in the Columbia River.

7) Estimation of E benefit and retiming benefit for hypothetical sites employs study-area average estimates of crop water requirement, irrigation efficiency, and distribution of irrigation losses. Once pilot sites are identified, it may be desirable to perform calculations based on the actual crops and practices specific to the site. While irrigation methods associated with a given site are typically fixed over time, crop selection may vary from year to year. Estimation of conservation benefit can be relatively sensitive to the month-to-month distribution of crop requirements (and associated total applications). Irrigation diversions are based on total applications, and conservation benefits (for surface-water sourced agriculture) provide nearly instantaneous benefits to reduced irrigation diversions. Thus, the assumed monthly distribution of irrigation diversions particular to a given crop (or a historical average of crops) can have a significant influence on the monthly distribution conservation benefit.

8) This report focuses on irrigation benefits through retiming, and therefore evaluates flowpaths and flow dynamics in the subsurface – including the groundwater system and the unsaturated sediments which overlie the water table ("vadose zone"). PGG modeling analyses suggest that retiming of subsurface return flow will create conservation benefit in all three study areas. In addition to the conservation benefit associated with retiming, additional conservation benefit would be gleaned based on reduced evaporation. This report includes estimates of both retiming benefit and E benefit.

9) PGG's calculations suggest that subsurface return flows from irrigation recharge are likely to be highly damped in many locations throughout the study areas. Damped conditions provide a fairly uniform, year-round return flow to rivers[3]. PGG's analyses provide a basis for estimating retiming benefit based on the difference between the portion of reduced irrigation diversions/withdrawals associated with deep percolation losses and the retiming of subsurface irrigation return flow to the river(s). At one location in the SFC study area, PGG employed a modified analytical approach to evaluate the conservation benefit of groundwater-sourced irrigation.

10) All sites evaluated suggest highly damped subsurface return flows and good potential for retiming benefit. However, candidate sites located particularly close to the river(s) or exhibiting otherwise unfavorable hydrogeologic conditions could provide reduced benefit. If new pilot sites are identified in areas different from those documented in this report (or with other significant differences), supplemental characterization and modeling may be required to estimate retiming benefit. Additionally, because RH2's irrigation loss estimates are based on study-area averages and the assumption of maximum theoretical reduction of deep percolation loss, updated calculations may be needed to estimate conservation benefits based on *actual* irrigation losses specific to the irrigation methods employed at the sites.

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[3] For the purpose of this report, "damping" is defined as one minus the ratio of the seasonal variation of subsurface return flow to the river vs. irrigation recharge at the land surface. For instance, 90% damped return flow means that only 10% of the seasonal variation of irrigation recharge remains in the associated discharge to the Columbia River.

11) In order to issue new water rights based on conservation benefits, Ecology's Office of the Columbia River (OCR) must be able to ensure that:

- No new water right would issue without the 4 part test in RCW 90.03.290 being met.
- If additional statutory or regulation requirements exist (e.g. Columbia River consultation under WAC 173-563-020, Voluntary Regional Agreement "no negative impact" standard), they must also be met.

RCW 90.90 does not specify the balance of instream and out-of-stream benefit for water made available for conservation projects. Assuming a pilot project is demonstrated to be successful, OCR may decide to issue new irrigation permits for less than the full amount predicted to be available under the pilot to benefit instream flows and/or to cover any modeling uncertainty associated with the pilot.

Horse Heaven Hills Study Area

12) Crops in the Horse Heaven Hills study area are primarily potato, corn (sweet/field), and wheat. These crops are efficiently irrigated, with the majority of the land being under center pivot systems. Upgrading current irrigation methods to center pivot with LEPA and IWM practices may be the most feasible method of conserving water. In doing so, evaporative losses would be greatly reduced, surface runoff would be eliminated, and a significant reduction in deep percolation would occur.

13) Over much of the Horse Heaven Hills study area, relatively fine-grained sediments (loess and "Touchet Beds") overlie a thick sequence of Columbia River Basalt. Most of the recharge is due to irrigation applications, and both natural recharge and stream baseflows are relatively insignificant. Irrigation recharge percolates downward through the sediments that overly the basalts ("suprabasalt" sediments), and most of the subsurface return flow to the Columbia River is expected to occur as a result of lateral flow within these sediments. Some portion of the recharge, however, is expected to enter the basalts and either remain in fairly isolated "cells" or flow back to the Columbia River.

14) Data are sparse regarding the character of the saturated flow system conducting subsurface return flow back to the Columbia River. In addition, a variety of hydrologic conditions can occur within the vadose zone. PGG employed both modeling and qualitative analyses to assess various possible conditions within the vadose and saturated zones.

15) The fine texture of the loess and Touchet beds is expected to cause substantial damping of the seasonal irrigation recharge pulse between the land surface and the water table. Further damping is expected within the saturated flowpath between the potential conservation sites and the Columbia River. Combined predictions of high damping in both the vadose and saturated zones suggest combined damping in excess of 90%. This level of damping can be approximated by uniform year-round subsurface return flow.

16) Based on RH2's estimates of irrigation recharge (deep percolation losses) and the assumption of uniform year-round subsurface return flow, retiming benefits of 0.119 and 0.112 feet are be estimated for the critical months of July and August[4]. Associated E benefits are estimated to be 0.053 and 0.043 ft/d, resulting in total conservation benefits of 0.172 and 0.155 feet. These estimates can be refined for individual pilot sites based on irrigation-method specific estimates of pre-conservation and post-conservation losses.

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[4] Benefits are expressed in feet (ft) so that they can be multiplied by the area placed under conservation to yield monthly volumes of acre-feet (af).

Southern Franklin County (SFC) Study Area

17) The SFC study area is largely comprised of alfalfa, potatoes, and wheat crops. The majority of the irrigation in the study area comes from center pivot structures, but there is also a sizable percentage of land under sprinkler and wheel line irrigation. Upgrading current irrigation systems to center pivot systems with LEPA and implementing IWM will yield the greatest conservation potential within this study area. In doing this, surface runoff will be eliminated and the remaining losses will be mainly from evaporation and a minor amount of deep percolation.

18) Identification of pilot sites within the SFC study area which meet the project criteria is likely to be challenging. Most surface-water sourced farms use federal (U.S. Bureau of Reclamation) water rights delivered through the South Columbia Basin Irrigation District (SCBID). Arrangements for transfer of federally held water rights to the Washington State water-right system are likely to be complex. Non-federal surface-water rights in the Franklin Irrigation District now largely serve residential uses, and the FID is located particularly close to the Columbia River where the vadose zone is coarse-grained and relatively thin. Improvements in the “Greenbelt”, an area sourced by groundwater with moderate vadose-zone thicknesses, could provide conservation benefit, but less than for surface-water sourced farms.

19) PGG divided the SFC study area into three hydrogeologic provinces based on the dominant hydrogeology:

- The “Quaternary Province”, dominated by gravels of the Quaternary Flood Deposits and the Middle Ringold Formation;
- The “Upper Ringold Province”, dominated by the fine-grained Upper Ringold Formation in the northwestern portion of the study area; and,
- The “Basalt Province”, dominated by Columbia River basalts in the eastern portion of the study area.

20) The hydrogeology of the Quaternary Province is relatively straightforward and reasonably well defined. This province was therefore selected for modeling analysis, and three hypothetical conservation sites were selected by FCD to demonstrate conservation benefits under differing conditions. Two of the sites, located within Block 1 and Block 17, employ irrigation from surface water from the South Columbia Basin Irrigation District (SCBID). The third site is located in the “Greenbelt” and is sourced from groundwater. PGG used slightly different modeling analyses to estimate conservation benefit from surface-water vs. groundwater sourced sites.

21) The hydrogeology of the Upper Ringold Province is complex and requires better documentation commensurate with the level of complexity. Hydrogeologic features include: interception of significant portions of irrigation recharge by subsurface drains, locally perched aquifers, lateral flow through the fine-grained sediments to the White Bluffs and to buried exposures (“subcrops”) against adjacent Quaternary sediments, and downward flow to the underlying Middle Ringold Formation. Conservation efforts in this Province are initially expected to provide little retiming benefit, as reduced irrigation recharge will be initially matched by reduced drain interception. However, once conservation efforts are sufficient to lower the water table below the drains, retiming benefits would be expected. PGG did not attempt to model this province due to the high level of complexity, existing data gaps, and relatively low marginal benefit (at least initially) expected from conservation efforts.

22) The hydrogeology of the Basalt Province consists of basalt "interflows" (capable of transmitting water) and "flow cores" (relatively impermeable). Groundwater flow in the basalts interacts with flow in adjacent and overlying sediments; however, recent studies indicate that flow patterns are relatively localized and regional flow to the Columbia and Snake rivers is likely insignificant. PGG performed qualitative analysis of the basalt system and found that a portion of irrigation recharge in the northern half of the province could potentially discharge into wasteways and take a fast route back to the Columbia River, thus providing little retiming benefit. This return flow pathway does not occur in the southern half of the province, where irrigation recharge will either percolate into the basalts or be transmitted to the adjacent Quaternary sediments. Among these two pathways, the minimum retiming benefit is associated with the Quaternary pathway, which could be evaluated with the model developed for the Quaternary Province.

23) PGG's analyses within the Quaternary province included modeling of irrigation recharge within the vadose zone and within the saturated flow system. Although the vadose zone consists of relatively coarse-grained sediments (e.g. sandy gravel, gravelly sand, coarse sand), flow modeling based on hydraulic properties developed for the Hanford Gravels suggests that the significant depths to the water table (65 to 155 feet among the three sites) provide between 82% to 93% damping of the recharge pulse within the vadose zone.

24) PGG designed, constructed and calibrated a groundwater flow model for the Quaternary Province, and used the model to estimate the timing of subsurface irrigation return flow. At the two surface-water sourced sites, the model predicted that the (already significant) damping realized in the vadose zone would be further damped to factors generally exceeding 98%. This level of damping can be approximated as constant year-round return flow to the rivers. Based on RH2's recharge estimates for these two sites, PGG estimates July/August retiming benefits of 0.124/0.085 ft (Block 1) and 0.114/0.078 ft (Block 17). With E benefits included, PGG estimates July/August total conservation benefits of 0.190/0.137 ft (Block 1) and 0.184/0.133 ft (Block 17).

25) Evaluation of conservation benefit for the Greenbelt site involved less total damping because groundwater pumping has a direct impact on the aquifer that is not mediated by damping within the vadose zone. In order to estimate conservation benefit at the Greenbelt site, PGG used the model to simulate baseflow impacts from the combined stresses of irrigation pumping and associated deep percolation recharge (including recharge transport through the vadose zone). Similar to the other two sites, uncertainty analysis was included in the modeling predictions. Conservation benefit was estimated as the difference between modeled baseflow impacts before and after conservation. With this method, E benefits and retiming benefits could not be separated and the (minimal) effects of surface-water runoff were disregarded. For the model realization using PGG's calibrated aquifer parameters, total July/August conservation benefits were estimated to be 0.016/0.025 feet. These smaller numbers occur because the predicted impacts of groundwater pumping on the river are damped almost as much as is irrigation recharge (whereas for surface-water sources, the impacts of reduced diversion are instantaneous and relatively high during the July/August critical months).

Walla Walla Study Area

26) The Walla Walla study area is the smallest of the three study areas and has the lowest average irrigation efficiency. Currently the majority of the area, comprised of wheat and alfalfa/ alfalfa seed, is under wheel-line and sprinkler irrigation, both of which are predisposed to evaporative and deep percolation losses. Upgrading the current irrigation systems to center pivot systems with LEPA will provide the greatest conservation potential. Further adopting IWM practices will minimize evaporative and deep percolation losses while nearly eliminating surface runoff losses.

27) WSCC performed an extensive search for potential pilot sites in the Walla Walla study area and encountered difficulty in finding sites likely to provide significant retiming benefit. Many farms do not have full-irrigation-season surface-water rights, instead relying on groundwater for various portions of the season (including the July-August critical period). Farms with full-season surface-water rights are typically located too close to the Walla Walla River to provide significant retiming benefit. WSCC and PGG narrowed the search focus to the Gardena Terrace, a terrace deposit in the lower basin with higher potential for retiming due to a thick vadose zone. Two sites were identified with full-season surface-water rights, and ultimately only one was available as a pilot site. Additional surface-water sourced sites are likely to be scarce; however, PGG's retiming analysis for the single pilot site provides "proof of concept" of retiming benefits under similar conditions, including: a site located along a tributary (rather than along the Columbia River) and relatively close to the receiving water body (with retiming benefit achieved via damping in the vadose zone rather than via damping in the saturated flow system).

28) The groundwater flow system underlying the Gardena Terrace primarily occurs within a gravel aquifer comprised of older (mio-pliocene) and younger (recent alluvium) gravels. The gravel aquifer is separated from the underlying Columbia River Basalts by a thick clay unit, and is overlain by a fine-grained unit mainly consisting of Touchet Beds (layered fine sand and silt). The Touchet beds are typically unsaturated along with portions of the underlying gravels (typically set within a matrix of finer-grained sediments). Although the Gardena Terrace is located relatively close to the Walla Walla River, this thick vadose zone provides significant damping of the irrigation recharge pulse.

29) PGG evaluated retiming of the irrigation recharge pulse within the vadose zone based on conditions expected at the pilot site: about 30 feet of unsaturated Touchet Beds underlain by as much as 20-60 feet of unsaturated gravelly deposits. PGG considered a range of hydraulic properties for the Touchet Beds derived from published grain-size analyses from local exposures and a published database relating soil texture to hydraulic properties. Predicted damping in the Touchet Beds ranged from 45% to 79%, with the most realistic value estimated to be about 76% when 33 feet of gravelly sediments were simulated below 33 feet of layered Touchet Beds. PGG used the full range of predicted timing of recharge reaching the water table as input to a saturated groundwater flow model.

30) PGG developed a groundwater flow model for the Gardena Terrace area using the USGS "MODFLOW-2000" modeling code. Model layering was based on published stratigraphic characterization of suprabasalt sediments in the Walla Walla Basin, and a range of aquifer properties was defined based on previous modeling performed by the USGS and others. In order to address hydrogeologic uncertainty, PGG input the range of vadose-zone prediction into the range of MODFLOW model configurations, and produced a range of model results. All model results showed moderate-to-high (68% to 98%) damping, and results from the highest-confidence model configurations showed 98% damping.

31) PGG recommends using our interpreted highest-confidence results as a basis for estimating retiming benefits for the Walla Walla study area. These results can be approximated by a uniform, year-round groundwater discharge to the Walla Walla River (and likewise the Columbia River). Based on RH2's estimates of irrigation recharge over the 80 acres assumed available for conservation at the proposed site and model predictions of subsurface irrigation return flow, retiming benefits of 10.5 and 5.7 acre-feet (af) were estimated for the critical months of July and August. With associated E benefits, total conservation benefits are predicted to increase to 15.0 af (July) and 9.0 af (August).

32) The vadose zone beneath the Gardena Terrace provides significant retiming benefit. It may be worthwhile to consider retiming benefits from groundwater-sourced farms with wells near the Walla Walla

River, especially if pumping impacts show little damping but subsurface irrigation return flow is highly damped within the vadose zone.

3.0 HORSE HEAVEN HILLS

The Horse Heaven Hills study area covers about 410 square miles, predominantly in Benton County Washington. The plateau-like area extends from the crest of the Horse Heaven Hills, which rises immediately south of the Yakima River, gently downslope (south) to the Columbia River. Irrigation in the area is predominantly by center pivot. With the addition of conservation, both though mechanical upgrades and irrigation water management, it is estimated that a reduction of up to 67,000 af/yr in irrigation recharge could be obtained and available for retiming of subsurface return flow. Irrigation recharge progresses downward from the land surface through the vadose zone into saturated portions of the suprabasalt sediments or the underlying Columbia River Basalts (CRB's). Hydrogeologic conditions within the suprabasalt sediments are not well defined; however, the suprabasalt sediments are estimated to transmit more of the irrigation recharge to the Columbia River than the CRB's. Based on available hydrogeologic understanding, PGG performed a variety of quantitative and qualitative analyses to estimate the retiming of subsurface irrigation return flow. Although not all of the return flow pathway is well characterized by field data, consideration of all segments of the return flow pathway suggests that irrigation recharge returns to the river as fairly constant, year-round discharge. PGG's analysis further suggests that conservation (reduced irrigation recharge and evaporation losses) would increase water availability in the Columbia River during the irrigation season.

3.1 IRRIGATION ANALYSIS

The Horse Heaven Hills study area comprises lands located north of the Columbia River located in southern Benton County. The Study area comprises approximately 139,000 acres of irrigated crop lands as shown in **Figure 3-1**. The majority of the crop types grown in the study area include a variety of potatoes, sweet and field corn, onions and other irrigated crops.

3.1.1 Information Sources

Analysis of the irrigation practices, estimates of conservation potential and surface return flow pathways for the Horse Heaven Hills study area included review of crop and irrigation type data from GIS mapping, water application data and other technical information. GIS data were supplied by Franklin Conservation District (FCD) which included historical crop type and irrigation data obtained from the Washington State Department of Agriculture (WSDA). Crop data, irrigation method data and water use data was provided by FCD for the 2009 crop year and were used in estimating current practices and water use for the study area. Irrigation Water Management (IWM) values were obtained from the *"Columbia Basin Ground Water Management Area"* (2005). Literature references and technical data used to develop the memorandums included as appendices to this memorandum include: *State of Washington Irrigation Guide: Appendix A, Climatic Stations for Consumptive Use* (USDA *1985), AgriMet Data(USBR* 1988-1994), *Irrigation Efficiency, (*Howell, Terry A., 2003), *Rocky Reach Dam Initial Consultation Document (Chelan County PUD No. 1,* 1999).

Technical memoranda prepared by RH2 Engineering to support the potential irrigation conservation, surface irrigation losses, and travel time estimates presented in this memorandum include: *study area Water Use – Current Practices and Conservation Potential (***Appendix A**), *Estimates of Irrigation Surface Losses,(***Appendix B**)*, Estimate of Particle Travel Times (* **Appendix C**).

3.1.2 Current Practices and Water Use

Irrigation water for the Horse Heaven Hills study area is predominantly diverted from the Columbia River, although a portion of irrigation is supplied by wells. The predominant irrigation method used in the study area is center pivot systems which account for approximately 89% of the total irrigated acreage. Sprinkler line and drip irrigation systems account for approximately 9% the remainder of the irrigation methods used in the study area.

Estimates of the total irrigation requirement for the study area have been calculated based on the acreages for the various crop types, as summarized in the RH2 memorandum, Study Area Water Use - Current Practices and Conservation Potential, in **Appendix A**, Tables 1(b), 2(b), 3(b). These three tables show that the combined weighted average irrigation efficiency (WAIE) for the Study Area using 2009 crop data (current condition) is approximately 87%. Using WAIE, it is estimated that the total irrigation requirement for the study area is approximately 373,600 acre-feet during the irrigation season. Of this value, approximately 324,400 acre-feet are estimated for the crop irrigation requirement. The difference between the two values totals 49,200 acre-feet and is the volume of water that is lost to mechanical inefficiencies associated with the irrigation system. Losses resulting from these mechanical inefficiencies are divided into three pathways which are comprised of evaporation, surface runoff and deep percolation.

The months of June, July and August account for a largest percentage of the total application volume in the study area. Approximately 79% of the crop water needs occurs in these three months. This totals to approximately 295,000 acre-feet of irrigation water. A breakdown of the monthly irrigation requirement and associated losses for the study area is shown below with the break-down of losses discussed in the next section.

Current Weighted Avg. Irrigation Method & Crop Distribution – w/o Conservation & IWM

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Crop Requirement	0.000	0.000	0.000	0.016	0.100	0.334	0.774	0.741	0.321	0.049	0.000	0.000	2.34
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
Application Inefficiency Deep Percolation	0.000	0.000	0.000	0.001	0.003	0.011	0.026	0.025	0.011	0.002	0.000	0.000	0.08
Over Application Deep Percolation (1)	0.000	0.000	0.000	0.003	0.017	0.058	0.134	0.128	0.056	0.008	0.000	0.000	0.40
Total Application	0.00	0.00	0.00	0.02	0.12	0.38	0.89	0.85	0.37	0.06	0.00	0.00	2.69

(1) This loss value is included in the crop requirement and therefore not added separately to the total application. See **Appendix A** for discussion of IWM.

Additional deep percolation losses (shown as "Over Application Deep Percolation" above) are associated with the intrinsic management and safety factors associated with current irrigation practices. Current research estimates that irrigation requirements can be reduced by 17.31% with intensive Irrigation Water Management (IWM) techniques. Currently this water is lost to deep percolation and totals approximately 55,800 acre-feet.

It is important to note that the above estimates are based on the assumption that 50% of the center pivot irrigation systems are using LEPA sprinkler heads. Actual irrigated acreage using center pivot systems with LEPA was not available from the WSDA.

Values used in the development of the crop irrigation requirement and average irrigation efficiencies along with the assumptions used in analyzing the current irrigation practices for various types of irrigation methods are reported in **Exhibit A.**

3.1.3 Irrigation Loss Estimates

An estimate of irrigation losses associated with evaporation, surface water runoff and deep percolation has been developed for the study area based on a review of the literature from prior irrigation studies (see **Appendix B**). Both evaporation losses and surface losses are attributed to mechanical inefficiencies that are associated with the currently implemented irrigation equipment. Deep percolation losses are expressed as two terms: the first attributed to mechanical inefficiencies associated with the application method and the second attributed to crop over application associated with current irrigation practices. Implementation of IWM practices can reduce the apparent crop water need and thus reduce deep percolation. RH2's analysis indicates that adopting IWM practices presents the greatest potential for water conservation (see **Appendix B**). Using the loss estimates presented in Appendix B, a summary of the various loss volumes and pathways is presented below.

Irrigation Loss Estimates for Horse Heaven Hills Study Area

Type of Loss	Annual Loss (Acre-Feet)	Percent of Total Loss
Evaporative	36,100	34%
Surface Flow	2,100	2%
Application Inefficiency Deep Percolation	10,800	10%
Pre-IWM Over Application Deep Percolation	55,800	54%
Total:	104,800	100%

Based on discussions with FCD, there are no known drains located in the study area. However, there are several surface features that appear to act as natural drains for the area. Of these natural features, several are intermittent streams and runoff channels. Depending on the soil moisture content and time of year, it is assumed that the majority of the surface runoff either infiltrates into the ground and returns back to the Columbia River as subsurface flow or is lost to evapotranspiration within spring/seep areas or streambeds.

3.1.4 Timing of Surface Water Return Flows and Source Water Left Instream

Theoretical estimates of the timing of surface runoff return flow to the Columbia River has been estimated based on the general topography and time of concentration calculations for the study area. Given that the farthest point, from the Columbia River within the study area is approximately 15 miles, it is assumed that the travel time for surface return flows is on the order of magnitude of approximately two to four days. However, it should be noted that there is only one perennial stream in the study area and based on visual observations, it appears that little if any of the surface runoff actually makes it to the Columbia River. More likely pathways for surface runoff include loss to evapotranspiration and infiltration to the subsurface. Should the surface water infiltrate into the subsurface prior to entering the river, the travel time could significantly increase depending on the subsurface soil conditions and soil moisture content.

Travel time estimates for source water left in the Columbia River is based on information provided by Chelan County PUD, the Northwest Power and Conservation Council and the Army Corps of Engineers. This travel time information is summarized in a RH2's Memorandum entitled Water Particle Travel Times, in **Appendix C**. The Columbia River diversion supplying the Horse Heaven Hills irrigated lands is from the John Day Pool. Travel times through the John Day Pool during the irrigation season range from 4.8 to 14.4 days (**See Appendix C**).

3.1.5 Conservation Potential and Return Flow Distribution

Because the majority of the irrigation systems in the Horse Heaven Hills study area are center pivot irrigation systems, the addition of LEPA to these systems could result in the greatest mechanical conservation potential through the reduction of evaporative losses. With the addition of both LEPA and implementation of irrigation water management (IWM) is the greatest overall change that could be made to increase the conservation potential of the existing irrigation systems. It is estimated that up to 87,000 acre-feet could be saved annually (across the entire study area) if the existing center pivot irrigation systems were upgraded with LEPA and IWM.

No estimates are available for the percentage of current irrigation systems employing IWM within the study area. However, RH2 has estimated that if only IWM were employed by all existing irrigation systems within the study area, the conservation potential could be up to 64,000 acre-feet annually[5].

Upgrading all existing irrigation systems to center pivot with LEPA and implementing IWM (full conservation potential) is estimated to result in a savings of up to 91,000 acre-feet annually. See Table 3(b) in **Appendix A** for estimates of potential irrigation savings for the other types of irrigation systems within the study area.

Based on the literature review of irrigation surface losses presented in **Appendix B**, it is assumed that the addition of center pivot systems with LEPA or other high-efficiency irrigation methods (e.g. drip) will result in irrigation efficiencies in the 88% to 95% range (as compared to a current weighted average irrigation efficiency of 87%. Switching to these high-efficiency irrigation systems will result in reduced surface and deep percolation losses. With the implementation of both mechanical upgrades and IWM, it is projected that both surface runoff and deep percolation losses could decrease to zero under ideal conditions. This leaves evaporation as the only remaining loss pathway. This is considered the full conservation potential for the study area and results in the greatest savings of water for use in retiming. This estimate is based on a simplifying assumption that post-conservation deep percolation losses are reduced to zero (the *theoretical* maximum reduction in deep percolation). RH2 recognizes that a small amount of deep percolation will continue (and is needed to prevent salt buildup in the soil); however, actual residual rates of deep percolation will depend on final post-conservation irrigation methods and will have little effect on the estimates above.

It is important to recognize that this is the theoretical maximum conservation potential that could be obtained under ideal conditions. The table below summarizes RH2's estimates assuming full conservation potential based on the above assumptions:

Conservation Estimates for Horse Heaven Hills Study Area

Type of Loss	Current Loss (af/yr)	Estimated Loss with Full Conservation (af/yr)	Estimated Conservation Savings (af/yr)	Percent Reduction
Evaporative	36,100	13,800	22,300	62%
Surface Flow	2,100	0	2,100	100%
Total Deep Percolation	66,600	0	66,600	100%
Total:	104,800	13,800	91,000	87%

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[5] This number includes reduction in WIG related losses and associated reductions in application (mechanical) losses due to reduced overall application.

The following table presents RH2's monthly estimates of irrigation losses under current conditions (study-area averages) and post-conservation (maximum conservation). These estimates were used as input for modeling subsurface irrigation return flow later in this section.

Summary of Monthly Irrigation Loss Pathways – Horse Heaven Hills Study Area

(acre-feet/acre)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Current Condition (1)													
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
Maximum Conservation (1)													
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	0.00
Evaporation	0.000	0.000	0.000	0.001	0.010	0.015	0.034	0.040	0.014	0.002	0.000	0.000	0.10
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	0.00
Total Losses	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.04	0.01	0.00	0.00	0.00	0.10

1 – Values based on weighted average irrigation method and crop distribution for the study area.

As discussed above, post-conservation deep percolation is represented as the maximum *theoretical* conservation potential, and a small amount of deep percolation is expected for any post-conservation condition. Post-conservation deep percolation should be included during (future) individual analyses of pilot sites. For the current analysis, the effect on estimating reduction in total deep percolation (0.48 ft/yr) is small.

It is important to note that the estimates of potential conservation savings for this study area are based on WSDA datasets of both the crop distribution and irrigation system type as provided by the Franklin County Conservation District. These data are not linked, i.e.; it is not specifically known how much of each crop is irrigated by a specific irrigation method. As a result the estimates are based on a geographic distribution for the entire study area but are not crop or field specific. Therefore, while the analyses of the irrigation practices and conservation potential provides a good understanding of the entire study area, it is not recommended that this analytical approach be assumed accurate to a given individual farm or a specific small geographical area.

Both the crop irrigation requirement and irrigation efficiencies used are based on best available information but, as previously noted, the dataset is limited to general categories of both crops and irrigation types. Irrigation loss estimates are based on the assumption that 50% of the center pivot acreage employs LEPA. The dataset does not indicate how much of the acreage in each of the study areas are already employing IWM. RH2's estimates of total conservation potential will be sensitive to these assumptions and could differ to varying degrees if actual conditions depart significantly from these assumptions..

A detailed discussion of the assumptions used in developing the conservation potential for the various types of mechanical upgrades including the addition of IWM and the results of this analysis for the study area is summarized in **Appendix A**.

3.2 HYDROGEOLOGIC CONDITIONS

Over much of the Horse Heaven Hills study area, relatively fine-grained soils (loess and Touchet Beds) cover the land surface, comprising the top of the "suprabasalt" sediment profile that overlies a thick sequence of Columbia River Basalts (CRB's). Both natural recharge and stream baseflows are fairly insignificant, with most of the recharge due to irrigation applications. Irrigation recharge percolates downward through the suprabasalt sediments, and subsurface return flow to the Columbia River is expected to occur either within these sediments or via the CRB groundwater flow system. Groundwater conditions have been studied (and modeled) within the CRB's, but saturated conditions within the suprabasalt sediments are not well defined. As part of this study, PGG used available data to further characterized vadose-zone conditions within the suprabasalt sediments; however, the data did not support improved characterization of the saturated zone. Where data gaps exist, PGG employed best professional judgment to define a reasonable range of hydrogeologic conditions to constrain our evaluation of subsurface irrigation return flow timing.

3.2.1 Information Sources

PGG's analysis of hydrogeologic conditions in the Horse Heaven Hills included review of: well logs on file with Department of Ecology; groundwater level data in the USGS National Water Information System (NWIS) database; GIS coverages of surficial geology and hydrography; Ecology's Water Supply Bulletin 51 (Molenaar, 1982), and documentation of a U.S. Geological Survey computer model of the local groundwater flow system (Packard et al, 1996). The study areas for the USGS and Ecology publications are larger than the study area defined by FCD. The FCD study area is limited to irrigated areas in the south-central and southeast portions of the USGS study area (**Figure 3-2**), which extends further to the north and west.

3.2.2 Surficial Geology and Hydrostratigraphic Units

Description of the surficial geology and hydrostratigraphy of the Horse Heaven Hills area is summarized from the reports mentioned above. Molenaar (1982) writes:

> The rocks underlying the Horse Heaven Hills – exposed or beneath a thin soil mantle – are basalt and some sedimentary interbeds of the Columbia River Basalt Group of Miocene Age. The basalt occurs in flow layers ranging in thickness from a few feet to more than 100 ft, and their cumulative thickness beneath the study area is probably 5,000 ft or greater, as determined by drillers' logs of wells in areas adjacent to the study area. Overlying the basalt, particularly in the eastern half of the area, are unconsolidated fine-grained materials of lacustrine (lake) and loessal (wind carried) derivation, mostly deposits of silt and sand. The higher lands are mantled by silt of variable depths (a few inches to 10 feet or more); the areas of intermediate altitude (up to 1,000 ft) have lacustrine sediments of layered silt and very fine sand (the Touchet Beds of Flint, 1938); and the areas nearer the river are underlain by alluvial sand and gravel. The Horse Heaven Hills is part of a structural upwarp affecting the basalt and interbedded sediments of the Columbia River Basalt Group. The axis of the Horse Heaven anticline extends generally east and west across south-central Washington and northeastern Oregon. The north limb of the anticline descends steeply to the Yakima and Walla Walla valleys, whereas the south limb forms the relative gentle, plateau-like slope descending to the Columbia River and Umatilla basin. Several smaller east-west trending anticlinal ridges and synclinal valleys and minor faults occur in this area.

Figure 3-2 shows the surficial geology of the study area. Unconsolidated suprabasalt sediments (ranging in thickness from 10 to 200 feet) overly most of the area with basalt outcrops observed in the bottoms of many drainages. Loess sediments overly the eastern half of the study area, whereas sand and silt outburst flood deposits (Touchet Beds) are exposed over much of the western study area. Lindsay (2010) reports that coarse-grained Ringold Formation crops out on the Columbia Hills anticline (which parallels the Columbia River at a distance of 2 to 4 miles).

One key factor for analyzing the timing of subsurface return flow of irrigation recharge is the thickness and texture of the vadose zone. Analysis of grain-size distribution from loess soils in the Horse Heaven Hills shows a combination of sand, silt and clay in an approximate ratio of 55%/30%/15%[6] (Flury, 2010). Packard et al (1996) report that the loess sediments typically range from 10 to 40 feet thick (the higher end of the range occurring in the eastern Horse Heaven Hills area) and that they are typically unsaturated. As illustrated in Section 3.3.2, the fine-grained texture of loess is expected to significantly dampen the timing of downward transmission of irrigation recharge in the vadose-zone prior to entering the underlying (saturated) groundwater flow system. Although grain-size distributions and hydraulic properties estimates are not available for local occurrences of the Touchet Beds, their relatively fine-grained texture (silt and very fine sand) is expected to similarly offer vadose-zone damping of irrigation recharge.

PGG reviewed drillers logs at least 2 miles from the Columbia River to evaluate the thickness and texture of the suprabasalt sediments. The logs are located by driller-reported quarter-quarter sections (nearest ¼ mile), which is not always accurate. Thickness of unconsolidated sediments (i.e. reported depth to basalt) is expected to be reasonably accurate; however, PGG's experience shows that driller's care in interpreting sedimentary texture can vary widely. When care is taken, differentiation between coarse-grained sands and gravels and fine-grained silts and silty sands should be fairly straightforward. However, with target well depths hundreds to over one thousand feet deep, drillers are not always careful in reporting the texture of unconsolidated "overburden". **Figure 3-2** shows a considerable number of logs in the eastern study area where the suprabasalt sediments were interpreted as predominantly fine or fine-medium textured (e.g. clay, ash, silt, silt and sand) with thicknesses typically ranging from 10 to over 100 feet. However, some coarse-textured interpretations (e.g. sand and gravel) are also noted which could reflect Ringold Formation or driller misinterpretation of texture or well location. The extent to which drillers logs can be used to better define the texture and thickness of fine-grained loess deposits (taken at face value or field checked to confirm locations) is uncertain.

Aspect Consultants (2001) state that inland from the Columbia River, the unconsolidated Quaternary (suprabasalt) deposits are generally unsaturated or in places partially saturated, and represent a marginal component of the groundwater occurrence. Molenaar (1982) states that groundwater occurs principally in the basalts and associated sedimentary interbeds. Packard et al (1994), however, estimate that only 20 to 30% of recharge enters the CRB's – the rest remaining within the suprabasalt sediments (Section 3.2.4). The reported emphasis on groundwater occurrence in the CRB's may partly reflect the higher likelihood of success for developing high flow-rate wells in the CRB's rather than indicating an overall lack of groundwater occurrence in the suprabasalt sediments.

Three major basalt formations are identified within the study area as (top to bottom) Saddle Mountains Basalt, Wanapum Basalt, and Grande Ronde Basalt. Each formation is comprised of several basalt members, sometimes separated by sedimentary interbeds of the Ellensburg Formation. The basalts have undergone significant structural deformation, including folding and faulting. The basalt rocks are moderately porous and their permeability is, to some extent, related to major structures. Major faults and tightly folded anticlines tend to form low permeability "flow barriers" relative to higher permeability undisturbed areas ("cells"). GSI have characterized flow conditions in the Columbia River Basalts for the Columbia

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[6] Professor Flury notes that loess textures show a strong increase in sand content from eastern to central Washington. For example, Loess is sandy in the Horse Heaven Hills relative to Pullman, Wa.

Basin Groundwater Management Area (GWMA). Most of the groundwater flow occurs in higher permeability interflows (flow tops and flow bottoms), whereas flow cores are more solid and tightly fractured, providing relative restriction to vertical flow. GSI concludes that while the basalts store and transmit groundwater locally in cells, regional flow across the bounding flow barriers (and interflow pinch-outs) towards the Columbia River is minimal (Lindsay, 2010). Given the scale of the study area and the locations/spacing of structural geologic features, it is possible that some flow cells within the basalts may discharge to the Columbia River.

3.2.3 Vadose Zone

Within the study area, the vadose zone typically occurs in the suprabasalt sediments and in portions of the basalts. The suprabasalt sediments can range in thickness from less than 10 feet to several hundred feet **Figure 3-2**). Packard et al (1996) report that the loess sediments are typically unsaturated, and that portions of the Saddle Mountain and Wanapum basalts can be unsaturated in the eastern study area, along the crest of the Horse Heaven Hills and along steep canyons incised through these units. Saturated conditions, however, *can* occur within the suprabasalt sediments. Localized perching can occur upon zones of mineral accumulation referred to as "duripans[7]. Mark Nielson of the Franklin Conservation District notes that these perching zones can cause "ponding" within an irrigated field, that they are typically about 30 inches deep, exhibit low permeability (rather than a complete restriction to flow), and are not commonly associated with discharge to seeps or springs (Nielson, 2011). Perched conditions within the loess deposits associated with irrigation recharge are inferred along lower Glade Creek (western study area, **Figure 3-2**), and support baseflow in the creek.

PGG reviewed drillers well logs to evaluate saturation, and while we found that reported depth to water was typically deeper than the unconsolidated sediments, the wells were commonly completed in much deeper (basalt) aquifers and are unlikely to reflect shallow saturation. During recent field reconnaissance, PGG observed small springs or seeps emanating from the suprabasalt sediments supporting local patches of lush vegetation, which suggests local perched conditions similar to Glade Creek. Mark Nielson (2010) reports that these springs/seeps emit fairly constant year-round outflow, which suggests that the combined hydraulic effects of the fine-grained vadose zone and the saturated return-flow pathway cause significant damping of the seasonal recharge pulse. Measured variation in average monthly Glade Creek discharge (9.1 to 14.8 cfs over the course of 1981) is also relatively small given that over the 7-month irrigation season, most of the irrigation recharge is expected to occur during an 4-month period between June and September (Section 3.1.5).

Loess and Touchet Beds overly large portions of the study area (**Figure 3-2**). The textures of suprabasalt sediments are reported to range from silt and fine sand (in the loess and Touchet Beds) to alluvial sand and gravel along the Columbia River (Molenaar, 1982). As noted above, some drillers logs are inconsistent with this representation; which may indicate problems with the drillers interpretations, well locations, or occurrence of Ringold Formation. In all but the Columbia River alluvium, the vadose zone is expected to contain surficial occurrence of fine-grained sediments. Grain size analysis of local loess indicated proportions of sand (55%), silt (30%) and clay (15%) (Flury, 2010). Well logs suggest that the suprabasalt sediments range in thickness from several tens of feet to 200 feet (**Figure 3-2**). In cases where the most of the suprabasalt sediments are unsaturated, the finer-grained loess could comprise only a portion of the vadose zone and could overlie other unsaturated sediments of variable texture.

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[7] Duripan is a diagnostic soil horizon of the USDA soil taxonomy that is cemented by illuvial silica into a subsurface hardpan. Duripans contrast with fragipans, which are formed by of pedogenesis and occur in the siltier loess soils and moister climate of northern Idaho (Flurry, 2011).

Packard et al note that the texture of the loess significantly influences the timing of irrigation recharge transmission downward through the vadose zone:

> "It is apparent… that in a zone of ever-changing soil-moisture content (such as in the root zone), computations of downward (or upward) flux become extremely complex and tenuous. With increasing depth, however, seasonal moisture fluctuations tend to damp out. Moreover, if for some depth intervals, the soil properties and moisture content are uniform, it can be seen… that the downward flux is simply Q = K. In the eastern part of the Horse Heaven Hills study area, the loess soil properties are very uniform with depth and in some areas it is sufficiently thick that the above conditions were found."

Packard et al encountered such a zone of uniform moisture (and uniform downward flux) below a depth of 9 feet in the loess deposits. The associated recharge conditions (low precipitation recharge vs. high irrigation recharge) were not reported. Nevertheless, their observation suggests that a fine-grained vadose zone may provide significant damping of the seasonal irrigation recharge pulse prior to its arrival at the water table. This concept is also supported by limited seasonal variation of irrigation-sourced, groundwater-fed baseflows in Glade Creek and reports of year-round flow from springs/seeps perched above the basalts (Nielson, 2010). Where duripan zones locally perch water, concentration of saturation could potentially hasten the timing for delivery of irrigation recharge to the water table or to spring/seep discharge points.

Unsaturated portions of the CRB's (where present) can also comprise portions of the vadose zone. After passing through the vadose zone within the suprabasalt sediments, irrigation recharge would need to pass through unsaturated sequences of basalt interflow zones (rubbly basalt flow tops and bottoms), sedimentary interbeds, and tight fractures within dense basalt flow cores.

The vadose zone is of key importance to evaluating the timing of the seasonal irrigation recharge pulse and how it ultimately affects groundwater discharge to the Columbia River. Discussion of flow timing within the vadose zone is presented in Section 3.3.2.

3.2.4 Recharge, Discharge and Key Hydrologic Boundaries

The groundwater system is recharged by infiltration of precipitation and irrigation applications. Packard et al estimate both precipitation and irrigation recharge for the study area; however, PGG notes both incomplete documentation and inconsistencies among their findings. Over the FCD study area, Packard et al estimate that precipitation recharge ranges from zero in/yr (covering a significant portion of the study area) to values exceeding 0.25 in/yr. Most of the precipitation recharge is estimated to occur west of the FCD study area, with values ranging from 0.1 to 3 in/yr. Packard et al estimate total precipitation recharge to the Horse Heaven Hills to be about 50,500 af/yr.

Packard's estimate of irrigation recharge is poorly documented, but appears to be based on the assumption that 25% of irrigation applications recharge the groundwater system while the remaining irrigation water is used by plants or runs off. Packard estimates typical application rates of 3.0 and 2.5 ft/yr for groundwater and surface water (respectively), thereby assuming associated irrigation recharge of 0.75 and 0.63 ft/yr. By applying this assumption to irrigated rates and areas, one can estimate irrigation recharge. For instance, in 1982 about 8,000 acres were irrigated by groundwater and 70,000 acres by surface-water over the USGS study area – thus resulting in an irrigation recharge of about 50,000 af/yr. This irrigation recharge occurs predominantly within the FCD study area and is much more significant than precipitation recharge over the same area. Packard et al apparently also assume that 70% to 80% of this recharge remains within the suprabasalt sediments (about 37,500 af/yr), with only 20% to 30% recharging the basalts (about 12,500 af/yr). Their report specifically estimates that basalt recharge from imported surface-water irrigation averaged about 9,800 af/yr between 1973 and 1982.

Packard's recharge estimate assumes an efficiency of less than 75% (25% going to deep percolation, undocumented portions going to evaporation and runoff) applied to 78,000 irrigated acres. Under current conditions, RH2 estimates total irrigation of 373,640 acre-feet applied to 139,095 irrigated acres in the study area with an average efficiency of 87%, an average application of 2.69 ft, an associated deep percolation recharge of 0.48 feet – all resulting in an estimated total irrigation recharge of about 66,615 af/yr.

Packard et al identify the major groundwater discharge features surrounding the Horse Heaven Hills as Rock Creek (to the west), Satus Creek and the Yakima River (to the north), and the Columbia River (to the east and south). Within the non-irrigated area west of the FCD study area, Packard et al report groundwater discharge expressed as baseflow in secondary streams (Alder Creek, Pine Creek, Glade Creek, Wood Gulch) and various springs. Many of these western drainages are eroded into CRB aquifers. Baseflow discharge to these streams, as well as to Satus and Rock creeks, is estimated to total 25 cfs (18,000 af/yr). Given that most of the 50,500 af/yr precipitation recharge (approximately 70 cfs annual average) is estimated to occur in this western region, it seems reasonable that these secondary streams receive a portion of the precipitation recharge with the remainder discharging to the Columbia and Yakima rivers.

On the west side of the FCD study area, baseflow at the mouth of Glade Creek was reported to average 11 cfs (8,000 af/yr) in 1981. Packard et al interpret this baseflow as sourced from irrigation recharge perched in the loess deposits which overly the basalt. Streams in the central and eastern portions of the FCD study area are reportedly ephemeral and springs are scarce or absent. Zero flow years have been commonly observed on peak flow gages in Fourmile Canyon and the East Branch of Glade Creek; and peak flow data show no water in the upper reaches of the Glade Creek system during most years (Aspect, 2004).

While local springs/seeps were observed during recent field reconnaissance and a review Google Earth coverage clearly shows patches of non-irrigated area supporting lush vegetation, total discharge to springs/seeps is unknown and not likely to be high. A review of U.S. Fish & Wildlife GIS shows about 168 acres (about ¼ square mile) of freshwater emergent wetlands within the study area (USFWS, 2010). Assuming that these wetlands evapotranspire about 4 ft/yr, associated discharge would be on the order of 700 af/yr (about 1 cfs). Spring discharge may also be conveyed down streambeds; however, as noted above, most streams in the central and eastern FCD study area are reported as ephemeral with insignificant spring occurrence.

Given that estimates of total recharge to the FCD study area have ranged from about 67,000 af/yr (current) to about 50,000 af/yr (1982), the limited discharge to streams, springs and seeps suggests that this recharge is either conveyed to the Columbia River within the suprabasalt sediments or delivered to the Columbia River Basalts. The distribution of recharge between the suprabasalt sediments and the basalts, estimated by Packard as about 75%:25%, is not well known. The concept of minimal regional flow within the basalts (Lindsey, 2010) suggests that the basalt recharge may be mostly removed by pumpage. The concept of regional flow within the suprabasalt sediments to the Columbia River contradicts Molenaar's interpretation that groundwater occurs predominantly within the basalt system; however, driller's reports are unlikely to focus on occurrence of thin saturation above the basalts, as development of such groundwater is impractical. Nevertheless, these inconsistencies suggest that the occurrence and flow pathways of groundwater within the FCD study area are not well understood.

3.2.5 Groundwater Levels and Aquifer Properties

While existing reports focus on saturation in the CRB's, areas do exist where saturation accumulates above the basalt, in rare cases discharging to streams (e.g. lower Glade Creek). Packard et al.'s estimation that 20% to 30% of irrigation recharge reaches the CRB's requires a saturated flow system in portions of the suprabasalt sediments. Too few wells are completed in the suprabasalt sediments to evaluate groundwater occurrence and/or water-table elevations; field data (e.g. well tests) are unavailable to assess the hydraulic properties of saturated portions of the sediments; and existing modeling of the groundwater system did not focus on flow in the suprabasalt sediments. Flurry and Sing (2011) performed field and laboratory testing on 11 surficial loess samples from two sites in the Horse Heaven Hills and obtained saturated hydraulic conductivities (K) measurements ranging from 7 to 123 cm/d (0.23 to 4.0 ft/d) and averaging about 50 cm/d (1.6 ft/d) (**Appendix H**).

During preparation of their groundwater flow model of the basalt aquifers, Packard et al evaluated groundwater occurrence, groundwater elevations, and basalt aquifer properties. Maps were made of the saturated thickness and water-level elevations in the Saddle Mountains and Wanapum aquifers. Topography, structural features, and the contrast between horizontal and vertical permeability (e.g. interflow zones vs. flow interiors) largely influence groundwater levels and flow patterns. Downward flow occurs from the Saddle Mountains to Wanapum aquifer, except near the Columbia and Yakima rivers. Linear zones of steep hydraulic gradient are observed within the Wanapum (and sometimes Saddle Mountains) aquifers associated with fault zones and zones monoclinal flexure. Portions of the basalt flow system are unsaturated along topographic crests and deeply incised canyons.

Aquifer property estimates by Packard et al were developed as "bulk estimates" for each of the three major basalt formations (data were very limited for the Grande Ronde formation). Estimates were not developed for individual members within the formations, nor were interflows distinguished from flow centers. Aquifer properties were initially assessed based on specific capacity data from wells, and later refined through modeling analysis and review of observed hydraulic gradients. The distribution of K is complex, with significant anisotropy (ratio of horizontal to vertical K), variations between anticlinal and synclinal areas, and variations associated with structural features. Geometric mean values of anisotropy ranged from 160 (between the Saddle Mountains and Wanapum aquifers) to 500 (between the Wanapum to Grande Ronde aquifers). Major faults and tightly folded anticlines tend to form low permeability "flow barriers" which effect groundwater flow patterns. Whereas modeled values of horizontal permeability (Kh) typically ranged from 0.09 to 9 ft/d for the Saddle Mountain aquifer and 0.009 to 9 ft/d for the Wanapum aquifer, modeled flow barriers were assigned minimum values an order of magnitude below the lower end of these ranges and modeled zones of enhanced permeability were assigned maximum values an order of magnitude above the upper end of these ranges. Storage coefficient (S) was estimated during calibration, with typical values of 0.01 to 0.03 for the Saddle Mountains Aquifer and 0.001 for the Wanapum and Grande Ronde aquifers.

3.3 RETIMING OF DEEP PERCOLATION LOSSES

Current understanding of hydrogeologic conditions in the Horse Heaven Hills study area indicates a variety of possible flow paths for irrigation recharge. Vadose flow occurs in the suprabasalt sediments and in portions of the CRB's. Within the suprabasalt sediments, variability is related to vadose-zone thickness and texture, localized perching, and whether perching concentrates water towards continued subsurface flow (downward to the water table) or towards discharge at springs and seeps. Within the CRB's, irrigation recharge would pass through unsaturated sequences of basalt interflow zones, sedimentary interbeds, and basalt flow cores. Saturated flow paths can occur within the suprabasalt sediments and the CRB's;

however, saturated conditions in the suprabasalt sediments are poorly defined. Given the variability and uncertainties associated with the possible flow paths, in this section PGG presents a variety of qualitative and quantitative analyses to constrain the timing of subsurface irrigation return flow under the range of expected conditions. PGG's analysis suggests that under most expected conditions, irrigation return flows are expected to be highly damped such that conservation would provide significant retiming benefit.

For quantitative analyses, PGG defined a "damping factor" as one (1) minus the ratio of the range of predicted irrigation recharge flux at the end of the flowpath vs. the range at the beginning of the flowpath. For instance, in the case of vadose-zone analysis, a damping factor of 1.0 (also expressed as 100%) indicates that all of the seasonal variability of irrigation recharge at the land surface is removed by the time the recharge reaches the water table.

PGG estimated the retiming of deep percolation losses associated with irrigation conservation by comparing the portion of reduced Columbia River diversion associated with deep percolation losses to the change in subsurface irrigation return flow from deep percolation losses back to the Columbia River. The "retiming benefit" due to reduced deep percolation losses is equal (at any time) to the reduced diversion from the Columbia River minus the change in groundwater discharge to the river due to reduced deep percolation losses:

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

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} = portion of diversion supplying deep percolation irrigation loss before conservation
DP_{POST} = portion of diversion supplying deep percolation irrigation loss after conservation
RD_{PRE} = river discharge from subsurface return flow before conservation
RD_{POST} = river discharge from subsurface return flow after conservation

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

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

For the purpose of this project, only the retiming benefit during the Columbia River critical period (July and August) has been defined as important for making water rights decisions. The reduced diversion associated with deep percolation losses (Δ_{DP}) is calculated based on RH2's monthly estimates of deep percolation losses shown above in Section 3.1.5. The change in the timing of groundwater discharge to the Columbia River associated with reduced deep percolation losses requires consideration of: 1) deep percolation losses from the root zone; 2) migration of the irrigation "recharge pulse" downward within the vadose zone (from the root zone to the water table); and 3) conveyance of the recharge pulse through the groundwater system to nearby surface-waters. PGG evaluated the latter two elements of subsurface return flow independently over a range of possible flow paths – most all of which show highly damped return flow to the Columbia River[8].

In addition to the subsurface pathway for irrigation recharge to reach the Columbia River (vadose zone followed by saturated groundwater flow), it is also possible that irrigation recharge locally perches within the suprabasalt sediments and then discharges to streams (Section 3.2.4). Given the general lack of perennial streamflow within the study area and the sparse distribution of groundwater supported wetlands, this pathway likely accounts for only a small percentage of irrigation recharge. Furthermore, given the sparse occurrence of lush vegetation in streambeds near springs and seeps, it seems reasonable to conclude that this discharge pathway predominantly concludes with evapotranspiration of irrigation recharge by streambed vegetation. In the rare case where perched irrigation recharge provides perennial baseflow (e.g. lower Glade Creek in the western study area), damping of the recharge pulse within the vadose zone seems to alter this timing and create a relatively uniform, year-round discharge. The downstream extent of perennial conditions within Glade Creek would need to be defined to further assess this return-flow pathway to the Columbia River.

3.3.1 Deep Percolation Losses from the Site

Average deep percolation losses under current (2009) conditions were estimated across the study area by RH2 for the current combination of irrigation practices (see summary table in Section 3.1.5). Deep percolation for the month of October was assumed to occur in the first half of the month, based on a 6.5-month irrigation season from April 1 through October 15. Deep percolation for the post-conservation condition (center pivot with LEPA and IWM) was assumed to be zero. RH2's monthly pre-conservation deep percolation estimates were converted into monthly rates and used as input for evaluation of the vadose zone.

3.3.2 Irrigation Recharge through the Vadose Zone

Irrigation recharge through the vadose zone can take a variety of pathways and encounter a variety of conditions:

1. Downward flow from the root zone towards the water table can encounter a range of vadose-zone thickness. Available information suggests that the suprabasalt sediments range in thickness from less than 10 feet to several hundred feet and that loess deposits range in thickness from 10 to 40 feet.
2. Downward flow towards the water table within the suprabasalt sediments will first pass through fine-grained sediments mapped at the land surface (i.e. loess or Touchet Beds), but may also pass through underlying unsaturated sediments for which driller's logs suggest a variety of textures.
3. Downward flow towards the water table may encounter localized perching layers within the suprabasalt sediments, which may concentrate the recharge to the point of saturation and route it to either further downward to the water table or to discharge at the land surface via springs and seeps.
4. Downward flow through the loess may encounter a capillary fringe which affects the timing or return flow. A capillary fringe can form above the water table (e.g. where shallow basalt immediately underlies the loess deposits), and a quasi-capillary fringe can occur where fine-grained loess deposits overly coarser-grained suprabasalt sediments (which form a "capillary barrier"). In either case, the possible effect of a capillary fringe must be considered in estimating the timing of vadose-zone flow

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[8] Given the wide range of possible flow paths within the vadose zone, PGG generally did not use vadose-zone results for saturated zone input. However, saturated zone simulations suggest considerable damping even without the added benefit of vadose zone damping.

through loess sediments. A thinner capillary fringe is expected for Touchet Bed sediments, and is therefore expected to have less impact on the timing of downward unsaturated flow.

5. Where unsaturated conditions persist down into the CRB's, downward migration of irrigation recharge will first pass through the suprabasalt sediments and then through the various components of the CRB's: interflow zones (rubbly/highly fractured basalt flow tops and bottoms), sedimentary interbeds, and tight fractures within dense basalt flow cores

PGG used the modeling code Hydrus-1D (Simunek et al, 2008) to evaluate conveyance of the recharge pulse through unsaturated portions of the fine-grained surficial soils under current pre-conservation conditions. **Appendix H** provides a detailed description of PGG's Hydrus analysis. The Hydrus model was run for 50 years; within that timeframe predicted annual variations in soil moisture at all considered depths ceased to change from year to year (the condition of repeated model results from one year to the next is herein termed "cyclic steady state"). PGG's modeling results illustrate that the fine-grained, low-permeability characteristics of the surficial loess is expected to provide significant damping of the seasonal recharge pulse. Our modeling also suggests that a capillary fringe significantly reduces lagging and damping of the recharge pulse in the 13 feet (4 meters) immediately overlying the water table (a similar reduction is also expected in the 13 feet immediately overlying a capillary barrier such as coarse gravels). The capillary fringe condition is expected to be more likely than the free draining condition[9]. For the purpose of this analysis, PGG estimates that retiming through a loess soil of a given thickness *with a capillary fringe* is conservatively represented by the retiming predicted for a *free draining* loess soil that is 13 feet thinner. Actual retiming of a loess soil *with a capillary fringe* will be slightly more lagged and damped than under this conservative assumption. In addition, further lagging and damping will occur in any variably textured sediments which extend downward from the bottom of the loess to the underlying water table.

PGG's simulation of vadose-zone flow through the loess considered a range of hydraulic properties (lower end, upper end, and central values of saturated hydraulic conductivity (Ksat)). **Figure 3-3** presents estimated retiming of the seasonal recharge pulse through various thicknesses of loess soils based on the central value predictions (all predictions are documented in **Appendix H**). Damping factors for central-value predictions range from about 60% for 10 feet of free-draining loess (23 feet with a capillary fringe) to 96% for 20 feet of free-draining loess (33 feet with a capillary fringe). At a free-draining loess thickness of 16 feet (29 feet with basal capillary fringe), predicted damping factors range from 79% (higher-end Ksat) to 85% (central Ksat value) to 93% (lower ksat value).

In the western portion of the study area, geologic mapping shows that Pleistocene outburst flood deposits (Touchet Beds) blanket the land surface and available well logs show thicknesses ranging from several feet to several tens of feet and sedimentary textures ranging from fine to coarse (**Figure 3-2**). Additional data were unavailable to define the characteristic textures of Touchet Beds in the Horse Heaven Hills study area. Textures are expected to vary based on the specific conditions of deposition. PGG characterized a range of Touchet Bed textures in our analysis of vadose zone flow in the Walla Walla study area (**Appendix K**). This same range of textures was applied to RH2's estimates of irrigation recharge for the Horse Heaven Hills to develop a rough range of predicted retiming within the Touchet Beds. Adjustments were not made for occurrence of a capillary fringe, which is expected to be thinner in the Touchet Beds than in the loess. **Figure 3-4** shows the results of these model simulations for Touchet Bed thicknesses of 10, 20 and 33 feet. While we expect that vadose-zone retiming is likely to occur within this range, lack of textural analysis of local Touchet Beds prevents us from suggesting a "most likely" retim-

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[9] In this case, "free draining" means sufficiently far from the water table or perching layers such that they do not influence downward vertical flow. This definition is consistently with the terminology employed by Hydrus-1D.

ing estimate. It is worthwhile to note that the predicted retimed irrigation pulse is considerably damped (71%-94%) for all textural representations at a depth of 33 feet, moderately damped (44%-82%) at a depth of 20 feet, and only somewhat damped (18%-55%) at a depth of 10 feet.

Irrigation recharge that passes through the unsaturated portions of the suprabasalt sediments *and* the upper portions of the CRB's is likely to be highly damped. Along with damping that occurs in the suprabasalt sediments, significant damping is expected to occur as vadose-zone water passes through the sequence of interflows, tightly fractured flow cores, and sedimentary interbeds that comprises the CRB's. This concept is based on best professional judgment. Verification would require monitoring of moisture content within the basalt vadose zone and fluctuations in the uppermost basalt water-table elevation.

Retiming predicted within the vadose zone is compounded with retiming within the saturated groundwater flow system, as the two pathways occur in series. The following section discusses retiming within the saturated flow system.

3.3.3 Irrigation Recharge through the Saturated Flow System

PGG employed STRMDEPL08 (Reeves, 2008), a simple analytical model of stream-aquifer interaction provided by the USGS, to estimate the timing of subsurface return flow through the suprabasalt sediments to the Columbia River. PGG's analysis is conservative in that it uses RH2's estimates of irrigation recharge as input, and therefore does not consider the additional retiming that occurs within the vadose zone. Saturated conditions within the suprabasalt sediments are not well defined; therefore, PGG's analysis employs a range of hypothetical aquifer properties (saturated thickness, K and S) based on best professional judgment to define a range of likely subsurface conditions for retiming. Additionally, in order to illustrate the cumulative retiming effects of both the vadose and saturated zones, several supplemental simulations were performed with Hydrus model output used as input for STRMDEPL08. Finally, in order to evaluate retiming through the saturated CRB flow system, PGG also developed a simple two-dimensional (vertical slice) numerical model using the USGS code MODFLOW-2000 (Harbaugh et al, 2000).

The STRMDEPL08 model represents a single, straight-line stream assumed to fully penetrate a constant-transmissivity aquifer based on the method of Jenkins (1968). Both the (2-D) aquifer and the (1-D) stream are assumed to be of infinite areal/lineal extent. The model applies the superposition principle to calculate changing stream flux due to changing flux at a recharge (or pumping) location. The model estimates instantaneous effects on streamflow (Qs) relative to pumping/injection rate (Qp), and its mathematical linearity allows calculation of percent impact (Qs/Qp) independent of the modeled value for Qp. Although these assumptions simplify actual conditions, the model provides a reasonable estimate of the timing of irrigation recharge on Columbia River flow commensurate with the available understanding of saturated conditions within the suprabasalt sediments.

PGG modeled the saturated groundwater flow path in STRMDEPL08 assuming two conceptual models of the basalt groundwater flow system: a "thin" saturated zone with high K and a "thick" saturated zone with low-moderate K. The "thin" configuration assumed a 3-foot thick basalt rubble zone with a K value of 1,000 ft/d and an S value of 0.2. The "thick" configuration assumes a 50-foot thick aquifer with a K value of 10 ft/d and an S value of 0.2[10]. These values were used to calculate aquifer diffusivity (T/S) values of 15,000 ft^2/day and 2,500 ft^2/day, respectively, as summarized below.

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[10] This K value is 6x larger than the average K estimated for loess, as discussed in Section 3.2.5.

Parameter	Units	“Thin”	“Thick”
Thickness	ft	3	50
Hydraulic Conductivity (K)	ft/d	1,000	10
Transmissivity (T)	ft^2/day	3,000	500
Storage Coefficient (S)	- - -	0.2	0.2
Aquifer Diffusivity (D)	ft^2/day	15,000	2,500

PGG ran STRMDEPL08 using RH2’s irrigation pre-conservation irrigation recharge schedule simulated over an irrigated area of 40 acres at distances of 0.5, 1, 2 and 4 miles from the Columbia River. The model was run over a period of 220 years after the initiation of irrigation in order to allow STRMDEPL08 to reach either cyclic steady state or asymptotic convergence on cyclic steady state (asymptotic convergence was characterized by little year-to-year change in model results but annual average flux below the average annual recharge rate). Model results indicate that recharge areas more than 1 mile from the river may take hundreds of years or longer to reach true cyclic steady state.

Figure 3-5 presents the results of the STRMDEPL08 simulations, which indicate substantial damping of seasonal variation of irrigation recharge with increased distance from the Columbia River. All iterations of the “thick” case predict greater than 99% damping at distances greater than 0.5 miles from the river. All iterations of the “thin” aquifer case have damping greater than 98% at 1 mile and beyond; damping drops to 87% at 0.5 miles from the river. The following table presents the predicted damping factors for the various STRMDEPL08 simulations.

STRMDEPL08 Configuration \ Distance to River	0.5 miles	1 mile	2 miles	4 miles
“Thin”	87%	98%	100%	100%
“Thick”	99%	100%	100%	100%

Subsurface return flow within the CRB’s could not be represented with the analytic method employed by STRMDEOL08 due to hydrogeologic complexities such as: multiple layers and anisotropy between water-bearing zones. 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 differs from Packard’s configuration in that it includes more vertical discretization (more layers) and uses constant aquifer properties rather than the variable properties simulated by Packard (e.g. low permeability barriers to groundwater flow associated with structural features such as faults were not included). The 2-D configuration of the slice model will reduce predicted damping from a point-source of recharge (i.e. single field) relative to a 3-D configuration such as Packard’s. The slice model is intended to provide a generalized depiction of the CRB’s and *rough estimates* of irrigation pulse retiming. More detailed description of PGG’s slice model is presented in **Appendix H**.

The slice model was run to estimate the timing of groundwater discharge to the Columbia River from an irrigation location 1 mile away. Irrigation recharge was represented based on RH2’s estimates of deep percolation applied over an acre of land[11]. This representation adds another level of conservatism, as lagging/damping in the vadose zone is not considered. Based on this configuration, the model still predicted a damping factor of 99% for the irrigation recharge (**Appendix H**).

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[11] The model is linear and employs the principal of superposition, such that predicted return-flow timing is insensitive to the magnitude of the assumed irrigation recharge.

3.3.4 Estimation of Conservation Benefit

The discussion above has presented a variety of potential subsurface pathways for irrigation recharge and has estimated the associated return-flow timing to the Columbia River. The most common pathway is likely to include movement through the vadose zone from the land surface to the water table, followed by movement through the saturated groundwater flow system to the Columbia River. The saturated flow path within the suprabasalt sediments is not well defined, and PGG has estimated a range of hypothetical conditions within these sediments to be used for model estimation. The saturated flow path within the CRB's was considered to be an approximation of Packard's model. In most all cases considered, the recharge pulse through the saturated zone (without the additional benefit of retiming through the vadose zone) is predicted to be highly damped (damping factors ranging from 98.5 % to 100 %). One model simulation of return flow through the suprabasalt sediments and/or uppermost flow-top basalt rubble (PGG's "thin" scenario at a distance of 0.5 miles) suggested slightly less damping (87%). However, when damping from modest free draining loess vadose-zone thicknesses of 3 and 10 feet (thicknesses of 16 to 23 feet with capillary zone included) are added to this flow path, resulting predictions of Columbia River discharge again become highly damped (92 % and 96%, respectively). **Figure 3-5** shows the results of the two "thin" simulations with input taken from the referenced Hydrus simulations.

It should be noted that PGG's predictions of retiming in the vadose zone do not include the scenario where local perched conditions concentrate the irrigation recharge and create a saturated downward pathway to the regional water table. This flow path could locally "short circuit" a portion of the vadose zone retiming (PGG did not attempt to estimate retiming under these conditions). However, where retiming in the saturated zone is likely to provide high damping factors, the ability to predict retiming in the vadose zone becomes less significant.

Predictions of retiming differ from the highly damped estimates (above) under two remaining flow paths. In one case, perched conditions within the vadose zone discharge to small seeps and springs, and discharged water is largely lost to evapotranspiration. Given the lack of perennial streams in the eastern and central study area and sparse density of mapped lush wetlands, this scenario is most likely in these areas. In this case, conservation benefit is increased, because irrigation recharge (currently lost to evapotranspiration) would be *fully* recovered when the associated water is left in the Columbia River (i.e. RD_{PRE} goes to zero in the *Equation 2* presented above). In the second case, perched conditions within the vadose zone or the regional aquifer within the suprabasalt sediments discharges to surface water which is not lost to evapotranspiration. This condition is documented in the western study area at Glade Creek, but is not documented elsewhere in the study area. If the timing of groundwater sourced streamflow is not well damped, the associated return flow pathway to the Columbia River will also be poorly damped. In the case of Glade Creek, significant damping is evidenced by perennial flow with only moderate seasonal baseflow variations (Section 3.2.4).

Most subsurface flow paths for irrigation recharge are predicted to be highly damped (greater than 98% damping factor). While PGG's model runs generally did not represent the cumulative damping of transport through the vadose and saturated zones, this cumulative effect further increases the likelihood of highly damped subsurface return flow to the Columbia River and offsets some of the uncertainty relating to saturated conditions in the suprabasalt sediments. For the purpose of estimating retiming benefit, >98% damping can be reasonably represented as fully (100%) damped. Using *Equation 2* and RH2's monthly values of irrigation losses, the monthly retiming benefit from conservation simply becomes the difference between the pre-conservation monthly average diversion associated with irrigation recharge and the monthly portion of the constant year-round subsurface return flow:

(values in ft)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Irrigation Recharge	0.000	0.000	0.000	0.003	0.021	0.069	0.160	0.153	0.066	0.010	0.000	0.000	0.482
Return Flow	0.041	0.037	0.041	0.040	0.041	0.040	0.041	0.041	0.040	0.041	0.040	0.041	0.482
Retiming Benefit	-0.041	-0.037	-0.041	-0.036	-0.020	0.029	**0.119**	**0.112**	0.027	-0.031	-0.040	-0.041	0.000

The highest predicted retiming benefit occurs during the maximum irrigation application months of July and August, which are coincident with the Columbia River "critical period"[12]. Columbia River baseflow reductions are predicted to occur outside the irrigation season or when irrigation recharge is relatively small, as the associated change in surface-water diversion is smaller than the reduction in subsurface irrigation return flow. The predicted net, year-round retiming benefit is zero. This is because retiming does not change the amount of water in the system, it just changes the timing of availability. The two exceptions to this condition are where irrigation recharge has been historically lost to evapotranspiration (seeps and springs) or recharged isolated flow cells within the CRB's. In both cases, reduced diversions would not be offset by reduced subsurface return flow, and the conservation benefit would be net positive. However, in the latter case, reduced recharge to portions of the CRB's could result in groundwater level declines, which could effect groundwater pumpers.

Total conservation benefit can be estimated as the retiming benefit (above) plus the reduced evaporation associated with conservation ("E benefit"). RH2's estimates of pre-conservation and post-conservation evaporation losses in Section 3.1.5 suggest that E benefit will amount to 0.053 and 0.043 feet for July and August. Thus, total conservation benefit during this critical period is predicted to amount to 0.172 and 0.155 feet for July and August. Volumes of conservation benefit can be calculated by multiplying these values by the irrigated acreage of the farm.

Although PGG ran STRMDEPL08 model out over 220 years, cyclic steady state was not fully reached for subsurface return flow to the Columbia River. PGG performed supplemental Jenkins calculations to estimate the timing for cyclic steady state to occur (i.e. when irrigation recharge is no longer absorbed by increasing aquifer storage, and storage doesn't change from year to year). Our calculations employed annual average irrigation recharge rather than seasonally varying recharge, and predicted streamflow capture of irrigation recharge is presented over time on **Figure 3-6** (Qs/Qp, the ratio of streamflow augmentation to irrigation recharge rate, approaches 1 at steady state). Higher values of diffusivity lead to faster convergence towards cyclic steady state. PGG's Jenkins calculations for the suprabasalt sediments predicted that 150 years were required for the "thin" aquifer representation to reach a Qs/Qp of 90%, and 240 years were required for the "thick" aquifer representation to reach a Qs/Qp of 80%. In contrast, for the CRB's, the slice model predicted that 54 years were required to reach a Qs/Qp of 90% (this is likely somewhat underestimated due to the conservative configuration of the model). Note that none of these estimates include the time required for irrigation recharge to pass through the vadose zone, and that the time required for hydraulic transmission of the recharge pulse to the Columbia River is much smaller than the time required for a water molecule to travel from the recharge location to the river.

These simulations suggest that some portion of the irrigation recharge occurring since the early 1970's (when large scale irrigation began) may not yet have reached the Columbia River, but is still filling up aquifer storage between the recharge location and the river. For example, **Figure 3-6** suggests that for the "thick" aquifer representation, after 40 years of irrigation recharge, as much as 45% of the annual recharge is still accumulating in aquifer storage and 55% is reaching the river (20%/80% for the "thin" representation and less for the CRB's). If cyclic steady-state has not yet been achieved and a portion of the

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[12] Crop requirements are predicted to be highest during these two months (Section 3.1.2).

annual average volume of irrigation recharge is not yet reaching the river, then the retiming benefit would be higher than predicted above. Even if cyclic steady-state has already been achieved, reduced subsurface return flows on the Columbia River will take as long to exert themselves as the estimated build-up time for return flow. This means that subsurface return flows will not be immediately lost when conservation is applied, and benefits to streamflow will be *temporarily* higher than predicted above.

3.4 FURTHER CONSIDERATIONS FOR CONSERVATION EFFORTS

Once pilot sites are identified within the study area, the conservation benefit numbers above can be used as a rough estimate of conservation potential. However, more specific estimates of conservation benefits can be generated by considering the exact irrigation application method used at the site and by using a non-zero estimate of post-conservation irrigation recharge. The conceptual model of highly damped, uniform return flow would apply to both the pre-conservation and post-conservation conditions. Given the variability of possible conditions likely to be encountered in the suprabasalt vadose zone, and the fact that retiming in the saturated suprabasalt sediments is estimated based on best professional judgment, it may be worthwhile to confirm shallow vadose zone conditions for a given site. This can be achieved by drilling a shallow (e.g. 50-foot) well, preferably using a method that allows good recovery of soils (e.g. sonic drilling), to confirm the presence of a fine-grained surficial vadose zone. Moisture measurement or monitoring could also be used to confirm that vadose zone conditions conform to the modeling analysis presented above.

In addition to estimating conservation benefit from a specific site based on *actual* irrigation methods used on the site, consideration of typical cropping patterns may also be desirable. The conservation benefits above are based on estimates of total application (streamflow diversion) assuming study-area average crop types. Conservation benefit will be sensitive to the monthly distribution of irrigation requirement for particular crops. Some consideration is required to address how to best select “representative” cropping assumptions for estimating site-based conservation benefits.

The portion of irrigation recharge delivered to the CRB’s is unknown. Packard et al estimate that 20-30% of the total irrigation recharge flows into the CRB’s. Reduction of irrigation recharge to the CRB’s could result in associated groundwater level declines and could impact farmers sourcing irrigation from wells completed in the CRB’s.

4.0 SOUTHERN FRANKLIN COUNTY

The Southern Franklin County (SFC) study area is located in the eastern Pasco Basin, north of the confluence of the Snake and Columbia Rivers. Irrigation water primarily comes from the Columbia Basin Irrigation District, with smaller contributions from the Franklin Irrigation District and groundwater sources in the basalt and suprabasalt aquifer systems. Irrigation systems in the study area are predominantly center pivot, with lesser occurrence of sprinkler lines. Conservation from mechanical upgrades and Irrigation Water Management practices could result in a reduction of irrigation application by up to 125,300 acre-feet per year.

The site is underlain by flat to gently dipping Columbia River Basalts and overlying Tertiary and Quaternary sedimentary deposits ("suprabasalt sediments"). Irrigation recharge has significantly changed the hydrology of the groundwater system, with between tens of feet to several hundred feet of water-level rises in various suprabasalt aquifers from 1950 to 1986 and initiation of year-round springs along the White Bluffs. The majority of irrigation recharge and transport to the Columbia and Snake Rivers is expected to occur within the suprabasalt aquifers. Subsurface irrigation return flow though the basalt aquifer is expected to be insignificant (GSI, 2010).

The SFC study area meets many of the criteria identified for an "ideal" area; however, because the majority of irrigation water is delivered by the South Columbia Irrigation District (SCBID), new reallocations of this water due to conservation and retiming would need to be performed through the Bureau of Reclamation (USBR). Mechanisms for transfer of USBR water to Ecology's Trust Water Rights Program have not yet been established. In addition, portions of the SFC study area exhibit hydrogeologic complexities and/or data gaps that are less-than-ideal for developing a defensible basis for new water-right allocations based on retiming. PGG differentiated these sub-areas by dividing the SFC study area into three hydrogeologic provinces:

- The Quaternary Province has potential for retiming benefits and the least hydrogeologic uncertainty.
- The Basalt Province has promise for retiming benefit because much of the infiltrating irrigation water has return flow timing ranging from highly damped to no-return flow to the surface water, depending on the return flow pathway.
- The Upper Ringold Province has limited potential for conservation benefit through retiming. Conservation efforts are not expected to provide retiming benefits until the water table drops below the drain system. The amount of conservation required to drop the water table below the drains is variable across the province, unknown, and difficult to predict.

The basis for differentiating the conservation benefits for these three provinces is presented in the subsections below. Under this project, PGG has focused our modeling efforts on the Quaternary Province, with supporting calculations as needed for the adjacent provinces. PGG did not attempt to estimate retiming benefits within the Basalt and Upper Ringold provinces due to the significant uncertainty and/or complexity associated with those areas. Retiming benefits were estimated for the combined Columbia and Snake rivers, as predicted impacts to the Snake River occur within Lake Wallula (a Columbia River feature). PGG's analysis suggests considerable retiming benefit associated with three hypothetical sites within the Quaternary province.

4.1 IRRIGATION ANALYSIS

The SFC study area comprises lands east of the Columbia River and north of the confluence with the Snake River in southern Benton County. The study area comprises of approximately 129,300 acres of irrigated crop lands, as shown in **Figure 4-1**. The crop types grown in the study area include alfalfa hay, timothy hay, potatoes, wheat and other irrigated crops.

4.1.1 Information Sources

Analysis of the irrigation practices, estimates of conservation potential and surface return flow pathways for the SFC study area included review of GIS, water application data and other technical information. GIS data was supplied by the Franklin County Conservation District (FCD) and included both the South Columbia Basin Irrigation District's irrigation (SCBID) and farm data for Blocks 1,13,14,15,16,17,19,161 and historical crop type and irrigation data from the WSDA. Crop data, irrigation method data and water use data was provided by FCD for the 2009 crop year and was the basis for estimating current practices and water use. Historic (1951-1986) water application data and crop distributions were provided by USBR for the SCBID. Irrigation Water Management (IWM) values were obtained from the "*Columbia Basin Ground Water Management Area"* (2005). Literature references and technical data used to develop the memorandums included as appendices to this memorandum include *State of Washington Irrigation Guide: Appendix A, Climatic Stations for Consumptive Use* (USDA 1985); *AgriMet Data* (USBR 1988 – 1994); *Irrigation Efficiency* (Howell, Terry A., 2003), *McNary Dam Forebay Temperature Improvements Computational Fluid Dynamics (CDF) Numerical Model Study* (Weber, Larry J., et al. University of Iowa, 2005); and *Rocky Reach Dam Initial Consultation Document* (Chelan County PUD No. 1, 1999).

Technical memorandums prepared by RH2 to support the potential irrigation conservation, surface irrigation losses, and travel time estimates presented in this memorandum include *Study Area Water Use – Current Practices and Conservation Potential*, (**Appendix A**), *Estimates of Irrigation Surface Losses, (**Appendix B**), Estimate of Particle Travel Times*, (**Appendix C**); *South Franklin County Study Area – Current Practices and Conservation Potential Segregated by Geological Province*, (**Appendix D**); *Estimated Pre-IWM and Post IWM Over-Application Deep Percolation Losses for the Potholes East Canal 1951-1986* (**Appendix E**); *Draft Revised Current Practices and Conservation Potential Estimates – March 21, 2011* (**Appendix F**) and *Water Use, Efficiencies and Loss Pathways for the Potholes East Canal 1951-1986* (**Appendix G**).

4.1.2 Current Practices and Water Use

The vast majority of the irrigation water for the SFC study area is provided by the SCBID from the USBR Columbia Basin Project. Source water for the district is from the Potholes Reservoir, which is supplied partially by return flows from the Quincy-Columbia and East Columbia Basin Irrigation districts. Quincy District return flows result from irrigation under the West Canal and return predominantly through the Winchester and Frenchman Hills wasteways. East District return flows result from irrigation under the East Low Canal and return predominantly through the Rocky Coulee and Lind Coulee wasteways. Part of the Potholes Reservoir supply is direct feed from the Columbia River via the Frenchman Hills Wasteway and the East Low Canal. Irrigation water for the remainder of the study area not served by the SCBID is either supplied by private wells (lands east of Highway 395, known as the "Green Belt") or from the Franklin County Irrigation District (FCID) (southern portion of the study area, roughly paralleling I-182). The predominant irrigation method used in the study area is center pivot systems which account for approximately 75% of the total irrigated acreage. Sprinkler line and wheel line systems account for approximately 18% of the irrigation methods used in the study area.

Estimates of the total irrigation requirement for the study area have been made based on the acreages for the various crop types, as summarized in an RH2 memorandum entitled Study Area Water Use - Current Practices and Conservation Potential (**Appendix A**, Tables 1(a), 2(a), 3(a)). Based on the results of this analysis, RH2 estimates that the total current (2009) irrigation requirement for the study area is approximately 448,000 acre-feet during the irrigation season. Of this value, approximately 370,800 acre-feet is estimated for the crop irrigation requirement and approximately 77,200 acre-feet is associated with evaporation, surface runoff and deep percolation losses as a result of the currently implemented irrigation equipment.

The months of June, July and August account for a largest percentage of the total application volume in the study area. Approximately 66% of the crop water needs occurs in these three months. This totals to approximately 304,000 acre-feet of irrigation water. A breakdown of the monthly irrigation requirement and associated losses for the study area is shown below, with the break-down of losses discussed in the next section.

Current Irrigation Requirement and Loss Estimates

(acre-feet/acre)

	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	2.88
SW Runoff	0.000	0.000	0.000	0.002	0.007	0.010	0.013	0.010	0.005	0.002	0.000	0.000	0.05
Evaporation	0.000	0.000	0.002	0.012	0.056	0.077	0.100	0.079	0.044	0.015	0.000	0.000	0.38
Application Inefficiency Deep Percolation	0.000	0.000	0.001	0.005	0.024	0.033	0.044	0.035	0.019	0.006	0.000	0.000	0.17
Over Application Deep Percolation (1)	0.000	0.000	0.002	0.016	0.072	0.099	0.130	0.102	0.057	0.019	0.000	0.000	0.50
Total Application	0.00	0.00	0.02	0.11	0.50	0.69	0.91	0.71	0.40	0.13	0.00	0.00	3.48

(1) This loss value is included in the crop requirement and therefore not added separately to the total application. See **Appendix A** for discussion of IWM.

Additional deep percolation losses (shown as “Over Application Deep Percolation” above) are associated with the intrinsic management and safety factors associated with current irrigation practices. Current research estimates that irrigation requirements can be reduced by 17.31% with intensive Irrigation Water Management (IWM) techniques. Currently this water is lost to deep percolation and totals approximately 64,200 acre-feet.

It is important to note that the above estimates are based on the assumption that 35% of the center pivot irrigation systems are using LEPA sprinkler heads. Actual irrigated acreage using center pivot systems with LEPA was not available from the WSDA.

Values used in the development of the crop irrigation requirement and average irrigation efficiencies along with the assumptions used in analyzing the current irrigation practices for various types of irrigation methods are reported in **Appendix A.**

4.1.3 Irrigation Loss Estimates

An estimate of irrigation losses associated with evaporation, surface-water runoff and deep percolation has been developed for the study area based on a review of the literature from prior irrigation studies (see **Appendix B**). Both evaporation losses and surface losses are attributed to mechanical inefficiencies that are associated with the currently implemented irrigation equipment. Deep percolation losses are expressed as two terms: the first attributed to mechanical inefficiencies associated with the application method and the second attributed to crop over application associated with current irrigation practices. Implementation of IWM practices can reduce the apparent crop water need and thus reduce deep percolation. RH2's analysis indicates that adapting IWM practices presents the greatest potential for water conservation (**Appendix B**). Using the loss estimates presented in **Appendix B**, a summary of the various loss volumes and pathways is presented below.

Current Irrigation Loss Estimates for SFC Study Area

Type of Loss	Annual Loss (Acre-Feet)	Percent of Total Loss
Evaporative	50,000	36%
Surface Flow	5,800	4%
Application Inefficiency Deep Percolation	21,400	15%
Pre-IWM Over Application Deep Percolation	64,200	45%
Total:	141,400	100%

The SFC study area was divided into three hydrogeologic provinces based on differences in the hydrogeologic regimes observed for the study area. Using the available crop and irrigation system GIS data from the WSDA, estimates of irrigation losses for each of these three sub-study areas were developed for the purpose assisting in the location of an on-farm demonstration conservation project. A summary of the loss estimates by sub-area is presented below, and supporting documentation is presented in **Appendix D**.

Irrigation Loss Estimates by Geologic Sub-Area

	Quaternary Province		Basalt Province		Upper Ringold Province	
	Annual Loss (acre-feet)	Percent of Total Loss	Annual Loss (acre-feet)	Percent of Total Loss	Annual Loss (acre-feet)	Percent of Total Loss
Evaporative	21,600	36%	9,800	37%	19,100	34%
Surface Flow	2,400	4%	900	3%	2,700	5%
Application Ineffícacy Deep Percolation	8,500	14%	3,500	13%	10,100	18%
Pre-IWM Over Application Deep Percolation	27,800	46%	12,600	47%	24,400	43%
Total:	60,300	100%	26,800	100%	56,300	100%

Note: The loss total for the three sub-areas does not add up to the loss total for the entire study area due to the farm boundaries that straddled the geologic sub-area boundaries. For those farm areas, the entire area was assigned to a sub-area based on the location of the majority of the farm area.

Numerous shallow, subsurface drains are located in the Upper Ringold province (and to a lesser extent in the basalt province). The primary function of the drains is to maintain the non-saturated soil zone to a depth of four feet or more below the surface of the farm unit. Significant portions of the "deep percolation losses" may ultimately discharge to drains, but are not grouped into "surface flow" category above. The drains are tied into a series of wasteways and canals that are used to collect both drain- and surface- return flows. These flows are either conveyed to lower elevation farm units or ultimately to either the Columbia or Snake Rivers. The percentage of the irrigation loss associated with deep percolation that is captured by a drain system depends on many variables, including hydraulic continuity of the soil column, depth of the drains, drain spacing, drain size and depth to an impermeable layer. The percentage of loss that is captured by the drains is poorly constrained (Section 4.3.2). However, for those areas within the SFC study area that have drains, it is assumed that the quantity of irrigation loss to deep percolation is less than those areas without drains due to the capture of some of this water by the drains.

In order to calibrate the groundwater flow model (Section 3.4), PGG required long-term historical estimates of annual average deep percolation losses and monthly estimates of deep percolation losses for the final year of model calibration (1985). PGG obtained historical crop reports and net application rates for the SCBID from USBR. RH2 estimated annual crop water requirements and compared to reported application rates to estimate historic irrigation losses over time. An alternative method, similar to the assumed-efficiency-based calculations presented above and in **Appendix B**, was also used to estimate total irrigation losses over time. For both methods, total losses were divided among surface flow, evaporative and deep percolation losses as illustrated above. Further documentation of RH2's historical analysis is presented in **Appendices E** and **G**.

4.1.4 Timing of Surface Water Return Flows and Source Water Left Instream

Estimates of the timing of surface runoff return flow to the Columbia River have been developed based on the general topography of the study area, locations of drainage canals and wasteways, and travel time estimates for the wasteway system. Return flows from the drains to the wasteways are not measured, so estimates of travel times within these reaches are approximate (further complicating the estimate of travel time for the return flow is the fact that some of this water is reused for irrigation in the lower blocks). Based on the locations of the drains and wasteways, RH2 estimates that blocks 15, 16 and the southeast quadrant of 19 have travel times in the order of 1 to 2 days before returning to the Columbia River. For the eastern blocks 17, 161 and 13, RH2 estimates the travel times in the order of 2 to 4 days before returning to the Snake River below Ice Harbor Dam, which for practical purposes is part of the Columbia's McNary Pool.

Travel time estimate for source water left in the Columbia River is based on information provided by Chelan County PUD, the Northwest Power and Conservation Council and the Army Corps of Engineers (ACE). This travel time information is summarized in a RH2's Memorandum entitled Water Particle Travel Times, (**Appendix C**). It is estimated that the average travel time during the irrigation season for water left in the Columbia River from Grand Coulee Dam to McNary Dam ranges from 11.8 to 30.7 days.

4.1.5 Conservation Potential and Return Flow Distribution

Because the majority of the irrigation systems in the SFC study area are center pivot irrigation systems, the addition of LEPA to these systems holds the greatest mechanical conservation potential through the reduction of evaporative losses. The addition of both LEPA and implementation of irrigation water management (IWM) to the existing center pivot systems is the greatest overall change that could be made to increase the conservation potential of the existing irrigation systems. It is estimated that up to 108,000 acre-feet could be saved annually (across the entire study area) if the existing center pivot irrigation systems were upgraded with LEPA and IWM.

No estimates are available for the percentage of current irrigation systems employing IWM within the study area. However, RH2 has estimated that if only IWM were employed by all existing irrigation systems within the study area, the conservation potential could be up to 77,600 acre-feet annually[13].

Upgrading all existing irrigation systems to center pivot with LEPA and implementing IWM (maximum conservation potential) is estimated to result in a savings of up to 125,300 acre-feet annually. See Table 3(a) in **Appendix A** for estimates of potential irrigation savings for other types of irrigation systems within the study area.

Based on the literature review of Irrigation Surface Losses, as presented in **Appendix B**, it is assumed that the addition of center pivot systems with LEPA or other high-efficiency irrigation methods such as drip, will result in irrigation efficiencies in the 88% to 95% range. Switching to high-efficiency irrigation systems will result in reduced surface and deep percolation losses. With the implementation of both mechanical upgrades and IWM, it is projected that both surface runoff and deep percolation losses could decrease to zero under ideal conditions. This leaves evaporation as the only remaining loss pathway. This is considered the maximum conservation potential for the study area and results in the greatest savings of water for use in retiming. This estimate is based on a simplifying assumption that post-conservation deep percolation losses are reduced to zero (the *theoretical* maximum reduction in deep percolation). It is important to recognize that this is the theoretical maximum conservation potential that could be obtained under ideal conditions. RH2 recognizes that a small amount of deep percolation will continue (and is needed to prevent salt buildup in the soil); however, actual residual rates of deep percolation will depend on final post-conservation irrigation methods and will likely have little effect on the estimates above. The table below summarizes RH2's estimates assuming maximum conservation potential based on the above assumptions:

Conservation Estimates for Southern Franklin County Study Area

Type of Loss	Current Loss (af/yr)	Estimated Loss with Max. Conservation (af/yr)	Estimated Conservation Savings (af/yr)	Percent Reduction
Evaporative	50,000	16,000	34,000	68%
Surface Flow	5,800	0	5,800	100%
Total Deep Percolation	85,500	0	85,500	100%
Total:	141,400	16,000	125,300	89%

Note that reductions in evaporative loss provide direct, instantaneous benefit to Columbia River flows, reductions in surface-flow losses provide little significant benefit to the river (because of the fast return timing for surface flows), and reductions in deep percolation losses provide benefit to Columbia River flow due to "retiming" (i.e. no net change in associated consumptive use).

In order to support sub-surface hydrologic modeling of "retiming" for the Quaternary Province (discussed in Section 3.4), RH2 estimated associated monthly benefits of maximum conservation (LEPA plus IWM). These values were generated based on sub-area wide estimates using current irrigation system information from local GIS mapping. As such, these estimates should be used only for examining area-wide savings and should not be used for individual farm basis analysis without further review. The following table presents RH2's monthly estimates of irrigation losses in the Quaternary Province under both current conditions and post-conservation (maximum conservation). These estimates were used as input for modeling subsurface irrigation return flow.

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[13] This number includes reduction in WIG related losses and associated reductions in application (mechanical) losses due to reduced overall application.

Summary of Monthly Irrigation Loss Pathways – Quaternary Province

(all values in feet)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Current Condition													
SW Runoff	0.000	0.000	0.000	0.002	0.007	0.010	0.013	0.010	0.005	0.002	0.00	0.00	0.05
Evaporation	0.000	0.000	0.002	0.012	0.056	0.077	0.100	0.079	0.044	0.015	0.000	0.000	0.38
Total Deep Percolation	0.000	0.000	0.003	0.021	0.096	0.132	0.174	0.137	0.076	0.025	0.000	0.000	0.67
Total Losses	0.00	0.00	0.01	0.03	0.16	0.22	0.29	0.23	0.12	0.04	0.00	0.00	1.10
Maximum Conservation													
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	0.00
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	0.13
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	0.0
Total Losses	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.03	0.01	0.01	0.00	0.00	0.13

1 – Values based on weighted average irrigation method and crop distribution

Given an irrigated area of approximately 58,000 acres in the Quaternary Province, these estimates suggest that conservation savings from the implementation of LEPA and IWM in the Quaternary Province could result in up to 14,500 af/yr of evaporation losses, 2,900 af/yr of surface water losses, and 38,900 af/yr in total deep percolation losses. See **Appendix D** for a discussion of the current irrigation practices and conservation potential for the three different geological provinces.

As discussed above, post-conservation deep percolation is represented as the maximum *theoretical* conservation potential, and a small amount of deep percolation is expected for any post-conservation condition. Post-conservation deep percolation should be included during (future) individual analyses of pilot sites. For the current analysis, the effect on estimating reduction in total deep percolation (0.67 ft/yr) is expected to be small.

It is important to note that the estimates of potential conservation savings for both the three provinces and the entire study area are based on WSDA data sets of both the crop distribution and irrigation system type as provided by the Franklin County Conservation District. These data are not spatially linked; i.e., it is not specifically known how much of each crop is irrigated by a specific irrigation method. As a result, the estimates are based on a geographic distribution for the entire study area but are not crop or field-specific. Therefore, while the analyses of the irrigation practices and conservation potential provide a good understanding of the entire study area, it is not recommended that this analytical approach be assumed accurate to a given individual farm or a particular small geographic area. While estimates have been provided for the three hydrogeologic provinces, RH2 suggests these be used only for general comparative purposes among these three sub-areas.

Both the crop irrigation requirement and irrigation efficiencies used are based on best available information but, as previously noted, the dataset is limited to general categories of both crops and irrigation types. Irrigation loss estimates are based on the assumption that 35% of the center pivot acreage employs LEPA. The dataset does not indicate how much of the acreage in each of the study areas are already employing IWM. RH2's estimates of total conservation potential will be sensitive to these assumptions and could differ to varying degrees if actual conditions depart significantly from these assumptions.

A detailed discussion of the assumptions used in developing the conservation potential for the various types of mechanical upgrades including the addition of IWM and the results of this analysis for the study area is summarized in **Appendix A**.

4.2 HYDROGEOLOGIC CONDITIONS

Over much of the Southern Franklin County (SFC) study area Columbia River Basalts are overlain by a succession of Miocene to Quaternary sedimentary deposits. These suprabasalt sediments form the primary aquifers in the area with textures ranging from fine silts to coarse gravels. Irrigation practices have significantly changed the occurrence and flow of groundwater in the study area, and each province has different return flow pathways and timing for applied irrigation. The following sections describe the hydrogeologic framework of the study area along with information on groundwater levels, recharge, discharge and groundwater flowpaths for irrigation recharge

4.2.1 Information Sources

This analysis of hydrogeologic conditions in the SFC area included review of: GIS coverages of surficial geology, GWMA documents describing the suprabasalt and basalt geology of the study area and associated 3-D stratigraphic model grids (GWMA, 2007, 2009), USGS reports describing the hydrogeology of the area and responses to irrigation (Drost, 1993 and 1997), studies of the Ringold formation (Lindsey, 1993), Department of Ecology well logs, and studies describing the hydrogeology of the Hanford site immediately west of the study area (Liikala, 1994; Newcomber, 2002; Vermuel, 2001; Khaleel, 1995; Last, 2006). Supplementary information on historic and current irrigation practices were obtained from USBR (pers. comm.., O'Callaghan, 2011) and the Franklin County Irrigation District (FCID) (pers. comm.., Burns and Wright, 2011). Supplemental information about Columbia River stage elevations in Lake Wallula and management practices behind the dykes ("interior drainage system) were obtained from Army Corps of Engineers (pers. comm., Heitstuman, 2011).

4.2.2 Geology and Hydrostratigraphic Units

The study area is in the Pasco Basin, a structural low created by faulting and folding of the Columbia River Basalts. The structural low has been infilled with a succession of sedimentary units including the Ringold Formation, Missoula flood deposits, and surficial deposits of Quaternary loess, dunes and alluvium. Key hydrostratigraphic units and aquifer characteristics are described in **Table 4-1**. Hydrostratigraphic units in Southern Franklin County have been described in a number of reports with varying levels of consistency regarding unit names and subdivisions. Much of the study area is mapped as Quaternary dune deposits and underlying geology is inferred from comparison to outcrops at the edges of the study area and observations noted in drilling logs. For this study, PGG uses the stratigraphic framework presented in the GWMA studies (2007, 2009); with further division of the Wooded Island member of the Ringold Formation into basal, lower and middle units per the USGS (Drost, 1997).

PGG divided the study area into three hydrogeologic provinces based on the unit, or units, that dominate vadose and groundwater flow (**Figure 4-2**):

- The "Quaternary Province" (Q), dominated by gravels of the Quaternary Flood Deposits and the Middle Ringold Formation;
- The "Upper Ringold Province" (R), dominated by the fine-grained Upper Ringold Formation in the northwestern portion of the study area; and,
- The "Basalt Province" (B), dominated by Columbia River basalts in the eastern portion of the study area.

The Quaternary Flood Deposits (locally known as the Pasco Gravels) and Ringold Formation are the primary aquifers affected by irrigation recharge, with lesser irrigation recharge to the Saddle Mountain Basalt in the eastern portions of the study area. The Pasco Gravels were deposited by a succession of Pleistocene cataclysmic floods and mantle most of the study area at thicknesses ranging from absent or just a few feet thick in the eastern portions to over 200 feet thick near Pasco (**Figure 4-2**). Consistent with GWMA nomenclature, dunes of remobilized flood-deposited sands are included in the Quaternary Flood deposits. Quaternary deposits are present over basalts and the Upper Ringold Formation in the "B" and "R" provinces where they are largely the dune-facies, but are not the primary control on deep percolation in those areas. The Pasco Gravels are equivalent to the Hanford Gravels described west of the Columbia River, and are included in the GWMA Coarse Quaternary Deposits (unit "Qf") (GWMA, 2009). The Pasco gravels are lithologically variable ranging from open-matrix medium-coarse gravels through coarse-medium sand, but are dominated by sandy gravels, gravelly sands and coarse sands. The Pasco gravels are identified in drill logs by the lack of cementation and predominance of basaltic clasts.

The Ringold Formation is described in a number of reports, and we follow the sub-unit descriptions of Drost (1997) for consistency with previous work. Drost divided the Ringold Formation into four subunits including a basal conglomerate found primarily near the Columbia River, a lower unit consisting of silts and muds, a middle unit consisting of interbedded sands and gravels, and an upper silty sandy unit. The upper silty sandy unit is correlative with the GWMA Ringold Fines unit ("Trf") including the Taylor and Savage flat members, while the lower units are divisions of the member of Wooded Island (Lower Ringold in GWMA documents, "Trwie"). Caliche deposits are present in the upper portions of the Ringold Fines unit near the White Bluffs (GWMA, 2009). The GWMA studies mapped caliche deposits based on notes in drill logs and observation in outcrops. Caliche deposits appear to be about 10 feet thick and somewhat localized, although reporting in drill logs is likely to be inconsistent. Caliche cementation reduces effective porosity and hydraulic conductivity, reduces vertical flow in affected areas, and may enhance formation of perched aquifers. The influence of caliche on the vertical migration of groundwater is reportedly not as significant as the difference in vertical conductivity between silts, sands and gravels found in the various Plio-Pleistocene units (Lindsay, 2010).

Ringold Formation aquifers vary in lateral extent and hydraulic characteristics. Few wells are completed in the Upper Ringold due to the prevalence of silts and other low-permeability lithologies. The Upper Ringold Formation includes both the Savage Island and Taylor Flat members. Towards the top of the Upper Ringold, the Savage Island member includes laterally continuous, thickly bedded sands and silts which support more lateral than vertical flow. Towards the bottom of the Upper Ringold, the Taylor Flat member contains sandy zones deposited in a channelized geometry, which provides less lateral continuity but greater potential for vertical connections.

The Middle Ringold has the greatest areal extent, occurring beneath the Upper Ringold and much of the Quaternary Flood Deposits. The Middle Ringold is texturally similar to the Pasco Gravels, and a productive aquifer; the Pasco Gravels and Middle Ringold are often distinguished in drill logs based on a transition in the color of drill cuttings from black to tan, and an increase in cementation (caliche) in the Middle Ringold. Increased cementation may account for slightly lower hydraulic conductivity relative to the Pasco Gravels, as described in Section 4.2.4.

The Lower Ringold is a low-permeability aquitard generally restricted to areas near the Columbia River which further reduces the connection between the Middle Ringold and underlying Ice Harbor Basalt. The Basal Ringold gravels are thin and restricted to areas close to the Columbia River in the far western portion of the study area. The Basal Ringold does not constitute a significant aquifer due to its stratigraphic position and limited areal extent.

The Saddle Mountain Basalt is present beneath the entire study area (**Figure 4-2**). The Saddle Mountain Basalt unit is locally subdivided into the Ice Harbor Basalt, Levey sedimentary interbed, Elephant Mountain Basalt, Rattlesnake Ridge sedimentary interbed, and the Pomona Basalt. Basalts gently rise to the east exposing progressively deeper layers either at the surface or as subcrops at the base of the Ringold Formation. Groundwater flow into basalts and sedimentary interbeds will be most significant where basalt interflows crop out and directly receive irrigation recharge (GWMA, 2009). However, the current conceptual model for groundwater flow in the basalt aquifers suggests negligible regional groundwater flow. The basalt aquifers are believed to be compartmentalized by a combination of faults (few in study area), interflow pinchouts, dense flow cores, and paleotopographic features (GWMA, 2009; Lindsay, 2010). PGG is using the GWMA conceptual model of the basalt aquifer system as the most current and in-depth work on the basalt aquifer system. The Wanapum Basalt does not crop out in the study area and, due to the limited vertical hydraulic communication through the basalts, is not considered in this report.

4.2.3 Groundwater Levels

Groundwater levels in the suprabasalt aquifers have risen significantly between 1950 and the mid-1980's in response to irrigation recharge. Water levels rose at different rates at different times in different areas, as irrigation blocks were opened – cumulatively amounting to approximately 5 million acre feet of additional water in storage (Drost, 1997). Water-level rise was most prominent in the Upper Ringold Province, with as much as 500 feet of apparent rise in the Upper Ringold Province bringing water levels to near the ground surface (Drost, 1997) (**Figure 4-3**). A fairly dense network of drains was installed in the area between the White Bluff and Esquatzel Coulee between 1966 and 1988 to prevent the rising water table from reaching the root zone; drains also were installed in localized areas of the eastern Quaternary province that overly shallow subcrops of Ringold Fines. Water-table rise in the Quaternary Province was more modest, ranging from 5 to 50 feet with most hydrographs in the 10 to 20 foot range. Water levels have been relatively steady in the suprabasalt aquifers after the initial 5 to 25 years of water level rise after onset of irrigation. Some localized areas show declines of 10 feet or less near Smith Canyon, presumably in response to irrigation pumping beginning in the early 1970s. Observations of water levels in the late 1980s and early 1990's continue to indicate some degree of decline in selected wells, possibly in response to irrigation pumping and/or improvements in irrigation efficiencies (reduced deep percolation losses). Water levels in the Saddle Mountain Basalt wells have a more complicated response to changes in irrigation practices. Some SMB wells show up to 150 feet of water level rise while other wells show stable to declining water levels. SMB wells with significant rise in water level appear to be located in areas with basalt near the surface while declines are observed in areas with groundwater pumping. Even in areas with significant rise in SMB water levels, heads generally remain lower than heads in overlying suprabasalt aquifers.

Water levels in the suprabasalt aquifers are typically higher than in the underlying basalts throughout most of the study area. Depths to water in suprabasalt wells range from 0 to 300 feet bgs while water levels in wells completed in the underlying Saddle Mountain Basalt aquifers are generally 10 to 150 feet lower based on comparison of published water level maps (Drost, 1997). The head difference between the suprabasalt and basalt aquifers is greatest to the west and beneath the Upper Ringold Formation where water levels have risen the most since 1950. The observed downward gradient cannot be used to infer rates of flow between the suprabasalt and basalt aquifer systems.

Seasonal water level variations are observed to varying degrees in most wells in the area reflecting a combination of recharge from precipitation and irrigation, seasonal pumping, and variations in stage elevation of the Columbia and Snake rivers. The Columbia River has approximately 5 feet of seasonal variation at Ringold and 1 to 2 feet of seasonal variation at Lake Wallula, which includes the lower reaches of the Snake River in the study area.

Groundwater levels in the Upper Ringold Province exhibit seasonal variation of 5 feet or less in most wells. The seasonal trend appears to correlate with irrigation with a 1 to 3 month lag between peak July irrigation and hydrograph peak. Upper Ringold hydrograph peaks appear in September, 1-3 months after the peak July-August irrigation season, based on review of hydrographs in Drost (1997). Wells with shallow water levels (less than 10 feet bgs) generally show a damped seasonal response suggesting effective control of water table elevation by drains. Wells with greater depth to water do not show a consistent trend of hydrograph variability with depth to water or completion depth, although the peak usually occurred between September and November. The presence of drains near the top of the Upper Ringold Formation, and wells completed within the formation suggest that saturation is prevalent within much of the formation; however, seeps along the White Bluffs are indicative of perched conditions.

In the Quaternary Province, seasonal water-level variations in the Pasco Gravels range from less than 1 foot to more than 10 feet in available hydrographs, with most wells exhibiting 5 feet or less of variation. The timing of seasonal variations changes with location in the aquifer. Wells in the central and southeastern portion of the Quaternary Province have seasonal minimum water levels at the end of the irrigation season between August and October and peak in March to April. In contrast, wells in the northern and southwestern portion of the Province have water level peaks in July through September. This difference likely reflects differences in the dependence on groundwater irrigation sources in the Pasco Greenbelt (central and southeastern area of the Province) and surface water irrigation sources in the SCBID and FCID (northern and southwestern area of province respectively). Seasonal water-level variations beneath the Greenbelt area are predominantly influenced by pumping withdrawals, whereas other areas are more influenced by irrigation recharge. Water levels in wells in the northern portions of Esquatzel Coulee within the study area peak in October and November, approximately 2-3 months after the peak in the Upper Ringold Formation. Water level trends in the Middle Ringold are similar to variations in the Pasco Gravels.

Wells completed in the Saddle Mountain Basalt generally decline during the irrigation season in response to pumping, with seasonal variations ranging from 5 feet to as much as 100 feet. However, there is a subset of basalt wells near Eltopia and the Eltopia Branch Canal where hydrographs peak during the irrigation season. These wells are in the Basalt Province where basalts crop out or are near the ground surface.

4.2.4 Aquifer Properties

Aquifer properties for key hydrogeologic units are summarized in **Table 4-1**. Hydraulic properties for the individual suprabasalt sedimentary units are typically reported as hydraulic conductivity (K) and storage coefficient (S).

Drost (1997) provides estimates of K for all units in the study area including statistical analyses of hydraulic conductivity values estimated from specific capacities in wells. Hydraulic conductivity varies widely between units, with major units in the Quaternary Province (Pasco Gravels and Middle Ringold Formation) generally having higher K values than the less permeable silts of the Lower and Upper Ringold Formation. For the more permeable units, Drost found:

- The Pasco Gravels had K estimates ranging from 48 ft/d to 73,000 ft/d with a median of 880 ft/d, a 25th percentile of 440 ft/d and a 75th percentile of 3,100 ft/d (the highest median and 75th percentile of all units).
- The Middle Ringold had K estimates ranging from 7.5 ft/d to 5,000 ft/d with a median of 180 ft/d, a 25th percentile of 83 ft/d and a 75th percentile of 740 ft/d.

The lower hydraulic conductivity in the Middle Ringold relative to the Pasco gravels is due in part to more prevalent cementation within portions of the older unit. Drost also reported K values based on aquifer test data performed at the nearby Hanford Site. A median value of 1250 ft/d was calculated for the Hanford Gravels based on 12 aquifer tests and a median value of 41 ft/d was calculated for the Middle Ringold based on six aquifer tests. Drost also documents more recent studies at the Hanford Site that estimated an average hydraulic conductivity of 200 to 250 ft/d for the Middle Ringold. Drost (1997) reported significantly lower median K-values for the Upper and Lower Ringold Formation (25 and 46 ft/d respectively).

PGG also evaluated K within the Pasco Gravels and Middle Ringold Formation by analyzing specific capacity data from 275 wells completed within the Quaternary Province (detailed description in **Appendix I**). 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. Our analysis found that:

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

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/d), and higher than Drost's median K estimate for the Middle Ringold (180 ft/d).

The storage coefficient (S) is largely controlled by occurrence of either confined or unconfined conditions, and constraints are available from the literature for lithologic types and for specific units (Drost, 1997) (**Table 4-1**). The Pasco Gravels are largely unconfined with sparse semi-confined locations where interbeds of fine-grained sand or silt reduce conductance. Semi-confined conditions, identified over the time-scale of a pumping test, are expected to transition to unconfined responses over longer time scales, as drawdown propagates through lower permeability zones and reaches unconfined portions of the aquifer. The Upper Ringold is described in GWMA documents as unconfined to semi-confined (GWMA, 2009). Similar to the Pasco Gravels, semi-confined conditions are likely to occur where lower-permeability lithologies reduce hydraulic communication with the surrounding aquifer, but the long-term behavior of the aquifer is better described using unconfined storage coefficients. Middle Ringold is largely unconfined where in hydraulic connection with the texturally similar Pasco Gravels, but semi-confined or confined beneath the Upper Ringold Formation.

Reported S values for unconfined portions of the suprabasalt units are: 0.15 to 0.2 for Pasco Gravels; 0.11 for Middle Ringold; 0.07 to 0.21 for Upper Ringold Formation; and 0.02 to 0.21 for the Lower Ringold. S values for confined and semi-confined portions of suprabasalt units are: 0.03 to 0.07 for the Pasco Gravel; 0.00005 to 0.06 in the Middle Ringold; and 0.002 to 0.05 in the Lower Ringold. S values for the Middle Ringold and Pasco Gravels and semi-confined portions of the Middle Ringold are based on aquifer tests (Newcomb et al, 1972 and Drost, 1997), while S values for the Upper Ringold and Lower Ringold units reported in Drost are based on grain size analysis. S values used for groundwater modeling of the Hanford Gravels west of the Columbia River (equivalent to the Pasco Gravels) ranged from 0.1 to 0.3, with higher values assigned to coarser gravels and lower values assigned to sandier portions of the Hanford site (Thorne, 1996). Middle Ringold formation storage coefficients were set to 0.10 (ibid).

Hydraulic conductivities of the Saddle Mountain Basalts were generally lower than the superbasalt aquifers. The lowest median K value reported by Drost (2.3 ft/d) and the lowest K value (0.0073 ft/d) were both from the Saddle Mountain Basalt. The Saddle Mountain basalt maximum K value reported by Drost (3,200 ft/d) was nearly two orders of magnitude above the 75th percentile (36 ft/d), and five orders of magnitude above the 25th percentile (0.64 ft/d). Hydraulic properties for the basalt aquifers are more often reported as transmissivity (T), as effective saturated thickness sometimes includes one or several interflows and flow cores. Saddle Mountain Basalt aquifer T values reported for the Hanford site, including the Elephant Mountain and Ice Harbor Basalts, range from less than 10 to 5,400 ft^2/day (Spane and Webber, 1995). The variability of T is likely biased to more conductive zones that produce more water. The range of T in part reflects the heterogeneity of interflow and fracture zone permeabilities common to basalt aquifers. Many of the basalt aquifer pump tests analyzed at the Hanford site suggested ‘leaky confined aquifer conditions’ late in the pump tests, interpreted to indicate hydraulic connection with overlying or underlying interflows and/or sedimentary aquifers. It is likely that permeable zones near the edges of the basalt aquifers may have local connections to the surrounding suprabasalt aquifers; however, these zones likely do not have sufficient interconnectivity to provide regional-scale groundwater flow pathways. GWMA studies of the basalt aquifers suggest that basalt flow cores represent significant aquitards, and that vertical flow across basalts occurs over century to millennial timescales (Porcello, 2009).

The connectivity of vertical and horizontal flow in the basalt aquifers is an important factor in the overall hydrogeologic behavior of the study area. The current GWMA conceptual model for the basalt aquifer systems is a compartmentalized system that allows local flow and exchange of groundwater, but regional flow is restricted to negligible or extremely slow rates (Lindsey, 2010), suggesting that the SMB aquifer system is not a dominant return flow pathway to the Columbia and Snake rivers. Compartments are bounded by dense, low-permeability flow cores, interflow pinchouts, and erosional and structural discontinuities. This conceptual model is supported by calculations showing that changes in storage balance pumping withdrawals, suggesting that recharge is not reaching these aquifers (Lindsey, 2010; Porcello, 2009). Age dating of the deeper Wanapum and Grande Ronde basalts north of the study area suggest groundwater ages 5,000 years and older implying long transport times and little connection to surface recharge sources; younger ages less than 1,000 years are measured in areas where basalts crop out and young recharge enters compartments and mixes with deeper, older waters (Porcello, 2009). The compartmentalization model implies that the bulk transmissivity values from pump tests describe aquifer properties within a compartment, but overestimate groundwater flow when applied at a regional scale. Based on this conceptual model, groundwater entering the basalt aquifer system is unlikely to have a regional return flow pathway to discharge points[14].

4.2.5 Vadose Zone

Vadose zone textures in the study area range from basalt flows to silts to gravels. Sedimentary deposits make up most of the vadose zone within the study area. Basalt vadose zone is present in the eastern portion of the Basalt Province, but is not irrigated and not considered further. Vadose zone thickness in the study area currently ranges from 0 to 300 feet bgs (**Figure 4-3**). Vadose zone thickness has decreased significantly since the 1950’s in some places due to rising groundwater levels. Irrigation drains were installed in response to significant rises in groundwater level, primarily in the Upper Ringold Province. The vadose zone is expected to be relatively thin above the first occurrence of groundwater within the Upper

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[14] Historically, most groundwater models of the basalts in the Pasco Basin apply a locally high vertical conductivity along the Columbia River to account for hydraulic gradients suggesting flow convergence on the river (Vermeul, et al., 2001; Bauer, et al., 2000). These model reports do not provide additional rationale based on observations of basalt characteristics for the change in vertical conductivity in the area surrounding the Columbia River relative to regional basalt properties.

Ringold; however, multiple vadose zones may occur in areas with perched aquifers, such as the multiple perched zones observed at seeps along the White Bluffs. Vadose zone thickness has not changed as much in the Quaternary Province because the rise in water levels has been smaller due to higher aquifer transmissivity.

The vadose zone in the Quaternary flood deposits includes gravels and sands. The Pasco Gravels are dominated by sandy gravels, gravelly sands and coarse sands; but also include interbeds of mainly coarse, gravelly materials and lenses of silty material. Facies maps prepared by the GWMA show zones of higher gravel content along the Columbia River near Block 1 and the Esquatzel Coulee (near Eltopia), although the data don't distinguish between the unsaturated and saturated zones or whether gravelly materials were interbedded or massive (GWMA, 2009). Observations at the Hanford site suggest that the vadose zone is dominated by sandy gravel, gravelly sand, and coarse sand textures (Last et al., 2006). Coarse fractions dominated by gravels with a potentially open framework texture occur as lenses rather than thick, laterally continuous units, and are not volumetrically significant.

Flow regimes within the vadose zone are expected to vary based on the magnitude and timing of irrigation recharge, particularly in the coarser intervals. Lower rates of irrigation recharge, such as those associated with field applications, are expected to concentrate flow within the sandy fractions, thus allowing for damped transmission of the recharge pulse. Where higher rates of recharge, such as leakage from an unlined wasteway, overlie coarser materials, the gravel fraction can be highly transmissive and support rapid transport of 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). The effects of damping and lagging within the sandy materials can be significant, particularly where the unsaturated flood deposits are thicker, as discussed in Section 4.4.2 and **Appendix I**.

The vadose zone in the Basalt Province consists of a thin veneer of sandy, silty dunes with localized Quaternary flood deposits (**Figure 4-2**). The depth to water and thickness of sediments over the eroded basalt surface is poorly constrained and the vadose may include the upper portions of the basalts. The eroded basalt surface will have topographic relief that may locally perch groundwater over dense flow cores, or act as a capillary barrier at macropores until sufficient water has accumulated to migrate downward. There is insufficient data to evaluate the vadose zone transport pathway at the basalt-alluvium contact and deeper.

4.2.6 Recharge, Discharge and Groundwater Flow Patterns

Groundwater systems can be conceptually divided into recharge areas, discharge areas and the groundwater flow paths between them. Recharge in the study area includes irrigation applications, irrigation canal leakage and minor amounts from precipitation infiltration. Groundwater flow in the suprabasalt aquifers moves towards discharge points along the Columbia River and the Lake Wallula reach of the Snake River. Groundwater discharge in the study area includes groundwater flow through the suprabasalt aquifers to the Columbia River and Snake River (Lake Wallula), spring seepage along the White Bluffs, groundwater pumping, and discharge to agricultural drains and ditched wasteways. Groundwater flow in the basalt aquifers occurs in compartmentalized interflow aquifer zones at low rates and is not believed to discharge to regional surface-water features in significant amounts (Lindsay, 2010). Areas where water levels have been steady over the past couple decades (e.g. Upper Ringold Province) suggest a balance between recharge and discharge. Groundwater level declines in some wells in the Quaternary province may be attributed to either conservation (reduced irrigation recharge) or increased pumping (Section 4.2.3).

Irrigation field application and canal leakage (primarily from unlined wasteways) are the largest sources of recharge in the study area, and have substantially altered the occurrence and flow of groundwater. The USGS estimates deep percolation of applied field irrigation water at between 4.9 and 7.9 inches per year, generally increasing to the south within the study area (Drost, 1997). Assuming an average recharge rate across the study area of 6.4 in/yr and approximately 129,000 acres of irrigated fields, total irrigation recharge in the study area is estimated at about 68,800 af/yr. This recharge value is similar to RH2's estimate of 85,600 af/yr (8 in/yr), which includes recharge from application inefficiencies and over-application (Section 4.1). Canal leakage is also a major source of groundwater recharge in the study area. Drost estimates approximately 140,000 af/year of leakage from canals in the South Columbia Irrigation District within the larger USGS study area (Drost, 1997). Wasteways leakage is poorly constrained, but must include a minimum of 20,000 af/yr[15], based on constraints from USGS gauging data (Drost, 1997); however, the total leakage from wasteways is likely much larger. The Franklin Irrigation District in the southern portion of the study area near Pasco accounts for considerably less canal leakage recharge at about 870 af/yr.

Natural recharge from precipitation is small relative to irrigation-related recharge. The USGS estimates natural recharge from precipitation at 0.45 inches per year for the period from 1955 to 1975 (Drost, 1997). This is similar to other estimates of natural recharge in the area ranging from 0 to 1 inch per year (Bauer, 2000). Precipitation accounts for approximately 6,000 acre-feet per year (af/yr) of recharge to the aquifer system.

Groundwater elevation maps for the suprabasalt aquifer system indicate discharge to the Snake and Columbia Rivers in the study area (Drost, 1996; Newcomer et al, 2002; Vermeul, et al., 2001). Groundwater flow in the Pasco Gravels is predominantly to the southwest with an average gradient of 0.002. The low gradient is indicative of the high transmissivity of the flood deposits. Groundwater flow in the Upper Ringold Province is more complicated with mapped groundwater contours emulating topography, resulting in potentially misleading gradients. Water levels within the Upper Ringold Formation are variable, but higher than water levels in the underlying Middle Ringold Formation, which is also inferred to discharge to the Columbia River.

Quaternary Province

Groundwater pathways from recharge to discharge are simpler than the surrounding provinces. Recharge into the Quaternary gravels largely migrates vertically from the land surface to the water table, and then flows laterally through the Pasco Gravels and Middle Ringold Formation to discharge points along the Columbia and Snake rivers (with some flow discharged via Army Corps of Engineers pumping stations in Pasco). Recharge from irrigation comes from both canal leakage and field irrigation infiltration. Irrigation water in the province comes from the Franklin Irrigation District (FID), SCBID, and groundwater pumping from suprabasalt and basalt aquifers. The USGS estimated field irrigation recharge at 7.9 inches per year (Drost, 1997), which is similar to RH2's estimate of 8 inches per year (Section 4.1).

Irrigation recharge has increased over time between the 1920's (when irrigation was largely restricted to the Franklin Irrigation District) through the late 1980's, and most recently has likely decreased due to conservation improvements. Important milestones for irrigation development within the study area include:

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[15] This value is based on a summation of all discharge to groundwater from wasteways noted in Figure 10 of Drost (1997).

- 1922 Franklin Irrigation District, first irrigation
- 1948 SCBID Block 1, first irrigation
- 1953 Lake Wallula (Mc Nary Dam) reached operating level
- 1954 SCBID Block 15, first irrigation
- 1955 SCBID Block 16, first irrigation
- 1956 SCBID Block 19, first irrigation
- 1964 SCBID Block 17, first irrigation; first buried drains installed in SCBID
- 1966 SCBID Block 161, first irrigation
- 1973 Pasco Green Belt, first significant irrigation

PGG estimated total recharge over time for our model calibration period (1945-1986); with sources including precipitation, field applications, losses from ditches, canals and wasteways. Our analysis, documented in **Appendix J**, suggests that towards the end of this calibration period, recharge in the Quaternary Province is on the order of 250,000 af/yr, with the largest recharge sources derived from wasteway leakage (153,000 af/yr) and field irrigation recharge (42,000 af/yr) and the smallest source derived from precipitation (11,000 af/yr).

Recharge into the Quaternary Province also occurs as subflow from adjacent provinces. Lateral flow from the adjacent provinces is poorly constrained. Lateral flow from the Upper Ringold and Basalt Provinces will act as line recharge sources along the edges of the Quaternary Province.

The USGS estimates a combined 87,700 af/yr of pumping from the Pasco Gravels and Middle Ringold Formation, of which 75,000 af/yr was for irrigation. (Drost, 1997). Irrigation pumping is the largest use, and is generally applied near withdrawal points where return flows will infiltrate back into the suprabasalt aquifers. The majority of irrigation pumping occurs in the Pasco Greenbelt in the central and southeastern portions of the province. PGG independently estimated irrigation pumping from the Greenbelt at 63,000 af/yr for the same time period (**Appendix J**). Some pumping, particularly in the vicinity of Smith Canyon, is derived from basalt aquifers.

Upper Ringold Province

Groundwater pathways from recharge to discharge are complex in the Upper Ringold Province. Most of the complexity lies in deciphering how discharge is partitioned between irrigation drains, seeps along the White Bluffs, lateral flow into the adjacent Quaternary deposits, and vertical flow into the underlying Middle Ringold Formation. Recharge is well-constrained for 1986 conditions using estimates compiled by the USGS, while most of the discharge pathways are poorly constrained. Here, we briefly summarize estimates of recharge and flow along the groundwater pathways to discharge at the edges of the province. The pathways considered here begin with recharge at the surface with subsequent infiltration and migration to: interception of recharge by drain systems (and eventual discharge outside the Upper Ringold Province), infiltration through the Ringold Fines (Upper Ringold Formation) to the underlying Middle Ringold Formation, lateral migration within the Upper Ringold and discharge to seeps at the White Bluffs or laterally into the adjacent Quaternary deposits where the Ringold Fines subcrop against them.

PGG estimates total 1986 recharge to the Upper Ringold Province from canals and field application to be about 58,600 af /yr based on analysis of canal length and leakage rates from Drost (1997) and irrigated acreage. Our water budget calculations utilize 1986 USGS estimates of both recharge and discharge with adaptation to the differences in aereal extent of the respective study areas. Over time, canal leakage as a source of recharge has probably remained relatively steady since 1986 in the absence of major changes to the canal lining, however the rate of irrigation application may have changed since 1986 in response to field-level changes in water delivery and application.

PGG estimates that approximately 34,800 af/yr of potential recharge is intercepted by drains in the Upper Ringold Province. This estimate is based on the total drain capture estimate from Drost (1997) (72,000 af/yr) pro-rated by the number of miles of drains within the Upper Ringold Province (411 of 936 total miles of drains). The majority of drains in the USGS study area are located in areas overlying shallow depths to Ringold Fines. While this estimate does assume that all drains intercept equivalent amounts of recharge, which is unlikely to be accurate, the similarity of the geologic environment of the majority of the drains suggest that the estimate is reasonable within the available data. Subtracting the drain interception (34,800 acft/tr) from the total recharge estimate (58,600 af/yr) leaves 23,867 af/yr of infiltration into the Ringold Fines and associated groundwater flow paths to lateral seepage and migration to the Middle Ringold Formation.

Discharge from the Ringold Fines includes seepage along the White Bluffs, seepage along subcrops against Quaternary deposits to the north and south, and downward flow to the Middle Ringold Formation. Seeps started flowing along the Columbia River at the White Bluffs and Ringold Springs (within Ringold Coulee) following irrigation development in the area. Observations from landslide monitoring work along the White Bluffs suggest that seeps in the Upper Ringold are year-round features with little seasonal variation (Nielsen, 2010). PGG estimates annual discharge to springs along the White Bluffs at approximately 7,400 af/yr based on modification of USGS estimates of total discharge from springs along the White Bluffs (Drost, 1997). The USGS estimates include substantial flows at Ringold Springs, which include an unconstrained but likely large proportion of flow from the higher-transmissivity Quaternary deposits in Ringold Coulee and wasteway flows. Ringold Springs are therefore not included in the PGG estimate. Lateral discharge to subsurface seeps along the northern and southern subcrop contacts with Quaternary deposits (mostly Pasco Gravels) are estimated based on the length of the subcrop in map view and scaled against the length and estimated seepage at the White Bluffs. Total lateral flow from the Ringold Fines is estimated at 18,500 af/yr: 7,400 af/yr to the White Bluffs, 2,900 af/yr as subflow to northern Quaternary deposits and 8,200 af/yr to southern quaternary deposits, As shown in the summary table below, this estimate of lateral flow leaves 5,400 af/yr of recharge migrating vertically to the Middle Ringold Formation.

Water Budget Estimates for Upper Ringold Province

Water Budget Component	Estimated Flux (af/yr)	Derivation
Irrigation Recharge (fields + conveyances)	58,600	
Drain Discharge	-34,800	USGS total scaled to drain lengths
Lateral Discharge to White Bluffs	-7,400	
Lateral Discharge to Subflow Along North Boundary	-2,900	Scaled by distance relative to White Bluffs
Lateral Discharge to Subflow Along South Boundary	-8,200	Scaled by distance relative to White Bluffs
Downward Discharge to Middle Ringold Formation	-5,400	Remainder term to balance water budget

Because most of the above discharge estimates must be considered poorly constrained, the remainder term (downward discharge to the Middle Ringold) must also be considered poorly constrained. For instance, based on reasonable estimates of vertical gradients and K values for silts[16] (Freeze, et al., 1979), the Upper Ringold could *theoretically* be capable of passing between 0.44 and 438 ft/yr. The upper value

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[16] Assumes vertical hydraulic conductivity range of 0.001 to 0.1 ft/d and vertical gradient range of 0.1 to 1.

would allow transmission of the entire 58,600 af/yr recharge downward to the Middle Ringold; however, we know this not to be the case due to observed discharge to drains and the White Bluffs.

It should also be noted that irrigation recharge is not constant year-round. Application rates are higher during the irrigation season and, depending on local conditions, irrigation application may result in accumulation of water at the upper contact of the Ringold Fines. Accumulation of water at the upper contact and subsequent lateral migration could also result in increased drain interception away from the irrigation application area, and result in persistent drain interception beyond the irrigation season in some areas. Additional monitoring of the timing and quantity of drain flow at strategic locations could improve system-scale estimates of Upper Ringold flow partitioning between recharge and diversion to drains

Basalt Province

Recharge in the Basalt Province is estimated by the USGS at between 7.9 inches in the southern third of the province and 4.9 inches in the northern two-thirds of the province. Based on the area of the province, these rates would translate to an *upper limit* of about 26,000 af/yr recharge (assuming full irrigation). However, because the province is not fully irrigated, actual recharge is likely less. During model construction, PGG estimated the total field area in the adjacent Basalt Province and used estimates of deep percolation by RH2 (**Appendix A**) to calculate about 10,000 af/yr of irrigation recharge (**Appendix J**).

Groundwater contour maps of the Saddle Mountain and Wanapum basalts in many references (e.g. Bauer, et al., 1996; Drost, et al., 1997; Vermeul, et al., 2001) indicate convergent flow towards the Columbia and Snake Rivers. However, hydraulic behavior of wells completed in the basalts, water-balance evaluations of water-level declines and pumping withdrawals, isotope and groundwater chemistry analysis, and regional behavior of the basalt aquifer system suggest that the basalts are not regionally transmissive and do not convey significant amounts of flow to these major rivers (Lindsay, 2010). Because basalts generally rise away from the Columbia River and groundwater is contained in “compartments” within the basalts, groundwater flow directions implied from head distributions may be spurious. For consistency with previous and ongoing work by the GWMA, PGG is adopting the conceptual model that basalt layers are not laterally transmissive except in localized, compartmented areas. Sedimentary interbeds between basalt layers are assumed to be isolated from suprabasalt aquifers because the dense flow cores impede vertical flow.

Irrigation applied to fields over basalt in the eastern portion of the study area will either supply local recharge to the basalt system, migrate laterally across the alluvium-basalt contact into suprabasalt aquifers, or migrate laterally across the alluvium-basalt contact into Esquatzel Coulee (where it will either remain in the Quaternary alluvium (Qa) or flow into wasteways). These pathways differ in their relative timing and connectivity for subsurface return flow to the Columbia/Snake rivers, as discussed in Section 4.3.1.

The Basalt Province has drains and wasteways in much of its northern extent. The area surrounding and north of Eltopia has a number of drains, wasteways and laterals that may be intercepting some recharge. Drost (1997) notes that the Smith Canyon wasteway is above the water table, and therefore unable to intercept lateral migration of recharge and is unlined and therefore a net source of recharge (Drost, 1997). There are no mapped irrigation drains in the southern half of the Basalt Province. Therefore, the rapid “flows-to-wasteway” path can be excluded for the southern half of the Basalt Province. Within this area, recharge either enters the basalt aquifer system or migrates laterally to the suprabasalt aquifers.

4.3 RETURN FLOW TIMING IN UPPER RINGOLD & BASALT PROVINCES

PGG performed a qualitative assessment of the timing of return flow and conservation retiming benefits for the Upper Ringold and Basalt Provinces based on our conceptual understanding of the associated groundwater flow systems. The following subsections describe our general findings regarding return flow timing and conservation retiming benefit for these two provinces. Given the greater uncertainty associated with the Upper Ringold and Basalt provinces, the three locations selected for estimation of retiming benefit were all within the Quaternary Province. A quantitative evaluation of retiming benefits for the Quaternary Province sites is presented in Section 4.4.

4.3.1 Basalt Province

As noted in Section 4.2.6, transport of irrigation recharge from the basalt province can take several pathways through the hydrologic system. The following table summarizes these pathways, and PGG's qualitative interpretation of the associated timing of return flows to the Columbia and Snake rivers:

Basalt Province Subsurface Irrigation Return Flow Pathways

Path	Percolation into Basalt Aquifer	Lateral Migration to Suprabasalt Aquifer	Migration to Coulee	
			Flows Through Qa in coulee	Flows to Wasteway
Conceptual Timing Effect	Little to no direct discharge to rivers.	Timing equivalent to, or more damped than, application at contact with suprabasalt aquifers.		Rapid return to river

Water percolating into the basalt is assumed to have no significant regional flowpath to the Columbia and Snake Rivers. The most recent conceptual model of the basalt aquifer system is that there is insignificant discharge to the Columbia and Snake Rivers (Lindsay, 2010). Therefore any recharge to the basalt is effectively lost from the surface water system and reduced deep percolation from irrigation conservation will immediately provide a full benefit to the surface water balance at the point of withdrawal (newly available water should approach 100% of the reduced deep percolation due to conservation savings). Reduced recharge in the Basalt Province due to conservation could affect the water balance for the deeper basalt aquifers and therefore affect associated water levels

Water migrating laterally to the suprabasalt aquifers will have return flow pathway and timing similar to recharge applied at the edge of the Quaternary Province. The timing of discharge from the Basalt Province through the Quaternary alluvium to the Columbia and Snake rivers has the potential to be significantly damped, as illustrated in Section 4.4.3. The amount of damping from this flowpath should be similar to or more damped than recharge applied at the edge of the suprabasalt aquifer at basalt. Reduced recharge in the Basalt Province due to conservation could affect the water balance for the deeper basalt aquifers and therefore affect associated water levels.

Water that reaches the drain and wasteway systems in the northern portion of the Basalt Province may have a rapid remaining transit time to the Columbia and Snake rivers. Irrigation conservation affecting this pathway cannot be shown to provide significant retiming benefit because there is little difference in quantity or timing between water left in the river (after conservation) and irrigation water that returns to the river relatively quickly via the wasteway (before conservation).

If quantitative evaluation of retiming benefit for sites within the Basalt Province is desired, we recommend focusing on the southern half of the province. The southern half of the Basalt Province is amenable to evaluating conservation benefit because return flow pathways can be constrained through the use of conservative assumptions. Recharge in the southern half of the Basalt Province can be conservatively assumed to have equivalent return flow timing to recharge applied at the nearest contact with the suprabasalt aquifer system. The northern half of the Basalt Province has limited potential for conservation benefit from return flow retiming due to the rapid return through wasteways. Additionally, the complex relationships in the northern half of the province between subsurface, drain and wasteway return flows are difficult to defensibly model.

4.3.2 Upper Ringold Province

Both PGG's water budget estimates and RH2's irrigation analysis of the Upper Ringold Province suggest that drains play a significant role in intercepting deep percolation before it can become subsurface return flow. Based on this flow dynamic, the first stages of conservation efforts are more likely to affect drain flows rather than create conservation benefit. If conservation measures are implemented, the hydrologic system will respond in two stages (**Figure 4-4**). First, the water table will likely remain at a similar to slightly lower elevation, with reduced flow to the drain system and little change in flux to the deeper subsurface return flow pathway. Once the amount of infiltrating water is no longer adequate to maintain the water table at the drain elevation, the water table will drop below the drains, the drains will reduce to negligible flow, and the majority of infiltrating water will enter the deep subsurface return flow pathway. At that point in time, further conservation efforts would yield significant benefit towards retiming of subsurface irrigation return flow.

The amount of conservation needed to cause a transition from reducing drain flow (no retiming) to reducing subsurface return flow (conservation benefit) is unknown. However, given that drains are expected to capture a significant portion of deep percolation, we expect significant conservation measures would be needed before a benefit could be documented. Monitoring could be useful to determine when the water table falls below the drains, or when drain discharges cease for an area. While several areas exist in the Upper Ringold Province where drains are absent (i.e. hydrogeologic conditions presumably create a deeper water table), altering the water balance in these areas can have some effect on adjoining areas (with drains), and overall, the hydrogeology of the Upper Ringold Province is sufficiently complex that the defensibility of associated subsurface return flow calculations is reduced.

At this point in time, PGG recommends against modeling the retiming benefits from conservation in the Upper Ringold Province. Conservation efforts are less likely to lead to significant conservation benefits in this province, and are likely better directed to the other provinces for establishing conservation benefit and new water availability. Furthermore, the hydrogeology of the Upper Ringold Province is relatively complex with significant data gaps, and (without further field studies and monitoring) prediction of conservation benefit (once the drains have ceased intercepting recharge, or in areas where drains are absent) would be complex and less defensible than adjacent provinces.

4.4 RETIMING BENEFITS OF CONSERVATION IN THE QUATERNARY PROVINCE

PGG estimated the retiming of deep percolation losses associated with irrigation conservation at three hypothetical conservation sites by considering: 1) the portion of Columbia River diversions associated with deep percolation losses, 2) groundwater pumping for irrigation in the Pasco Greenbelt, and 3) model predictions of subsurface irrigation return flow from deep percolation losses back to the Columbia and

Snake rivers. As subsurface return flow to the Snake River discharges to the Lake Wallula reach, discharge estimates and retiming benefits are presented for a single Columbia River term, which includes this Lake Wallula reach. The three hypothetical site locations are shown on **Figure 4-5**, and were selected based on discussions with Mark Nielson of the Franklin Conservation District. Sites occur in SCBID Block 1, Block 17 and the Greenbelt. For the two surface-water sourced irrigation sites (Block 1 and 17), the "retiming benefit" due to reduced deep percolation losses (at any time) is equal to the associated reduced diversion from the river under consideration minus the change in groundwater discharge to the river due to reduced deep percolation losses:

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

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} = portion of diversion supplying deep percolation irrigation loss before conservation
DP_{POST} = portion of diversion supplying deep percolation irrigation loss after conservation
RD_{PRE} = river discharge from subsurface return flow before conservation
RD_{POST} = river discharge from subsurface return flow 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:

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

It should be noted that the benefit of the discontinued stream diversion term (DP_{PRE}) is implied for the Lake Wallula reach of the Snake River, as lake levels benefit from reduced upstream diversion. For the purpose of this analysis, a "critical period" of July and August has been defined on the Columbia River (including the Lake Wallula reach of the Snake River), during which time the retiming benefit represents the limiting factor on new water rights allocations.

Conservation benefits for the Greenbelt site are estimated differently; as the site is sourced by groundwater and associated subsurface impacts occur from the *combined* effects of irrigation recharge and pumping. Because both pumping and recharged components must be assessed, PGG defined pumping based on RH2's estimates of total irrigation application and recharge based on RH2's estimates of total deep percolation losses. These two estimates were summed up to calculate a "net recharge to groundwater" (R_N), which can be negative when pumping exceeds recharge. Along with crop requirements and losses to deep percolation, the pumping withdrawals also include losses to evaporation and a very small component of losses to surface-water runoff. PGG estimated conservation benefit by calculating the difference between estimated subsurface return flow to the Columbia Rivers for pre-conservation and post-conservation annual schedules of R_N. Because the pumping component of R_N includes evaporation losses and minimal runoff losses, it was not possible to separate the retiming benefits of reduced deep percolation from the conservation benefits of reduced ET.

In all cases considered, the change in the timing of groundwater discharge to the Columbia and Snake rivers associated with reduced deep percolation losses requires consideration of: 1) deep percolation losses from the root zone; 2) migration of the irrigation "recharge pulse" downward within the vadose zone (from the root zone to the water table); and 3) conveyance of the recharge pulse through the groundwater system to the referenced rivers. These three elements of subsurface return flow are discussed in the following sections.

4.4.1 Deep Percolation Losses from Hypothetical Sites

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 irrigation 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 monthly rates, and used as input for evaluation of the vadose zone.

4.4.2 Irrigation Recharge through the Vadose Zone

PGG estimated the transmission timing of recharge from field irrigation applications through the vadose zone to generate input for the saturated groundwater flow model. Vadose-zone conditions vary among the three hypothetical sites. Differences in depth to water and sedimentary texture are expected to affect the predicted timing of the seasonal irrigation recharge pulse. Vadose zone conditions beneath the three sites were defined as follows:

- Block 1: 155 feet of gravelly soils
- Block 17: 105 feet of sandy gravel
- Greenbelt: 65 feet of sandy gravel

Vadose-zone thicknesses were estimated based on depth-to-groundwater mapping (**Figure 4-3**). Vadose zone textures were defined based descriptions of the Pasco gravels and GSI sedimentary facies analysis (Section 4.2.5). Hydraulic properties for the referenced sedimentary textures were based on field characterization, laboratory testing and modeling analysis performed at Hanford (Last et al, 2006). PGG represented the vadose zone at the Block 1 site with Last's soil textural class which affords the fastest transmission of recharge from the root zone to the water table (Class "Hrg", with greater than 60% gravel). PGG represented the vadose zone at Block 17 and the Greenbelt with the next most transmissive textural class defined by Last (Class "Hg", sandy gravel). Other less transmissive textures will likely be encountered in the vadose zone beneath both sites; however, representation with "Hg" can be considered conservative (i.e. less retiming) relative to the remaining textural classes. **Appendix I** provides more detailed descriptions of the textural classes and associated hydraulic property estimates.

PGG used the modeling code Hydrus-1D (Simunek et al, 2008) to evaluate conveyance of the recharge pulse through the vadose zone under current (pre-conservation) conditions. **Appendix I** provides a detailed description of PGG's Hydrus analysis. As discussed above, for post-conservation conditions RH2 assumed the *maximum theoretical* conservation benefit of zero deep percolation loss from irrigation applications. RH2 recognizes that a small quantity of deep percolation loss will remain after conservation. This quantity is expected to have a minor effect on estimation of retiming benefit, and can be incorporated into site-specific analysis once pilot sites are identified in the Quaternary province. PGG's current analysis employs the maximum theoretical conservation savings as input to our retiming calculations.

Passage through the three vadose-zone conditions defined above is predicted to provide considerable retiming (lagging and damping) of the recharge pulse. **Figure 4-6** shows the Hydrus pre-conservation predictions for the three 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). Post-conservation fluxes are assumed to be zero.

As discussed below, the saturated flow model is predicted to further increase damping of the predicted return flows.

4.4.3 Irrigation Recharge through the Saturated Flow System

PGG constructed a groundwater flow model of the Quaternary Province to evaluate the timing of subsurface irrigation return flow to the Columbia River (including the Lake Wallula reach of the Snake River). Detailed description of the groundwater flow modeling is presented in **Appendix J**. The model was run using the U.S. Geological Survey's numerical modeling code "MODFLOW-NWT" (Niswonger et al, 2011) within "MODFLOW 2005" (Harbaugh, 2005). Model layering represents the Pasco Gravels and the Middle Ringold Formation based on stratigraphic analysis performed by the GWMA (2009) and local revisions performed by PGG during model calibration. The model represents all hydrologic features within the province, including: recharge from irrigation conveyances, wasteways, and fields; natural (precipitation) recharge; irrigation pumping from the Pasco Greenbelt; and surface water features (Columbia River, Snake River and coulees). The model was calibrated to pre-irrigation conditions, long-term responses to the growth in irrigation recharge between 1945 and 1986, and seasonal water-level variation in 1986.

The model was used to predict the timing of subsurface return flow from the Block 1 and Block 17 hypothetical conservation sites and the timing of net river impact (I_N) from combined irrigation pumping and irrigation recharge at the Greenbelt site. Irrigation recharge input to the model was based on the Hydrus prediction of vadose-zone delivery of recharge to the water table (discussed immediately above). The effect of hydrogeologic uncertainty was addressed by running predictive model simulations over ranges of aquifer property values. Along with the aquifer property values developed during calibration, PGG developed model realizations where overall aquifer diffusivity was increased and decreased. Diffusivity (D) equals aquifer transmissivity (T) divided by storage coefficient (S); with lower values of D causing greater damping and lagging of the recharge pulse. Predictions were performed based on three model "realizations" – simulations based on calibrated parameters, increased diffusivity and reduced diffusivity (**Appendix J**).

Figures 4-7 and **4-8** present Block 1 and Block 17 model predictions of subsurface return flow discharging to the surface-water features mentioned above. Comparing the return-flow predictions to RH2's estimates of irrigation recharge at the land surface illustrates the high degree of damping predicted by the model. Note that the model results incorporate the damping predicting by the vadose zone assessment (discussed above). Differences between the three model realizations are minor at each site, and predicted damping factors all exceed 93% (with most exceeding 98%). A significant portion of the damped return flow to the river(s) is due to the damping predicted in the vadose zone (Section 4.4.2). Without the contribution of the vadose zone, damping would be considerably less.

Figure 4-9 shows the results of the Greenbelt post-conservation simulation, where net recharge (R_N) to the model (recharge minus pumping) results in a predicted net river impact (I_N). In this case, post-conservation irrigation recharge is assumed to be zero and (I_N) equals just the Greenbelt pumping[17]. The three predictions of I_N show damping factors ranging from 56% to 93%. Similar damping factors are observed for the pre-conservation simulations of the Greenbelt (**Appendix J**).

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[17] Pumping is expressed in feet per day, and can be multiplied by the area of the farm to obtain values in af/day.

4.4.4 Estimation of Retiming Benefit

Retiming benefit for the Block 1 and Block 17 hypothetical sites was estimated based on the difference between: 1) the reduced irrigation diversion from the Columbia River due to reduced deep percolation losses associated with conservation, and 2) the reduced subsurface irrigation return flow reaching the river(s) due to conservation (*Equation 2*). Due to the highly damped nature of predicted return flow to the rivers, the second term (RD_{PRE}) can be approximated by a constant value equal to the average annual irrigation return flow. The first term (DP_{PRE}) is equal to RH2's monthly estimates of deep percolation losses. The tables present monthly values of retiming benefit based on *Equation 2*:

Block 1

(all values in feet)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Irrigation Recharge	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
Return Flow	0.060	0.054	0.060	0.058	0.060	0.058	0.060	0.060	0.058	0.060	0.058	0.060	0.707
Retiming Benefit	-0.060	-0.054	-0.057	-0.035	0.042	0.083	**0.124**	**0.085**	0.023	-0.033	-0.058	-0.060	0.000

Block 17

(all values in feet)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Irrigation Recharge	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
Return Flow	0.055	0.050	0.055	0.053	0.055	0.053	0.055	0.055	0.053	0.055	0.053	0.055	0.649
Retiming Benefit	-0.055	-0.050	-0.052	-0.033	0.039	0.076	**0.114**	**0.078**	0.021	-0.031	-0.053	-0.055	0.000

For the Block 1 site, PGG's analysis estimates retiming benefits during the critical flow months of July and August of 0.124 and 0.085 feet. In addition, RH2 predicts monthly conservation benefits from reduced evaporative losses ("E benefits") of 0.066 and 0.052 feet. Total conservation benefits during the critical period are estimated to be 0.190 feet (July) and 0.137 feet (August).

For the Block 17 site, PGG's analysis suggests retiming benefits during the critical flow months of July and August of 0.114 and 0.078 feet. In addition, RH2 predicts monthly conservation benefits from reduced evaporative losses ("E benefits") of 0.070 and 0.055 feet. Total conservation benefits during the critical period are estimated to be 0.184 feet (July) and 0.133 feet (August).

Retiming benefits for the Greenbelt hypothetical site was estimated based on the difference between pre-conservation and post-conservation model estimates of I_N. **Figure 4-10** shows the calculated difference between the pre-conservation and post-conservation estimates (ΔI_N). In contrast to the Block 1 and Block 17 simulations, the Greenbelt simulations show considerable differences between the three model realizations. PGG has the most confidence in the "calibrated model" realization; which predicts lower values of ΔI_N for the critical flow months of July and August than the "high diffusivity" realization. Average monthly values of ΔI_N for the "calibrated model" realization range from 0.00052 ft/d (July) to 0.00081 ft/d (August). Multiplying by 31 days in each month, associated total monthly values of ΔI_N (0.016 and 0.025 feet) comprise the estimated monthly conservation benefits (disregarding the timing of minor quantities of surface-water runoff[18]). These smaller numbers occur because, for the calibrated model, the predicted impacts of groundwater pumping on the river are damped almost as much as is irrigation recharge. As one moves towards maximum (100%) damping, conservation benefit approaches the annual average savings of the only consumptive portion of the irrigation water budget – evaporation losses.

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[18] RH2 estimates that surface-water runoff comprises about 1% of total application (Section 4.1.2).

4.5 FURTHER CONSIDERATIONS FOR CONSERVATION EFFORTS

Once pilot sites are identified within the study area, the conservation benefit numbers above can be used as a rough estimate of conservation potential. However, more specific estimates of conservation benefits can be generated by considering the exact irrigation application method used at the site, along with site specific estimate of vadose zone conditions, and by using a non-zero estimate of post-conservation irrigation recharge. In addition to estimating conservation benefit from a specific site based on associated *actual* irrigation methods, consideration of typical cropping patterns may also be desirable. The conservation benefits above are based on estimates of total application (streamflow diversion) assuming study-area average crop types. Conservation benefit will be sensitive to the monthly distribution of irrigation requirement for particular crops. Some consideration is required to address how to best select "representative" cropping assumptions for estimating site-based conservation benefits.

PGG's model is considered to provide good estimates of subsurface return flow timing over most of the model domain. Several areas of the domain, however, include stratigraphic complexity that could not be represented based on the level of detail associated with the GWMA stratigraphic model. For example, PGG notes the occurrence of perched or highly heterogeneous aquifer conditions near the contact between the Quaternary Province and Upper Ringold Province (e.g. near the Esquatzel Diversion canal and within the Esquatzel Coulee). Similar aquifer heterogeneities may also extend into the Block 17 area northeast of the hypothetical site considered in this study.

In addition to stratigraphic complexities, groundwater/surface-water interactions along reaches of the Esquatzel Coulee wasteway may be locally complex, and such local complexities may influence actual return flow timing for sites near these features beyond the current predictive capability of the model. If pilot sites are to be investigated in these areas, additional local hydrogeologic characterization and refinements to PGG's models may be required.

Conservation benefits estimated for the Greenbelt hypothetical site were much lower than conservation benefits estimated for the surface-water sourced sites. Despite this lower return on conservation efforts, pilot sites *could* be pursued in the Greenbelt. If pilot sites are identified, along with adjusting the analysis presented above to *actual site-specific* current and post-conservation irrigation water budgets, we recommend that the role of surface-water runoff be explicitly considered. PGG's analysis disregarded surface-water runoff because it is a small portion of the irrigation water budget and because its actual fate is unknown. It may runoff from the irrigated field into a pond, where it could infiltrate and recharge the groundwater system or be directed to another field and be lost to evaporation. Thus, consideration of surface-water runoff becomes highly site specific.

Based on PGG's evaluation of retiming potential in the Upper Ringold and Basalt provinces (Section 4.3), it can be reasonably inferred that if pilot sites are to be pursued in the Upper Ringold Province, significant additional hydrogeologic characterization and model development would likely be required. Assessment of retiming benefits for sites in the southern Basalt Province may be possible based on the Quaternary Province model; however, estimates of retiming from the northern Basalt Province are more complex and not supported by currently available hydrogeologic characterization.

5.0 WALLA WALLA BASIN

The Walla Walla basin covers approximately 1,760 square miles in Oregon and Washington, with the Walla Walla River tributary to the Columbia River. The basin was initially chosen as a study area by the FCD/IWG because significant opportunities exist for increasing irrigation efficiency at multiple sites, a large portion of irrigators employ surface-water sources, and existing water rights are not part of the Columbia Basin Irrigation Project (i.e. transfers to Ecology's Trust Water Right Program are possible). RH2 estimates as much 39,000 af/yr of conservation potential (28,000 af/yr of irrigation recharge subject to retiming). However, subsequent evaluation of irrigation practices by WSCC staff indicates that many farmers employ a mix of surface-water and groundwater sources, and that irrigation is commonly applied over longer periods than a typical 7-month irrigation season. Both of these practices tend to reduce the potential for retiming benefit, thus significantly reducing the number of farms suited for conservation under the goals of this project. In addition, although hydrogeologic conditions are regionally well defined, the hydrogeologic framework can be locally complex and surface-water occurrence and routing can also be highly complex.

WSCC staff expended considerable effort to identify potential pilot project sites in the Walla Walla basin (Washington). Conditions for sites to be considered favorable for retiming included: 1) irrigation fully sourced by surface water, and 2) irrigated fields located at least a mile from the Walla Walla River *or* at a land-surface elevation significantly higher than the river (such that a thick vadose zone is expected between the land surface and the water table). The second condition is needed to provide reasonable potential for retiming of subsurface irrigation return flow. Because most farms relying exclusively on surface water are located close to the river, WSCC ultimately focused their search on the higher-elevation "Gardena Terrace", located south of the river in the eastern basin. The Gardena Terrace is close to the river; however, it provides a significant thickness of vadose zone with considerable silt content. Two sites were originally identified; however, one site later became unavailable – leaving a single site to provide "proof of concept" that retiming can be beneficial at a near-river location if vadose-zone conditions are favorable and in a tributary watershed to the Columbia River. Given the overall lack of acceptable candidate sites identified by WSCC, the Walla Walla basin appears to have relatively low potential for significant retiming benefit from irrigation conservation - although other conservation benefits may apply.

Deep percolation losses (recharge) from irrigation were estimated by RH2. PGG analyzed retiming of the seasonal irrigation recharge "pulse" through both the vadose zone and the saturated (groundwater) flow system, expressed as a change in timing of groundwater discharge to the Walla Walla River. PGG's modeling addresses hydrogeologic uncertainty and provides families of "retiming curves" that demonstrate a reasonable range of retiming predictions. The curves suggest considerable retiming, which provides "proof of concept" for retiming benefits under these (and similar) conditions.

5.1 IRRIGATION ANALYSIS

The Walla Walla study area comprises lands both north and south of the Walla Walla River between Walla Walla and Touchet in southern Walla Walla County. The study area comprises of approximately 36,700 acres of irrigated crop lands, as shown in **Figure 5-1**. The crop types grown in the study area include wheat, alfalfa, alfalfa seed, grass hay and other irrigated crops. The following irrigation analysis was performed for the entire study area; however, conclusions of this analysis are applicable to the proposed pilot conservation site.

5.1.1 Information Sources

Analysis of the irrigation practices, estimates of conservation potential and surface return flow pathways for the Walla Walla study area included review of crop and irrigation type data GIS mapping, water application data and other technical information. GIS data were supplied by Franklin Conservation District (FCD) which included historical crop type and irrigation data obtained from the Washington State Department of Agriculture (WSDA). Crop data, irrigation method data and water use data was provided by FCD for the 2009 crop year and was used in estimating current practices and water use for the Study area. Irrigation Water Management (IWM) values were obtained from the *"Columbia Basin Ground Water Management Area 2005".* Literature references and technical data used to develop the memorandums included as appendices to this memorandum include: *State of Washington Irrigation Guide: Appendix A, Climatic Stations for Consumptive Use* (USDA *1985), AgriMet Data(USBR* 1988-1994), *Irrigation Efficiency, (*Howell, Terry A., 2003), *Irrigation System Analysis for the US Army Corp of Engineers,* (HDR 2004), *Walla Walla Watershed Report,* (US Army Corps of Engineers, 2002).

Technical memorandums prepared by RH2 Engineering to support the potential irrigation conservation, surface irrigation losses, and travel time estimates presented in this memorandum include: *study area Water Use – Current Practices and Conservation Potential, (*Appendix A), *Estimates of Irrigation Surface Losses,(*Appendix B)*, Estimate of Particle Travel Times, (* Appendix C).

5.1.2 Current Practices and Water Use

Irrigation water for the Walla Walla study area is pumped from either wells or surface diversions located along the Walla Walla River. While the role of groundwater is considered to be significant (particularly during periods of low river flow), previous estimates of 60 percent groundwater use (James et al, 1991) are likely too high (PGG, 1995). A significant number of farmers alternate between surface-water sources (during times of available streamflow) and groundwater sources (as needed). Surface-water scarcity also leads some farmers to extend their irrigation season (e.g. 8 to 10 months) to make use of seasonally available flows.

The predominant irrigation method used in the study area is sprinkler hand lines/solid set systems, which account for approximately 74 percent of the total irrigated acreage. Other irrigation methods include sprinkler wheel lines which account for approximately 14 percent and center pivot/drip systems account for approximately 9 percent of the remainder of the irrigated acreage within the study area.

Estimates of the total irrigation requirement for the study area have been made based on the acreages for the various crop types which are summarized in a RH2 Engineering memorandum, "Study Area Water Use - Current Practices and Conservation Potential" in Appendix A, Tables 1(c), 2(c), 3(c). These three tables show that the combined weighted average irrigation efficiency (WAIE) for the Study Area using 2009 crop data (current condition) is approximately 76 percent. Using WAIE, it is estimated that the total irrigation requirement for the study area is approximately 114,100 acre-feet during the irrigation season. Of this value, approximately 86,400 acre-feet are estimated for the crop irrigation requirement. The difference between the two values totals approximately 27,700 acre-feet and is the volume of water that is lost to mechanical inefficiencies associated with the irrigation system. Losses resulting from these mechanical inefficiencies area divided into three pathways which are comprised of evaporation, surface runoff and deep percolation.

Over an idealized irrigation season (March 15 through October 15), the months of June, July and August account for a largest percentage of the total application volume in the study area. Approximately 68% of the WIG crop water requirement occurs in these three months. This totals to approximately 77,000 acre-feet of irrigation water. A breakdown of the monthly irrigation requirement and associated losses for the study area is shown below with the break-down of losses discussed in the next section.

Current Weighted Average Irrigation Method & Crop Distribution – w/o Conservation & IWM

(all values in feet)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Crop Requirement	0.000	0.000	0.007	0.088	0.369	0.549	0.617	0.434	0.262	0.039	0.000	0.000	2.36
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	0.09
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	0.32
Application Inefficiency Deep Percolation	0.000	0.000	0.001	0.013	0.054	0.081	0.091	0.064	0.039	0.006	0.000	0.000	0.35
Over Application Deep Percolation (1)	0.000	0.000	0.001	0.015	0.064	0.095	0.107	0.075	0.045	0.007	0.000	0.000	0.41
Total Application	0.00	0.00	0.01	0.12	0.49	0.72	0.82	0.57	0.35	0.05	0.00	0.00	3.12

(1) This loss value is included in the crop requirement and therefore not added separately to the total application. See **Appendix A** for discussion of IWM.

Additional deep percolation losses (shown as "Over Application Deep Percolation" above) are associated with the intrinsic management and safety factors associated with current irrigation practices. Current research estimates that irrigation requirements can be reduced by 17.31% with intensive Irrigation Water Management (IWM) techniques. Currently this water is lost to deep percolation and totals approximately 15,000 acre-feet.

It is important to note that the above estimates are based on the assumption that thirty five percent of the center pivot irrigation systems are using LEPA sprinkler heads. Actual irrigated acreage using center pivot systems with LEPA was not available from the WSDA. Values used in the development of the crop irrigation requirement and average irrigation efficiencies along with the assumptions used in analyzing the current irrigation practices for various types of irrigation methods are reported in **Exhibit A.**

The proposed pilot site primarily employs hand line irrigation, which has a very similar irrigation efficiency as the basin average (75 percent vs. 76 percent) along with a very similar loss pathway distribution.

5.1.3 Irrigation Loss Estimates

An estimate of irrigation losses associated with evaporation, surface-water runoff and deep percolation has been developed for the study area based on a review of the literature from prior irrigation studies (see Appendix B). Both evaporation losses and surface losses are attributed to mechanical inefficiencies that are associated with the currently implemented irrigation equipment. Deep percolation losses are expressed as two terms: the first attributed to mechanical inefficiencies associated with the application method and the second attributed to crop over application associated with current irrigation practices. Implementation of IWM practices can reduce the apparent crop water need and thus reduce deep percolation. RH2's analysis indicates that adapting IWM practices presents the greatest potential for water conservation (Appendix B). Using the loss estimates presented in Appendix B, a summary of the various loss volumes and pathways is presented below.

Irrigation Loss Estimates for the Walla Walla Study Area

Type of Loss	Annual Loss (Acre-Feet)	Percent of Total Loss
Evaporative	11,600	27%
Surface Flow	3,300	8%
Application Inefficiency Deep Percolation	12,800	30%
Pre-IWM Over Application Deep Percolation	15,000	35%
Total:	42,700	100%

According to FCD, it is not known if there are drains located in the study area. However, there are several small creeks and drainage courses that act as natural drains for the area. Depending on the soil moisture content and time of year, it is assumed that the majority of the surface runoff is collected by these surface features and returns back to the Walla Walla River.

5.1.4 Timing of Surface Water Return Flows and Source Water Left Instream

Estimates of the timing of surface runoff return flow to the Walla Walla River have been made based on the general topography of the study area and time of concentration calculations. Given that the farthest point from the Walla Walla River in the study area is approximately 4 miles away, it is assumed that the travel time for surface return flows is approximately one to two days. However, it should be noted that should the surface water infiltrate into the subsurface prior to entering the River, the travel time could increase significantly depending on the subsurface soil conditions and soil moisture content.

Travel time for source water left in the Walla Walla River was estimated based on United States Geological Survey (USGS) streamflow data for the Walla Walla River. Assuming an average velocity of water in the Columbia River of 1.0 feet per second, then the travel time for any source water left in the River at the east end of the study area to the west end is in the order of magnitude of two to three days.

5.1.5 Conservation Potential and Return Flow Distribution

Since the majority of the irrigation systems in the Walla Walla study area are sprinkler and wheel line irrigation systems, the conversion of all mechanical systems to center pivot systems with LEPA including the implementation of IWM is the greatest overall change that could be made to increase the conservation potential of the existing irrigation systems within the study area. It is estimated that these changes could result in saving of up to 39,000 acre-feet annually.

Only converting the existing mechanical systems to center pivot systems with LEPA could result in a potential conservation savings of up to 23,000 acre-feet annually, if the existing irrigation systems within the study area were upgraded with these improvements.

No estimates of irrigation systems employing irrigation water management (IWM) are available for the study area. However, RH2 has estimated that of only IWM were employed by all existing irrigation systems within the study area, the conservation potential could be approximately 20,000 acre-feet annually[19].

See Table 3(c) in Appendix A for estimates of potential irrigation savings for other types of irrigation systems within the study area. It is important to note that this range of potential conservation savings is based on overall estimates of the types of irrigation systems located within the study area.

Based on the literature review of irrigation surface losses presented in Appendix B, it is assumed that the addition of center pivot systems with LEPA or other high-efficiency irrigation methods (e.g. drip) will result in irrigation efficiencies in the 88 to 95 percent range (as compared to a current weighted average irrigation efficiency of 76 percent). Switching to these high-efficiency irrigation systems will result in reduced surface and deep percolation losses. With the implementation of both mechanical upgrades and IWM, it is projected that both surface runoff and deep percolation losses could decrease to zero under ideal conditions. This leaves evaporation as the only remaining loss pathway. This is considered the full conservation potential for the study area and results in the greatest savings of water for use in retiming.

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[19] This number includes reduction in WIG related losses and associated reductions in application (mechanical) losses due to reduced overall application.

This estimate is based on a simplifying assumption that post-conservation deep percolation losses are reduced to zero (the *theoretical* maximum reduction in deep percolation). RH2 recognizes that a small amount of deep percolation will continue (and is needed to prevent salt buildup in the soil); however, actual residual rates of deep percolation will depend on final post-conservation irrigation methods and will have little effect on the estimates above.

It is important to recognize that this is the theoretical maximum conservation potential that could be obtained under ideal conditions. The table below summarizes RH2's estimates assuming maximum conservation.

Conservation Estimates for the Walla Walla Study Area

Type of Loss	Current Loss (af/yr)	Estimated Loss with Full Conservation (af/yr)	Estimated Conservation Savings (af/yr)	Percent Reduction
Evaporative	11,600	3,600	8,000	68%
Surface Flow	3,300	0	3,300	100%
Total Deep Percolation	27,800	0	27,800	100%
Total:	42,600	3,600	39,000	91%

The following table presents RH2's monthly estimates of irrigation losses under current conditions (study-area averages) and post-conservation (maximum conservation). These estimates were used as input for modeling subsurface irrigation return flow later in this section.

Summary of Monthly Irrigation Loss Pathways for the Walla Walla Study Area

(acre-feet/acre)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Current Condition													
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	0.09
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	0.32
Deep Percolation	0.000	0.000	0.002	0.028	0.114	0.176	0.198	0.139	0.084	0.013	0.000	0.000	0.75
Total Losses	0.00	0.00	0.00	0.04	0.18	0.27	0.31	0.21	0.13	0.02	0.00	0.00	1.16
Maximum Conservation													
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	0.00
Evaporation	0.000	0.000	0.000	0.004	0.016	0.024	0.027	0.019	0.011	0.002	0.000	0.000	0.10
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	0.0
Total Losses	0.00	0.00	0.00	0.00	0.02	0.02	0.03	0.02	0.01	0.00	0.00	0.00	0.10

1 – Values based on weighted average irrigation method and crop distribution for the Study Area

As discussed above, post-conservation deep percolation is represented as the maximum *theoretical* conservation potential, and a small amount of deep percolation is expected for any post-conservation condition. Post-conservation deep percolation should be included during (future) individual analyses of pilot sites. For the current analysis, the effect on estimating reduction in total deep percolation (0.75 ft/yr) is small.

It is important to note that the estimates of potential conservation savings for this study area are based on WSDA datasets of both the crop distribution and irrigation system type as provided by the Franklin County Conservation District. These data are not linked, i.e.; it is not specifically known how much of each crop is irrigated by a specific irrigation method. As a result the estimates are based on a geographic distribution for the entire study area but are not crop or field specific. Therefore, while the analyses of the irrigation practices and conservation potential provides a good understanding of the entire study area, it is not recommended that this analytical approach be assumed accurate to a given individual farm or a specific small geographical area. Furthermore, this estimated conservation savings has not been differentiated between groundwater, surface-water and mixed sources. As described in Section 5.4.3, groundwater and mixed sources are more common than purely surface-water sources, and provide significantly less potential for increasing water availability during the “critical period” of the irrigation season (July and August for the Columbia River) based on retiming from conservation.

Both the crop irrigation requirement and irrigation efficiencies used are based on best available information but, as previously noted, the dataset is limited to general categories of both crops and irrigation types. Irrigation loss estimates are based on the assumption that thirty five percent of the center pivot acreage employs LEPA. The dataset does not indicate how much of the acreage in each of the study areas are already employing IWM. RH2’s estimates of total conservation potential will be sensitive to these assumptions and could differ to varying degrees if actual conditions depart significantly from these assumptions..

A detailed discussion of the assumptions used in developing the conservation potential for the various types of mechanical upgrades including the addition of IWM and the results of this analysis for the study area is summarized in **Appendix A**.

5.2 HYDROGEOLOGIC CONDITIONS

The saturated groundwater flow system underlying the irrigated portion of the Walla Walla Basin consists of unconsolidated deposits (recent alluvium and underlying gravel and clay units) set within a structural basin of Columbia River Basalts. Hydrogeologic conditions are fairly well defined on the regional scale, but can be locally complex due to abrupt vertical and lateral transitions between units. Surface-water occurrence (in streams and ditches) and surface-water interactions with groundwater are not as well defined and can be highly complex, with significant influence of irrigation operations. Streams (and a number of ditches) exhibit both losing and gaining reaches, which can vary geographically and temporally due to irrigation operations and other hydrologic factors. The “typical hydrograph” of the Walla Walla River changed significantly in 2000 when three irrigation districts[20] began leaving a minimum flow in the river within reaches previously dry during summer months. Despite recent efforts to characterize the groundwater and surface-water systems, significant data gaps remain and are (partially) being addressed through current monitoring.

This section provides an overview of hydrogeologic and hydrologic conditions in the Walla Walla Basin along with associated data gaps, and provides a more detailed description of conditions associated with the Gardena Terrace “focus area”.

5.2.1 Information Sources

Early-on in this project, PGG reviewed available data in order to formulate a modeling strategy that considers system complexity and available data. Along with literature review, PGG performed field reconnaissance to familiarize ourselves with hydrogeologic/hydrologic conditions, and has communicated with staff from the WSCC, Walla Walla Conservation District (WWCD), Walla Walla Basin Watershed Council (WWBWC), and Aristides Petrides (an Oregon State University PhD candidate modeling hydrogeologic conditions over much of the basin).

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[20] Hudson Bay District Improvement Company (OR), Walla Walla River Irrigation District (OR), and Gardena Farms irrigation District #13 (WA) *together* left 32 cfs in the river in 2001 and 43 cfs in the river in 2002.

Basin-wide hydrogeologic conditions were described by Newcomb (1965) and GSI (2007a), and a digital 3D stratigraphic model was developed by GSI and the GWMA for WWBWC. Local hydrogeologic conditions at aquifer recharge sites are described by GSI (2007b) and Bower & GSI, (2010). Documentation of rigorous aquifer testing is limited to tests performed at the Hudson Bay District Irrigation Company recharge facility by Petrides (2010a), although aquifer properties were estimated basin-wide from specific capacity data (Barker & Mac Nish, 1976). Groundwater level monitoring data were reported by WWBWC (2010), Golder (2007), and are found online in the USGS NWIS database. Groundwater level contour maps were prepared by Newcomb (ibid), Golder (ibid), WWBWC (2010b) and Petrides (pers. comm.., 2011). Groundwater pumping was summarized by Newcomb (1965), Pacific Groundwater Group and NHC (1995, including references to various researchers), Wozniak (2007), and was estimated over a portion of the basin by Petrides (in press). Groundwater recharge from precipitation was estimated for the entire Columbia Plateau regional aquifer system by Bauer & Vaccarro (1990), and combined irrigation and precipitation recharge was estimated by Newcomb (ibid) and Petrides for a portion of the basin (in press).

Surface-water drainage has been described by Newcomb (1965). WWBWC has GIS coverage of the ditches and streams, has monitored streamflow and spring discharge (WWBWC, 2009a) and has performed seepage surveys (WWBWC, 2009b). Streamflow data are also available online from the USGS. Groundwater/surface-water interactions along the Walla Walla River have been assessed by WWBWC (2002 *Draft*), Stejskal (2003 *Draft*), and Ecology (2005). Seepage to/from irrigation ditches was evaluated by Barker & Mac Nish (1976), HDR (2004), and Petrides (pers. comm.., 2011).

Groundwater flow models have been developed for the gravel aquifer (Barker & Mac Nish, 1976), the basalt aquifer (Mac Nish and Barker, 1976) and for both aquifers with emphasis on the basalt (Golder, 2007). Petrides first developed a local-scale model of the gravel aquifer in the HBDIC vicinity (2008), and has recently completed a sub-basin model of the gravel aquifer, alluvial aquifer and overlying vadose zone for the portion of the basin upstream of Touchet and south of the Walla Walla River using the "Integrated Water Flow Model" (IWFM) computer code (California Department of Water Resources, 2011) and based on GSI/GWMA 3-D stratigraphic model (Petrides, in press).

5.2.2 Surficial Geology and Hydrostratigraphic Units

The surficial geology of the basin is presented on **Figure 5-2**, and includes a number of unconsolidated sediments (recent alluvium, older alluvium, Palouse loess deposits, younger loess deposits, terraces composed of reworked loess, and fine-to-medium grained Pleistocene flood deposits called "Touchet Beds"). The latter two units generally occur above the regional water table, and are therefore more relevant to vadose zone flow than groundwater flow. The unconsolidated sediments are enclosed within a structural basin of Columbia River Basalt that is exposed along the edges of the watershed. The total thickness of the suprabasalt sediments reaches as much as 800 feet (GSI, 2007a).

GSI developed structure-contour maps for the stratigraphic contacts between five major sedimentary units overlying the basalt ("suprabasalt sediments"), including Quaternary fine and coarse units, a Mio-Pliocene coarse unit (Newcomb's "Old Gravel"), a Mio-Pliocene fine unit (Newcomb's "Old Clay"), and a Mio-Pliocene basal coarse unit which has a discontinuous occurrence directly overlying the Columbia River Basalts (CRB's) GSI identified faults and folds within the underlying CRB's that seem to project upward into the overlying suprabasalt sediments, and note that the uppermost basalt immediately underlying the suprabasalt sediments varies between at least three different basalt units.

The Quaternary fine (QF) unit is the uppermost suprabasalt unit in the basin. It includes loess, Touchet Beds, and fine-grained alluvium, but is absent in spots along the Walla Walla River and where the river comes down from the foothills of the Blue Mountains onto the valley bottom. The Quaternary coarse (QC) unit typically underlies the Quaternary fine unit, but its deposition may be contemporaneous with the fine unit and some interfingering may occur. The coarse unit is absent in areas where stream channels have not occurred, and can therefore be discontinuous across the valley. In general, the Quaternary deposits become siltier in the central and western portions of the basin, where they sometimes consist of reworked Touchet Beds and loess.

The Mio-Pliocene units underlie the Quaternary units. The Mio-Pliocene coarse (MPC) unit generally overlies the fine unit, although the two may exhibit some interfingering due to contemporaneous deposition (e.g. streambed and overbank deposits). The upper coarse unit consists of well consolidated gravel in a sand and silt matrix. Cleaner gravel and sand portions are found in the southern and eastern basin in the alluvial fans of the Walla Walla River and Mill Creek. The unit is thickest and most widespread in the eastern portion of the basin, and grades to higher clay content to the west (i.e. interlayering with fine-grained sediments). Newcomb (1965) notes that:

> "…the gravel extends in narrow trains downvalley along the southern side of the basin, and apparently thickens and widens in places beneath the area south of Gardena School. Along the northern side of the lower part of the valley the gravel largely terminates upstream from Lowden, where wells penetrate only a few layers of sand and fine gravel interbedded with silt and clay… Downvalley from the common western limits of the main stratum of the old gravel, some coarse sand and fine gravel are penetrated by wells in the Mud Creek and Pine Creek areas as well as beneath the Gardena Terrace itself. Those sand and gravel layers are largely interstatified with finer materials, in which respect they contrast with the continuous thicknesses of old gravel that occur beneath areas farther upstream."

Structural controls (folding and faulting) may affect the thickness of this unit in places. GSI (2007) report east-west oriented trends of high and low elevations beneath the western half of the basin.

The Mio-Pliocene fine (MPF) unit is a weakly indurated claystone and siltstone, containing interstratified sand and gravels. It is thickest in the northeast, north, central and western portions of the basin, where it can range between 300 and 500 feet thick. The basal coarse unit is laterally discontinuous, ranges in observed thickness to up to around 80 feet, and could be more widespread than currently interpreted by GSI based on limited information.

CRB's underlie the suprabasalt sediments described above. Folds and faults affect the occurrence of basalt outcrops and subcrops, with at least three units constituting the "uppermost basalt" within the study area. GSI describes the distribution of uppermost basalt as follows:

- *"Beneath the eastern basin a previously unidentified basalt unit, informally designated the Walla Walla member of the Saddle Mountains Basalt, is the uppermost basalt unit;*
- *To the west, the uppermost basalt unit beneath the suprabasalt sediments is the older Ice Harbor member of the Saddle Mountains Basalt;*
- *On the highlands surrounding the basin, where the suprabasalt sediments are generally thin or are absent, the much older Frenchman Springs member of the Wanapum Basalt is the uppermost basalt unit."*

GSI further notes that *"Given these observations, basalt flow pinch outs beneath the suprabasalt sediment sequence provide potential hydrologic connections between portions of the uppermost basalt aquifer system and the alluvial aquifer system. Interconnections also may be provided by at least some of the faults* *mapped".* However, it should be noted that where significant thicknesses of undisturbed (i.e. unfaulted) Mio-Pliocene fine unit separate the overlying upper gravel unit from the basalt, groundwater transfer is not expected to be significant between the two units. Petrides (pers. com., 2010) notes that areas occur in the eastern basin near Milton Freewater where the upper coarse unit directly overlies the CRB's, and a hydraulic connection is likely under these conditions. However, subsequent conversations between PGG, GSI and Petrides suggest that while local interchanges between the alluvial aquifer and the CRB's may occur, they are unlikely to transmit significant quantities of water through the CRB's to the Columbia and Snake rivers. Lateral flow in the CRB is expected to be limited by low-permeability boundaries (e.g. faults, pinchouts) which form semi-isolated "cells" within the basalt (Lindsey, 2010).

5.2.3 Vadose Zone

Irrigation recharge travels through the vadose zone from the land surface to the water table. Irrigated areas predominantly occur on outcrops of Quaternary stream alluvium and Touchet Beds. Exposures of Touchet Beds commonly occur as hills and terraces, and therefore exhibit greater depths to groundwater beneath the land surface.

The texture of the vadose zone affects the transmission timing for irrigation recharge to reach the water table from the land surface. Touchet beds are moderately fine-grained – typically composed of layered silt and fine sand in their upper portions. This texture, together with greater depths to water, imparts significant time lag and damping to subsurface irrigation return flow through the vadose zone. The texture of Quaternary alluvium varies from extensive fine-grained deposits to slightly less extensive coarse-grained deposits. Sediments are typically coarser along major streams, and combined with the shallower water tables, are likely to provide faster vadose-zone transmission to the water table.

Much of the alluvial areas are irrigated, however irrigation atop the Touchet Beds is generally limited to areas with nearby canals. Upon the Gardena Terrace, the Burlingame Ditch delivers water to higher elevation fields which overlie the Touchet Beds. North of the Walla Walla River, many areas occupied by the Touchet Beds are not irrigated.

PGG characterized the thickness and texture of the vadose zone beneath the Gardena Terrace, with specific emphasis on conditions near the proposed pilot site. As the relatively fine-grained Touchet Beds are of particular importance to retiming in the vadose zone, the following Touchet Bed descriptions are excerpted from various reports.

Newcomb (1965) describes the Touchet Beds as a deposit of horizontally bedded silt and fine sand, marked by distinctive gravel, cobble and boulder inclusions and by peculiar structural features. He reports thicknesses in excess of 100 feet beneath the terrace lands in the lower part of the Walla Walla Valley, and a maximum depositional elevation of 1,150 feet. Composition is reported as principally light-gray silt and very fine sand with some clay, diatomaceous earth, and volcanic ash. In the lower parts of the deposits, considerable sand and a little interbedded gravel are noted. The water table is noted to occur at or near river level both beneath the Gardena Terrace and the equivalent terrace northeast of the town of Touchet. Newcomb notes that horizontal laminations within the Touchet Beds can cause lateral flow to seeps which are indicated by mineral incrustations from evaporation.

Spencer (1989) performed a detailed analysis of the texture and depositional environment of the Touchet Beds, comparing differences in texture beneath the Gardena Terrace (exposed in the Burlingame Canyon) to conditions across the river along the Touchet River. He describes the Touchet Beds as a "distinctive sequence of graded rhythmites laid down as water backed up behind a hydraulic dam at Wallula Gap, the only outlet for water entering the region". In the Burlingame Canyon, as many as 40 rhythmites are exposed which display well-developed graded bedding within each rhythmite, with the basal sand giving way upward to silt representing standing water, and in some cases, a thin veneer of massive silt capping the rhythmite. Spenser characterizes means and standard deviations of grain size for samples representing the base, middle, and top of rhythmites. Personal communication with Spencer indicates that rhythmites typically range from about 0.3 to slightly over 1 meter in thickness (Spencer, 2011). Additional summary of Spencer's Touchet Bed texture analysis is provided in **Appendix K**.

PGG reviewed Department of Ecology well logs to evaluate the thickness of the uppermost fine-grained unit beneath the Gardena Terrace. Both the thickness of fine-grained Touchet Beds and the depth to groundwater were reviewed for each well log, and the results plotted over a thickness map of the QF sediments from the GSI stratigraphic model. **Figure 5-3** shows generally good agreement between PGG's well log interpretation and the GSI model, and reveals areas where groundwater occurred within 25 feet of land surface[21]. Most of these groundwater depths are historic (measured at time of well drilling), and in some cases may reflect nearby leakage from irrigation canals.

In the immediate vicinity of the proposed pilot site, PGG evaluated vadose zone conditions in 6 nearby wells, as shown on **Figure 5-4** and summarized below.

Well ID	Aziumuth/ Distance (miles)	Depth to Bottom of Touchet Beds (ft)	Depth to Groundwater (ft)	Thickness of Unsaturated Coarser Sediments (ft)
F	N / 0.4	26	18.4	n/a
A	S / < 0.5*	27	60	33
B	SE / < 0.5*	43	65	22
C	SE / < 0.5*	27	80	53
D	SE / 0.5	32	60	28
E	SE / 0.5	20	77	57

* Well location based on quarter-quarter section in drillers log and may be inaccurate.

Observed Touchet Bed thicknesses range from 20 to 43 feet. The water table occurs beneath the bottom of the Touchet Beds in all wells except Well "F", which occurs in the bottom of the Walla Walla Valley. The well logs also show unsaturated sediments beneath the Touchet Beds, with textures ranging from clean gravel to sandy gravel to silty gravel to sand. Based on consideration of thickness of Touchet Beds and depth to groundwater, between 22 and 57 feet of these coarser sediments are noted in the wells listed above. Consideration of groundwater elevations shows about 40 feet of head difference between Well "D" and the river, with flow interpreted towards the river and a depth-to-water beneath the site interpreted to be around 50 to 60 feet below ground surface (**Figure 5-4**).

5.2.4 Aquifer Recharge and Discharge

Recharge to groundwater occurs from natural precipitation (rain and snow), seepage from streams and irrigation conveyances, and deep percolation (beyond the root zone) of irrigation water applied to fields. Bauer and Vaccarro (1990) estimated pre-development and post-development (1956-1977) recharge for the entire Columbia Plateau regional aquifer system using the Deep Percolation Model (DPM, Bauer and Vaccarro, 1987). Their estimates included recharge from precipitation and irrigation (canals, ditches and fields); recharge associated with stream seepage was not estimated. Their estimates report recharge generated at the land surface, and do not address the timing for delivery of this recharge to the water table. Whereas estimated recharge rates rarely exceed 2 in/yr under pre-development conditions, irrigation ac-

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[21] Groundwater depth was interpreted as first water encountered during drilling or depth to water in the completed well, depending on data availability.

tivities locally increase estimated recharge to over 10 in/yr. Although the DPM was used to estimate daily recharge over a 22-year period, existing documentation reports only average annual recharge values for this time period. Furthermore, although recharge was estimated at a finer resolution, the report summarizes recharge based on cell delineations used in the USGS RASA modeling, approximately 2 minutes longitude by 2.5 minutes latitude (about 8,500 by 15,200 ft). Overall, available documentation of DPM recharge estimates has fairly poor spatial and temporal resolution, with some loss of accuracy from the original calculations.

Petrides estimated daily values of groundwater recharge from 2007 to 2009 based on a soil moisture balance calculated within his IWFM model. The model considers climatic conditions, soil textures, precipitation and irrigation applications, crop types and plant water requirements to estimate runoff, evapotranspiration, and recharge. IWFM also employs a simplified ("kinematic wave") routine based on soil moisture content and saturated hydraulic conductivity to approximate the timing for recharge generated at the land surface to arrive at the water table; however, Petrides did not calibrate his basin-scale model to the timing of recharge in the vadose zone. Petrides' recharge estimates do not include recharge from surface-water conveyances, which he modeled explicitly with the ability to leak and interact with groundwater.

RH2 developed a basin-wide estimate of average irrigation recharge (deep percolation) of 0.76 feet (9 inches) over the course of the irrigation season (Section 5.1).

Irrigation conveyances (canals, ditches) are generally thought to be losing water via leakage, and leakage rates have been measured for some reaches. However some ditch reaches actually *gain* flow from groundwater (Petrides, pers com, 2010). The hydrology of irrigation conveyances is further discussed below. Streams also exhibit losing and gaining reaches, with most of the losses occurring in the upper elevations of the watershed and gains in the lower elevations. Patterns of stream leakage/gain are also discussed below in the "streams" section.

Groundwater discharge occurs via pumping, seepage into surface-water features, and evapotranspiration (where the water table approaches the land surface). Pumping and surface-water discharge are discussed below.

5.2.5 Groundwater Pumping

Land within the Walla Walla basin has been under cultivation since the 1850's, with shallow dug wells (in the gravel aquifer) and surface water originally supplying most of the irrigation needs. Deep wells tapping basalt aquifers began to appear in the late 1800's and early 1900's, and increased from 50 wells in the mid-1950's to more than 200 wells in 1971 (Mac Nish et al., 1973). Gravel aquifer wells were limited to shallow (<50 feet), large diameter (~5 feet) dug wells through the early 1940's, after which time drilled wells led to a sharp increase in pumping through the early 1970's. The following text is excerpted from PGG's Initial Watershed Assessment of the Walla Walla basin (PGG, 1995).

> Ground water withdrawals in the Walla Walla WRIA are not well documented or quantified, especially for the gravel aquifer. Metered pumping data are limited to the public water supply systems which typically report pumped volumes once every two months. Irrigation use is typically not metered. Investigators have often relied on indirect methods to obtain ground water pumpage estimates. Power consumption records have been used to estimate pumping volumes based on knowledge of pump type and required lifts. Crop distributions have also been used to estimate agricultural applications based on assumptions of crop requirements. Crop types and acreages are typically determined from Landsat imagery. Estimates of ground water withdrawal are usually oriented to the entire Walla Walla basin, and are often unavailable for the WRIA alone. The following table presents a summary of historical and current ground water pumpage estimates for the gravel and basalt aquifers.

Record Year	Gravel Aquifer Pumpage	Basalt Aquifer Pumpage	Total Pumpage	Reference
Estimates for Entire Walla Walla Basin:				
1958	16,050 af/yr	14,800 af/yr	30,850 af/yr	Newcomb, 1965
1969	25,000 af/yr	27,000 af/yr	52,000 af/yr	Mac Nish et al, 1973
1984	23,210 af/yr	27.290 af/yr	50,500 af/yr	Cline & Knadle, 1990 and Collins, 1987
1989	66,496 af/yr	25,031 af/yr	91,527 af/yr	James et al, 1991
Estimates for Walla Walla WRIA:				
1984	15,560 af/yr	21,940 af/yr	37,500 af/yr	Cline & Knadle, 1990 and Collins, 1987
1989	46,277 af/yr	21,986 af/yr	68,263 af/yr	James et al, 1991

> Estimates of basin-wide pumping from the gravel aquifer appear reasonable for 1958 and 1969, however the disparity between 1984 and 1989 suggests significant error in one of these values. Newcomb (1965) analyzed 2 to 3 years of pumpage data to estimate basin-wide pumpage for both the gravel and basalt aquifer systems. He also estimated utilization from springflow from the gravel aquifer to be 30,450 acre-ft/yr. Mac Nish et al (1973) used electrical records and measured pumping lifts in estimating basin-wide pumpage. Their work, in general, made extensive use of original field work for baseline characterization. The RASA study (Collins,1987 and Cline & Knadle, 1990) relied heavily on the work by Mac Nish et al (pers. comm., D. Cline, 1992). The RASA study evaluated the geographic distribution of pumping from the gravel aquifer. Figure 3-9 presents the 1984 RASA pumping estimates per ¼ township area, as well as the areal boundary of the gravel aquifer. The 1989 estimate by James et al relied on electrical consumption records from metered pumps obtained from the two main power distributors. Their study divided the basin into 20 “farm regions”, 19 of which comprise the Walla Walla WRIA. Questions remain as to the accuracy of the study, and members of its review committee reportedly had limited confidence in the study’s water use estimates (pers. comm., Bill Neve, 1995). Many pumps were not field checked to determine source of supply, nor were pump lifts measured in the field.
>
> The ground water pumped from the gravel aquifer is used predominantly for irrigation applications. According to Newcomb (1965), 97% of basin-wide gravel aquifer pumpage is used for irrigation, about 2% used for domestic supply, and the rest is divided between public water supply systems and industrial users. More recent investigations have indicated approximately the same distribution of gravel aquifer pumpage among these four categories of use. Mac Nish et al (1973) concluded that all of the gravel aquifer pumpage is for irrigation use, and the RASA study concluded that the majority of gravel aquifer pumping is for irrigation use.

Most recently, Petrides has estimated water use for irrigation over a significant portion of the basin (see Petrides model domain on **Figure 5-2**) based on consideration of water rights, irrigation requirements, streamflow availability, well completions and interviews with irrigators regarding typical reliance on groundwater and surface-water to apportion monthly irrigation use between surface-water, gravel aquifer and basalt aquifer sources. This information has been generalized into average values over sub-regional “pumping domains” in Petrides’ model.

5.2.6 Surface-Water Features

The interrelationships between surface-water features (springs, streams, ditches) are complex in the Walla Walla Basin. Spring discharge typically feeds into streams or irrigation ditches (canals, laterals, etc). Streams are also diverted into irrigation ditches, and receive discharge from ditches.

Streams

Stream reaches within the watershed can exhibit perennial, intermittent, or ephemeral flow depending on source areas, hydrogeologic conditions, and irrigation operations. The major streams supplying the watershed (e.g. North and South Forks of Walla Walla River, Mill Creek) are perennial upstream of irrigation diversions; however, flows are significantly depleted by irrigation diversions. Most other streams draining the lower Blue Mountains slope are non-perennial, with intermittent flows reported over reaches of Pine, Couse, Birch, Cottonwood, Reser, Russel and Dry creeks (Newcomb, 1965).

Groundwater interactions with streams vary between gaining and losing depending on local conditions. Newcomb (1965) described a general pattern of losing and gaining conditions, noting that most mountain-fed streams lose water while crossing the unconsolidated deposits on the upper parts of the valley floor, and then regain flow from groundwater discharge in the middle and lower parts of the alluvial fans. Barker and Mac Nish (1976a) note that stream reaches with elevations over 850 feet msl typically lose water to the aquifer during the entire year, reaches with elevations below 750 feet tend to gain water from the aquifer year-round, and reaches with elevations between 750 and 850 feet msl tend to have variable seasonal groundwater interactions.

USGS streamflow data in the basin are relatively sparse. The USGS is currently gaging at Mill Creek (both upstream and immediately downstream of the Yellowhawk Creek diversion) and the Walla Walla River near Touchet. Relatively long-term continuous data are also available for both North and South Forks of the Walla Walla River upstream of major diversions (although recent data are absent). USGS datasets of various lengths are also available from the Touchet River, Blue Creek and Garrison Creek.

The Walla Walla River exhibits both gaining and losing reaches. During the irrigation season, the river was historically dry over a reach between Milton-Freewater (i.e. below the Little Walla Walla River diversion) and the Washington-Oregon border (WWBWC, 2002). Flow returns to the river via groundwater discharge near the border. Between the 1970’s and the turn of the century, data regarding the occurrence and extent of dry riverbed conditions are largely unavailable. A major change in flow regime occurred in 2000 when three irrigation districts began leaving significant flows[22] in the river, expanding the perennial reach downstream into areas previously dry due to irrigation diversions.

WWBWC have been performing and evaluating seepage runs on the Walla Walla River twice yearly from 2002 through present (WWBWC, 2009c). Their runs generally begin on the north and south forks, and include both manual measurements and data from established gages. During the low-flow season (August), their analysis shows a spatial distribution of 4 gaining and 4 losing reaches (1 undetermined), with a small net seepage loss over the entire studied reach. Most of the seepage occurs in the reach between Mauer Land and the Grove School Bridge (Oregon), whereas a net gain occurs in the Washington reaches. A WWBWC water balance for October 2007 shows both higher diversions, tributary inflows, and a significant net positive seepage gain over the entire studied reach. The difference between these two seasonal “snapshots” likely reflects differences in antecedent and existent distribution of irrigation water, irrigation recharge and groundwater pumping for the entire river. WWBWC also performed seepage surveys on Mill Creek (fall 2008 and spring 2009), the Touchet River (early and late summer, 2009) and the east and west Little Walla Walla River (spring and late summer of 2009).

WWBWC has collected and compiled flow data from small order streams in the watershed since as early as 2002 (WWBWC, 2009). Their monitoring includes sites on the Little Walla Walla (east and west), Mud Creek, Big Spring Branch, Walsh Creek, Johnson Creek, Dugger Creek, Schwartz Creek, Crocket

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[22] About 13 cfs was left in the river in 2000, later increased to between 20 and 30 cfs in order to maintain wet conditions and support fish passage.

System, Ford Branch System, and others. The raw data are maintained in a database, which is currently under revision (QA/QC and import from Microsoft Excel into Access).

Ecology (2005) evaluated surface-water/groundwater exchange in the Walla Walla Watershed, with particular emphasis on the Touchet River and Mill Creek, based on fieldwork performed between July and October 2002. For the Walla Walla River, Ecology notes most of the groundwater inflow appears to occur between the confluence with Mill Creek and the Town of Touchet. While this observation is not substantiated with comparison to other reaches, instream mini-piezometer data from that reach do suggest gaining conditions. The USGS Walla Walla River gage near Touchet (below the confluence of the Touchet River) shows annual summer 7-day minimum streamflows typically ranging from several cfs to around 20 cfs, with no particular trend discernable between 1950 and 2010. Ecology's seepage runs generally showed losing conditions on the Touchet River as the river crosses unconsolidated sediments, losing conditions on Mill Creek between its headwater canyons (where it gains flow from groundwater) to the Yellowhawk Creek diversion, and losing conditions in Yellowhawk Creek through its confluence with the Walla Walla River.

Springs

Springs play a significant role in the hydrology of the basin, showing an estimated 56,000 af/yr of groundwater discharge compared to an estimated 177,000 af/yr groundwater recharge (Barker & Mac Nish, 1976a). Piper et al (1933) developed the first estimate of annual average spring discharge in the early 1930's (about 50,000 af/yr). Newcomb identified two spring zones (inner and outer) associated with the Mill Creek and Walla Walla River alluvial fans, as well other isolated springs. Newcomb cataloged a representative subset of these springs and provided estimates of discharge where available. Barker & Mac Nish (1976a) defined 5 spring zones and estimated approximate annual discharge for each zone. WWBWC has measured GPS locations for 7 selected springs (some spring elevation estimates have been refined by Petrides), and has monitored discharge in 42 surface-water bodies (streams and spring discharge conveyance, 18 in Washington and 24 in Oregon), predominantly since 2008. A published summary of spring/stream monitoring (WWBWC, 2009) only presents a small portion of the data, which are maintained in WWBWC's project database. Long-term spring discharge data and/or analysis of long-term trends are unavailable. Spring discharge is routed to various streams and conveyances, supporting streamflows, irrigation applications (consumptive use and irrigation recharge) and return to the aquifer via seepage losses.

Irrigation Canals and Ditches

Barker and Mac Nish estimated that about 750 linear miles of mostly unlined ditches and canals cross over the gravel aquifer with a total bottom area of around 170 acres. Relative to the lateral dimensions of the gravel aquifer (about 10 by 20 miles), ditches occur at a fairly high density. Barker and Mac Nish postulated that the ditch bottoms are above the water table almost everywhere, and employed various assumptions to estimate monthly patterns of wet/dry ditch conditions over time and associated leakage through the ditch bottoms. They note that ditches and canals can leak at maximum rates of 1.3 ft/d for the first few days of the irrigation season until their bottoms become sealed, and leakage rates reduce to 0.17 ft/d (and 0.26 ft/d for coarser bed materials).

The Barker and Mac Nish estimates are not well documented, and are significantly smaller than estimates developed by HDR (2004) for the Army Corps of Engineers from measurements on canals owned by the Walla Walla Irrigation District (WWRID), the Hudson Bay District Improvement Company (HBDIC) and the Gardena Farms Burlingame Ditch. Based on estimates of ditch loss (cfs/ft) and typical canal widths, the HDR data indicate estimated leakage rates of 0 to 25 ft/d from WWRID reaches, 5 to 75 ft/d from HBDIC reaches, and 2 to 4 ft/d from Burlingame Ditch reaches. The high values on WWRID and

HBDIC ditches may be associated with high permeability soils in the upper portion of the alluvial fan near Milton Freewater. HDR noted some gaining reaches on the WWRID (which were attributed to return flows from upstream flood irrigation) and seepage losses reappearing in lower elevation fields along some HBDIC ditch reaches.

Petrides has also estimated losses and gains on irrigation conveyances within his model area (**Figure 5-2**) based on field measurements at 35 locations collected in July 2007, October 2009 and August 2010. He reports that his estimates are likely more accurate than those made by HDR because they consider diversions occurring at the time of gaging measurements whereas HDR's utilized diversions measured at a different time than their seepage survey (i.e. assumed constant diversions throughout the irrigation season). Petrides resolved his field data to a GIS, in which reaches were defined and seepage loss/gain estimates were stored for the measurement events. Values of seepage loss were usually lower than estimates by HDR, and Petrides noted several gaining reaches, possibly associated with increased water-table height due to recharge from up-gradient unlined irrigation canals and applied excess irrigation. In addition, Petrides developed monthly estimates of gains/losses on conveyances between 2007 and 2009 based on modeling analysis.

5.2.7 Groundwater Levels and Flow Patterns

Groundwater elevations and water-level hydrographs are typically used as model calibration targets. Based on data availability, a model may be calibrated to mapped groundwater elevation "snapshots" and/or to transient (time-varying) groundwater hydrographs. Transient hydrographs may include long-term changes in groundwater elevations associated with development, seasonal water-level variations due to natural and irrigation recharge, or short term aquifer responses to stresses such as pumping or a river flooding event. This section addresses the availability of groundwater level data and its potential application to model calibration.

Groundwater elevation maps are typically constructed based on a "snapshot" of water-level measurements taken at about the same time. If the water-level map is representative of stable groundwater conditions (i.e. the groundwater flow system has fully adjusted to relatively stable hydrologic stresses), these conditions can be used for a steady-state (constant over time) groundwater calibration. In many cases, a nearly stabilized groundwater level distribution is considered appropriate for "quasi-steady state" calibration.

Barker and Mac Nish (1976a) developed a representative water-table map for typical January conditions between 1969 and 1973. The map was used for transient model calibration (over one annual cycle) in a manner that assumes a fairly stabilized water-table condition (similar conditions at the beginning and end of the simulated year). Golder (2007) assembled a set of water-level calibration targets for the gravel aquifer, predominantly based on depths to water on Ecology well logs and reported (quarter-quarter) well locations, but supplemented by data from City of Walla Walla observation wells. Potential errors in well locations and variation in the time of water-level measurement (1940's through 2005) suggest that the Barker and Mac Nish map may provide a more consistent picture of conditions at one single time. However, the individual points used to generate the Barker and Mac Nish map are not preserved in their report, making use of this map more difficult for current model calibration.

Monthly water table elevation snapshots have been prepared by Petrides (2007-2009) and WWBWC (2009-2010). The snapshots are based on shallow aquifer monitoring at sites described in a recent WWBWC (2010) report. Supporting data are relatively sparse north of the Walla Walla River and west of Touchet.

As of 2009, WWBWC's monitoring network included 94 wells (38 in WA, 56 in OR), with continuous dataloggers installed in 56 wells. Most of the monitoring data were collected after 2003, although about a dozen wells have long-term records. Data from the WWBWC network has been used to construct hydrographs and evaluate water-level trends. Long-term (30-80 year) hydrographs are available for 7 "historic wells" in Oregon, of which 6 show decline. WWBWC attributes these declines to increased irrigation efficiency, groundwater extraction for irrigation, and reduced use of ditches associated with leaving water in the Walla Walla River post 2001. Shorter-term trends are available for the remainder of the 94-well network; although some wells have too sparse data for trend analysis and 15 wells have data beginning only in 2009. Seasonal variations observed in some of the shorter-term Oregon wells range from several feet to as much as 60 feet, and are influenced by seasonal variations in both pumping and recharge. Newcomb (1965) presents hydrographs of 8 wells in the gravel aquifer, with records spanning between 1933 and 1959. The hydrographs show greater water-level variations near the apex of the Walla Walla River alluvial fan, and a time lag for the appearance of river-sourced recharge in a down-slope direction.

PGG reviewed the USGS NWIS for groundwater level data in Washington State, hoping to supplement the long-term trends in Oregon with similar data from Washington. Out of 98 wells with more than 6 data points each, only 6 had more than 24 data points. Review of these records shows that most of the data were gathered between 1933 and 1961 (often over smaller intervals within that range) and that available data were typically insufficient to define water-level trends (one well had a 10-foot drop over 15 years). Most of the remaining wells were measured twice annually (or slightly more frequently) between 1970 and 1972. Assuming that these summer/winter measurements account for seasonal water-level variation, it appears that most wells exhibit ≤ 5 feet of fluctuations although some wells show 10 to 20 feet.

5.2.8 Aquifer Properties

Barker and Mac Nish (1976a) estimated the hydraulic conductivity (K) and storage coefficient (S) of the gravel aquifer based on specific capacities (yield divided by drawdown) reported in wells and subsequent model calibration. They report higher K values near the upper alluvial fan altitudes and lower values where the fans broaden and coalesce near the lower, central area of the basin (as expected from sedimentary textures). K values were modified some during model calibration, and showed localized very-high K zones of 134-215 ft/d, broader high-K zones of 67-134 ft/d, extensive moderate-K zones of 13-67 ft/d, and low-K zones of less than 13 ft/d scattered around the margins. Calibrated values of S ranged from 0.10 to 0.25. The two lowest K ranges and higher values of S were interpreted to occur in the Gardena Terrace area. The model did not distinguish between aquifer properties in saturated portions of the MPC and QC units (i.e. a single value was used for the both units where commonly saturated).

Golder (2007) used specific capacity data from wells to estimate the transmissivity (T) of the gravel aquifer. They estimate that T ranges from about 30 ft^2/d to 90,000 ft^2/d, (mean 2,100, median 780); with higher values associated with younger, uncemented sands and gravels near stream and river channels. Cemented gravels have lower T values, with the lowest values associated with sand/gravel lenses in the silt aquitard or highly cemented gravels. Based on model calibration, Golder defined K zones of high (100 ft/d) and moderate (50 ft/d) values for the gravel aquifer, and a vertical hydraulic conductivity (K_v) for the underlying silt/clay aquitard of 0.008 ft/d. Golder employed the same S values estimated by Barker and Mac Nish of 0.10 to 0.25.

Petrides (2010a) summarizes the results of five aquifer tests conducted at the HBDIC infiltration basins near Milton-Freewater under variable conditions of background water-table trends and irrigation ditch conveyance. The tests employed a 4-inch diameter pumping well, three 2-inch diameter monitoring wells, and pumping rates between 33 and 82 gpm. Test results were analyzed by the method of Neuman (1974) for an unconfined aquifer with delayed gravity response. The tests suggest aquifer T values ranging from 12,600 to 19,600 ft^2/d and K values ranging from 72 to 108 ft/d. Aquifer drawdowns during four of the five tests were on the order of only several tenths of a foot; greater aquifer stresses might provide more representative values of aquifer properties over larger aquifer volumes.

During model calibration, Petrides varied K values for the QF, QC and MPC units to achieve "best fit" model calibration. Petrides' calibration efforts largely focused on upper and middle portions of the basin (i.e. near infiltration sites), with less consideration of downstream areas such as Touchet and the Gardena Terrace. K values for the MPC ranged from about 90 to 200 ft/d (average 125 ft/d) and K values for the QC ranged from about 200 to 500 ft/d (average 360 ft/d) (Petrides, pers. comm., 2010). Given the greater presence of silty materials in downstream areas, lower K values would reasonably be expected in downstream portions of the basin.

5.3 RETIMING OF DEEP PERCOLATION LOSSES

PGG estimated the retiming of deep percolation losses associated with irrigation conservation at the proposed site by comparing the portion of reduced Walla Walla diversion associated with deep percolation losses to the change in subsurface irrigation return flow from deep percolation losses back to the Walla Walla River. Transfer of changes to the flow regime of the Walla Walla River (reduced irrigation diversions and altered groundwater discharge) are assumed to influence the Columbia River without significant time lag, as discussed in Section 5.1.4. Under this condition, the "retiming benefit" due to reduced deep percolation losses (at any time) is equal to the reduced diversion from the Walla Walla River minus the change in groundwater discharge to the river due to reduced deep percolation losses:

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

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} = portion of diversion supplying deep percolation irrigation loss before conservation
DP_{POST} = portion of diversion supplying deep percolation irrigation loss after conservation
RD_{PRE} = river discharge from groundwater return flow before conservation
RD_{POST} = river discharge from groundwater return flow 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:

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

For the purpose of this project, only the retiming benefit during the critical period (July and August) has been defined as important for making water rights decisions. The reduced diversion associated with deep percolation losses (DP_{PRE}) is calculated based on RH2's monthly estimates of deep percolation losses shown above in Section 5.1.5. The change in the timing of groundwater discharge to the Walla Walla River associated with reduced deep percolation losses requires consideration of: 1) deep percolation losses from the root zone; 2) migration of the irrigation "recharge pulse" downward within the vadose zone (from the root zone to the water table); and 3) conveyance of the recharge pulse through the groundwater system to nearby surface-water discharge features. These three elements of subsurface return flow are discussed in the following sections.

5.3.1 Deep Percolation Losses from the Site

The WSCC reports that approximately 80 acres of the proposed site are available for conservation, and existing irrigation is predominantly performed with hand lines. The current (2009) basin-wide irrigation efficiency and distribution of irrigation losses has very similar values to those for hand lines (e.g. efficiency of 75.8 compared to 75 percent)[23]; therefore, the monthly deep percolation estimates presented in Section 5.1.5 were used to represent deep percolation at the site. 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 pre-conservation deep percolation estimates were converted into monthly rates and used as input for evaluation of the vadose zone.

Deep percolation for the post-conservation condition (center pivot with LEPA and IWM) 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. As further discussed below, model results can be easily adjusted to account for post-conservation deep percolation if needed.

5.3.2 Irrigation Recharge through the Vadose Zone

The vadose zone beneath the site is estimated to be comprised of approximately 20 to 43 feet of Touchet Beds overlying about 22 to 57 feet of gravelly materials (Section 5.2.3). PGG used the modeling code Hydrus-1D (Simunek et al, 2008) to evaluate conveyance of the recharge pulse through the vadose zone under both current (pre-conservation) and future (post-conservation) conditions. **Appendix K** provides a detailed description of PGG's Hydrus analysis. Passage through the layered silty-sand rhythmites of the Touchet Beds (simulated as 33 feet (10 meters) thick) is predicted to provide considerable retiming (lagging and damping) of the recharge pulse. Additional lagging and damping is predicted when an additional 33 feet of gravelly vadose zone (gravel with fine-sand matrix) is simulated beneath the layered Touchet Beds. Predicted timing of irrigation recharge at the bottom of the vadose zone represented by the model for pre-conservation conditions is shown on **Figure 5-5**. In order to demonstrate the sensitivity of Hydrus-1D predictions to uncertainty regarding vadose-zone texture, **Figure 5-5** also shows predictions where the Touchet Beds were simulated purely as fine sand and purely as sandy silt. Neither of these representations is considered to be a realistic depiction of the Touchet Beds, but they provide conservative "end-points" of how increased sand or silt content would affect the predicted timing of the recharge pulse through the Touchet Beds. While simulation of "layered Touchet Beds overlying gravelly materials" is considered to be the most realistic of the representations, the range of representations evaluated provides a conservative range of vadose-zone retiming which was used as input to the saturated flow model discussed below. Damping factors associated with these predictions range from 79% (silty end member) to 45% (fine-sand end member), with the values of 68% and 76% estimated for layered Touchet Beds and layered Touchet Beds overlying gravelly materials (respectively) considered to be most realistic.

Although the post-conservation deep percolation estimate of zero did not require Hydrus simulation to predict return flow timing, PGG performed supplemental Hydrus runs where the pre-conservation deep percolation was reduced by 60%. This lower recharge reduces soil moisture content and unsaturated hy-

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[23] Appendix A shows that about 90% of irrigation in the Walla Walla Basin is comprised of hand line, wheel line or solid set – all of which have the same irrigation efficiency and loss pathway distribution.

draulic conductivity (K_{UNSAT}) and increases predicted lagging/damping. Under this condition, the "layered" simulation of Touchet Beds was predicted to be over 90% damped for thicknesses exceeding 15 feet. Even lower values of post-conservation deep percolation would further reduce soil moisture content and increase predicted damping. With such high damping factors, the RD_{POST} term in *Equation 1* can be reasonably represented as the annual average value of post-conservation deep percolation for refinement of retiming benefit estimates.

5.3.3 Irrigation Recharge through the Saturated Flow System

PGG constructed a groundwater flow model of the lower Walla Walla basin to evaluate the timing of subsurface irrigation return flow in the Gardena Terrace vicinity. Detailed description of the groundwater flow model is presented in **Appendix K**. The model was run using the U.S. Geological Survey's numerical modeling code "MODFLOW 2005" (Harbaugh, 2005) along with MODFLOW NWT (Niswonger et al, 2011). Because monitoring data are relatively sparse in the lower Walla Walla Valley, PGG developed a number of model "realizations" to represent a reasonable range of uncertainty in depicting the subregional groundwater flow system. Realizations were developed for upper-end and lower-end values of the key parameters that influence transmission of the recharge pulse from the site to the Walla Walla River (and other nearby surface-water features). Parameters varied included aquifer K and Sy, for which PGG's selected combinations provided low, medium and high relative values of aquifer dispersivity. In addition to varying aquifer properties affecting predicted diffusivity, PGG used a number of the Hydrus results for delivery of the irrigation recharge pulse through the vadose zone to the water table assuming that 80 acres of irrigated area are available for conservation at the proposed site (pers. comm., Myrick, 2011). As shown on **Figure 5-6**, these permutations produce a variety of predicted curves for groundwater discharge to surface-water features associated with pre-conservation irrigation recharge at the proposed site. These predicted schedules of groundwater discharge to the Walla Walla River represent the RD_{PRE} term (in *Equation 2*) required for estimation of retiming benefit.

5.3.4 Estimation of Retiming Benefit

Figure 5-6 provides graphical depictions of the DP_{PRE} and RD_{PRE} terms used to estimate retiming benefit (B_{RT}) in Equation 2. RD_{PRE} is equivalent to the MODFLOW model results and DP_{PRE} was taken from RH2's irrigation recharge estimates. For any day, the difference between the DP_{PRE} and RD_{PRE} curves represents the retiming benefit associated with conservation. For the purpose of this project, only the retiming benefit during the critical period (July and August) has been defined as important for making water rights decisions. As discussed in **Appendix K**, the model realization based on the Barker Mac Nish ("BMN") model parameters is likely to be the most accurate depiction of actual conditions in this western portion of the basin. Combined with a layered Touchet Bed depiction, this realization predicts a highly (98%) damped delivery of groundwater discharge to affected surface-water features (essentially fully damped with uniform year-round discharge[24]). Other RD_{PRE} curves show a range of predictions, with realizations where the vadose zone is depicted as layered Touchet Beds considered more realistic than depictions where the vadose zone is depicted as purely fine sand. Associated damping factors range from 68% to 97%, with an 84% average of all predictions. Given the range of RD_{PRE} predictions and the likely greater accuracy of the BMN realization, it seems reasonable to use the BMN values on **Figure 5-6** as the basis of estimating B_{RT}. The table below summarizes monthly estimates of retiming benefit based on the BMN realization with a layered Touchet Bed vadose zone for the 80-acre area proposed for conservation. For the critical months of July and August, these monthly average rates of retiming benefit translate to volumes of 10.5 and 5.8 acre-feet (respectively) based on the assumed 80 acres of conservation.

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[24] Even greater damping would be predicted for BMN results with vadose zone input from layered Touchet Beds overlying gravelly sediments.

	Jan	Feb	Early Mar	Late Mar	Apr	May	Jun	Jul	Aug	Sep	Early Oct	Late Oct	Nov	Dec
Irrigation Recharge (cfs)	0.000	0.000	0.000	0.005	0.038	0.154	0.237	0.258	0.181	0.113	0.034	0.000	0.000	0.000
Return Flow (cfs)	0.081	0.081	0.081	0.082	0.083	0.084	0.085	0.086	0.086	0.086	0.085	0.085	0.084	0.082
Retiming Benefit (cfs)	-0.081	-0.081	-0.081	-0.077	-0.045	0.070	0.151	0.171	0.095	0.027	-0.052	-0.085	-0.084	-0.082

Total conservation benefit can be estimated as the retiming benefit (above) plus the reduced evaporation associated with conservation ("E benefit"). RH2's estimates of pre-conservation and post-conservation evaporation losses in Section 5.1.5 suggest that E benefit will amount to 4.5 and 3.2 af for July and August over 80 acres of conservation. Thus, total conservation benefit during this critical period is predicted to amount to 15.0 and 9.0 af for July and August.

If consideration of non-zero values of post-conservation deep percolation is desired, the expected high degree of post-conservation vadose-zone damping (previously discussed) suggests that the RD_{POST} term in *Equation 1* can be reasonably represented as the annual average of the post-conservation deep percolation. Thus, estimation of retiming benefit with *Equation 1* rather than *Equation 2* can be easily accomplished. If historic crop selections at the proposed site have irrigation requirements which differ greatly from the study-area wide requirements presented in Section 5.1.2, refinement of the above conservation benefit calculations may be desirable.

It should also be noted that after the initiation of conservation at the proposed site, time will be required for the hydrologic system to adjust towards the zero (or low) values of post conservation subsurface return flow. Water stored in both the vadose zone and the groundwater flow system in the site vicinity will slowly drain away, providing discharge to the Walla Walla River (and other surface-water receptors) greater than estimated for long-term conditions by PGG's model analyses. During this period, surface-water flows will likely receive additional retiming benefit because the entire reduction in the portion of river diversion supporting deep percolation loss will be realized due to the immediate effects of conservation but only a portion of the reduction in return flow will be realized.

5.4 FURTHER CONSIDERATIONS FOR CONSERVATION EFFORTS

If additional sites are identified on the Gardena Terrace focus area at a later date, PGG would recommend characterization of site conditions (thickness and texture of vadose zone) in a manner similar to above. Additional Hydrus runs may be required to simulated vadose zone conditions below the site, as well as additional MODFLOW runs to simulate retiming in the groundwater flow system. It should be noted, however, that if the site has thicker unsaturated sequences of Touchet Beds and/or is farther from the Walla Walla River, predicted retiming is likely to be even more damped than described above, and best professional may be all that's required to assess retiming at the new site.

The above analysis did not consider retiming benefit from groundwater sourced (or mixed groundwater / surface-water sourced) sites. Retiming benefit for such sites would be less than surface-water sourced sites, because the impact of groundwater pumping is expected to be damped similar (but not equal) to the predicted retiming for subsurface return flow of irrigation recharge. The less damped the impact of groundwater pumping on the river, the more similar the conservation benefit would be to surface-water sourced farms such as the proposed conservation site. Thus, optimal candidates for groundwater (or mixed) source sites would be farms close to the Walla Walla River which overlie considerable thicknesses of the fine-grained, Touchet Bed vadose zone.

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TABLES & FIGURES