GROUND AND SURFACE WATER IMPACTS ON SPRING FORMATION IN THE WALLA WALLA VALLEY, OREGON

by
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Abstract:

Since 2004, the Walla Walla Basin Watershed Council (WWBWC) has, in partnership with the Hudson Bay District Improvement Company (HBDIC), operated an aquifer recharge project southeast of Umapine, Oregon. The WWBWC and other groups have identified the shallow aquifer system of the Walla Walla basin as a system in decline (Bower, 2007). The goal of the HBDIC project is to increase the amount of recharge to this shallow aquifer system thereby increasing surface and groundwater supplies for salmon recovery efforts, irrigation demands, and recreational activities in the Walla Walla Basin. The recharge occurs under a limited test license between November and May. This analysis attempts to determine if there is an appreciable connection between the recharge during the winter months and the increase in local static water levels. Using a GPS survey, and structure-contour and isopach maps, two geologic cross sections were developed to model the subsurface geology from the recharge site to the North and South Fork of Johnson Creek. Static water levels along the transect lines were used to model the changes in the water table from 2003 to 2006. Since 2004, the HBDIC project recharged a total of 4,261 acre-feet[1] of water to the aquifer. Simultaneously the modeled rise in the water table from July 2003 to July 2006 is approximately 2.35 feet along the transect line A (from the White House domestic well to the springs at the headwaters of the South Fork of Johnson Creek, measured at WWBWC streamflow gauge at Grabner Lane); it is 2.96 feet along transect line B (the route from the White Ditch Gauge to the Dave Lee well). The estimated transit times, modeled using Darcy's law are approximately 8.64 years and 11.07 years along Transect A and Transect B respectively. The results are consistent with the hypothesis that the HBDIC recharge project positively affects the volume of discharge of Johnson Creek, although the effects are just now becoming apparent.

[1] A note on units. While the benefits of working in the metric system are clear, the data that we analyze here are all in English units. Further, the intended audience, those landowners in the Walla Walla Valley, are more comfortable in English units. We will continue to use English units throughout without including metric conversions.

Introduction:

The Walla Walla Basin has been experimenting with aquifer recharge projects since 2004, with the goal of restoring the water table levels to pre-irrigation levels, thereby replenishing the springs that feed the Walla Walla River. This will increase habitat for salmonids, increase water availability for irrigation throughout the basin, and provide increase opportunities for recreation.

The Walla Walla Basin Physical Parameters:

Geography and Climate:

The Walla Walla Basin sits in the northeastern corner of Oregon, at about 46° N latitude, 118º W longitude (See Figure 1); it covers approximately 1750 square miles

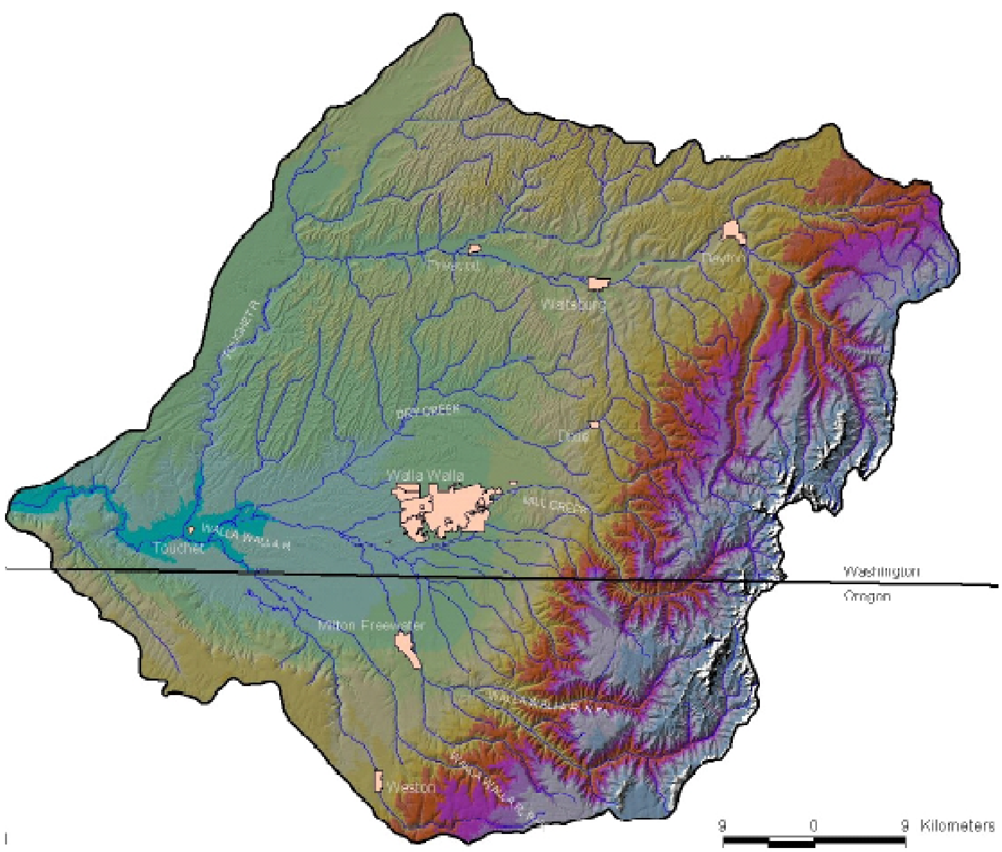

Figure 1. Map of Walla Walla Basin

(MacNish, 1973), although the Oregon portion of the Walla Walla River drains approximately 480 square miles (Walla Walla Local Agriculture Advisory Committee, 2002). The Walla Walla River, near the study area is naturally a distributary river system, splitting into three distributaries: the Tum-a-lum branch is the main stem; the East and West Prongs of the Little Walla Walla River also historically carried significant portions of the surface water flow (Bower, 2007).

Across the basin, total precipitation averages approximately 15-16 inches per year, although individual precipitation microzones range from 60 inches at the crest of the Blue Mountains, to less than ten inches at the confluence of the Walla Walla River with the Columbia (Newcomb, 1965). The total water budget for the basin is estimated to be 1.6 million acre feet, although the precipitation is not evenly distributed; most of it occurs during the winter months (MacNish, 1973). Peak flows for surface water and infiltration into the aquifers occur during the months from November to April; after May, flows decrease rapidly until the precipitation increases, often after October (Walla Walla Local Agriculture Advisory Committee, 2002).

Geology:

The whole region is underlain by multiple lava flows of the Columbia River basalt. This basalt is at least 2,500 feet thick (Newcomb, 1965). The geology closer to the surface, particularly near the headwaters of Mud Creek and near Umapine, OR where the Johnson Spring occurs (see Figure 3), is largely fine gravels and sand underlain by alluvium and cemented alluvial gravel (see Figure 2). This particular stratigraphy is similar to that described by Kevin Lindsey in 2003 letter to the WWBWC (Kennedy/Jenks, 2003) describing the geology near the recharge site. It is also similar to the description given in Newcomb (1965) meaning the project area geology is consistent with the rest of the Walla Walla Valley. Near Umapine the conglomerate is overlain with deposits described as "horizontally light-grey bedded silt, very fine sand, and volcanic ash, marked by distinctive gravel, cobble and boulder inclusions" (Newcomb 1965, p. 25) These layers, known as Touchet beds, range up to 100 feet thick. This project focuses only on the shallow aquifer; so we are concerned only with the soils, unconsolidated gravels, and conglomerate (see Figure 3).

Subsurface Profile

Thickness ft	Description
10	Soil: Mostly silt, interpreted to be eolian and fluvial.
25	Unconsolidated gravel(s): cobbles and pebbles with sandy matrix, interpreted to be Pleistocene and Holocene alluvium.
150	Conglomerate: Consolidated, cemented cobbles and pebbles with sandy matrix, interpreted to be Pleistocene and Holocene alluvium
350	Clay: Fine-grained sediment, impermeable, Miocene.
1000s	Basalt: Columbia River basalt flows, deep aquifer, Miocene

Figure 2. Typical stratigraphic Column near Johnson Creek.

Groundwater Movement

Newcomb (1965, p. 44) describes the shallow aquifer as an unconfined system with high permeability. He finds that "ground water moves down slope in the old gravel largely by pressure transfer and also by down gradient percolation along porous and permeable zones of loose gravel". Hydraulic conductivity values from OSU-WWBWC aquifer testing ranged 66-99 ft/day for the conglomerate unit. Our analysis is based on a mean value of 78.9 feet per day (Petrides, 2006). These tests also found (Bower, Petrides 2007) that the permeability for the unconsolidated gravel unit is significantly larger (~100 ft/day). Due to the recent date of the information, we are not able to incorporate the different conductivity values into the analysis, although later studies may find it useful.

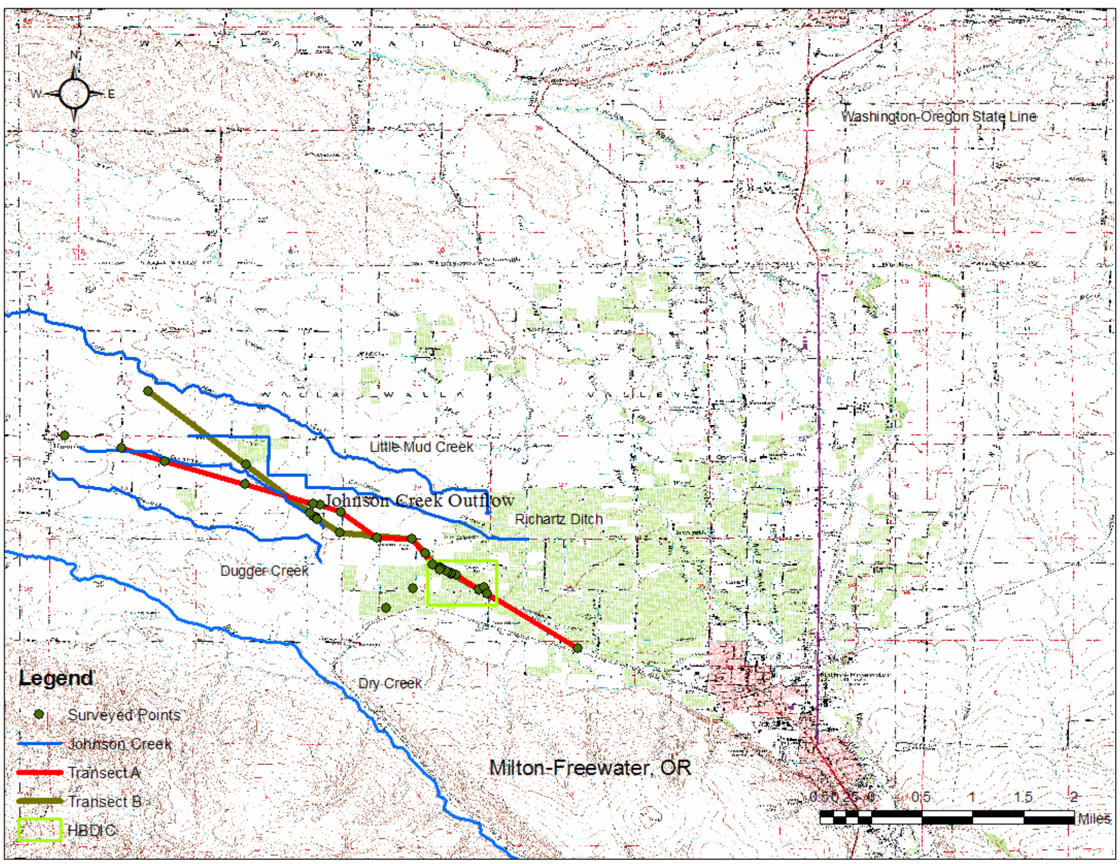

Figure 3. Map of Johnson Creek Study Area

History of the recharge:

For most of the 20th century, flows in the Walla Walla River were frequently diverted during the peak irrigation season between June and September (WWBWC, 2002). In 1998, the conservation organization, American Rivers, listed the Walla Walla River as the 18th most endangered river in the country citing the "low flows and no-flows" due specifically to agricultural use during the irrigation season (American Rivers, 1998). Agricultural use, however, was promoted under state law; indeed there were proposals to increase the amount of water diverted from the Walla Walla River by 100 cfs as late is 1998 (American Rivers, 1998).

In June, 1998 EPA listed both bull trout (*Salvelinus confluentus*) and steelhead (*Oncorhynchus mykiss)* in Oregon (and the Walla Walla River) as "threatened" under the Endangered Species Act (50 CFR. Part 17). The diversion of water leading to habitat destruction constitutes an incidental take, which is prohibited under the Endangered Species Act; under those circumstances, irrigators would then be liable for the fish destruction. This finding determined that the Walla Walla River would have to flow year round in order to preserve the threatened species habitat (WWBWC, 2002).

In 1999, after negotiations with the Confederated Tribes of the Umatilla, Kooskooskie Commons, and the Walla Walla Basin Watershed Council, the two districts committed to keeping a minimum of 25 cfs in the river during the peak irrigation season (WWBWC, 2002). While protecting bull trout and steelhead habitat, the agreement shifted the flow of surface water to the Tum-a-lum branch from other parts of the Walla Walla River system by reducing the irrigation demands placed on it during the summer months.

Landowners were able to partially adjust for the water shortfall by pumping greater volumes of water from both the basalt and shallow aquifers.

It is important to note that since the agreement to protect summer flows in the Walla Walla Basin, many stream restoration efforts have focused on maintaining flows in the Tum-a-lum branch. It has had the effect of reapportioning the total amount of water in the Walla Walla Basin to the Tum-a-lum branch, implying that there is less water infiltrated to other branches, meaning total inflow to the shallow aquifer has decreased. This has deleterious effects on the springs fed by this aquifer in the Walla Walla Valley (WWBWC, 2002).

The water table around the survey area has declined by 20 to 25 feet between 1933 and June 2007 (Bower, 2007 McKnight well recorded data 1933-2004). This decline in the local water table is likely due, in part to "changes in surface and subsurface water management including pumping of the shallow system" (Bower, 2007).

By 2004, the WWBWC and the Hudson Bay District Improvement Company formed a collaborative effort known as the Hudson Bay Aquifer Recharge (HBAR) project which has now run under a limited license that allowed the "use of water from the Walla Walla River...for the purpose of testing artificial groundwater research during a season of November 1 through May 15. Water may only be diverted under the license when there is adequate flow in the Walla Walla River to honor all existing water rights" (WWBWC, 2004).

The recharge site consists of three shallow spreading ponds with a combined surface area of 47,420 ft^2. Water is diverted from the Little Walla Walla River through an intake structure. The shallow aquifer was found to be approximately 30-35 feet below ground surface (bgs) at the time of construction (Bower, 2005).

The first year the total passive recharge was 410 acre-feet (WWBWC, 2004, Bower, 2007). In 2005 the total volume recharged passively was approximately 1038 acre-feet

(Bower, 2007); in 2005-6 the total recharge was 2814 acre-feet. In total, the HBAR project has recharged in excess of 4,261 acre-feet into the shallow aquifer. Since beginning of the project in 2004 there have been increases in static well levels near to the recharge project during the recharge season (WWBWC, 2004).

We attempt to correlate the change in year to year increases of water for the existence of the Johnson Creek. We tested the hypothesis that that the spring is situated in a local depression and its flows are contingent on the local level of the aquifer. In this model the gravel aquifer is directly connected to the spring formation, so as the HBDIC project continues to raise static water levels locally around the basin, it is likely that it increases the magnitude of flow from the springs.

Materials and Methods:

Surveyed Points:

Surveyed points were collected using Ashtech Solutions, Promark 2 Satellite Survey Device. Data collected included latitude and longitude and elevation above MSL for 47points. Of these, 28 were used for two transects (Figure 3 and 4).

Cross-sections along transects:

Newcomb's 1965 work and historic well logs indicate that the layering of the subsurface strata follow a model of soil, underlain by alluvial gravels, which in turn are underlain by a Mio-Pliocene conglomerate layer. This indication was confirmed and extended by Kevin Lindsey in 2003. We use his maps to develop cross sections along the transects surveyed (Kennedy/Jenks Consultants, 2003) (see Figure 2).

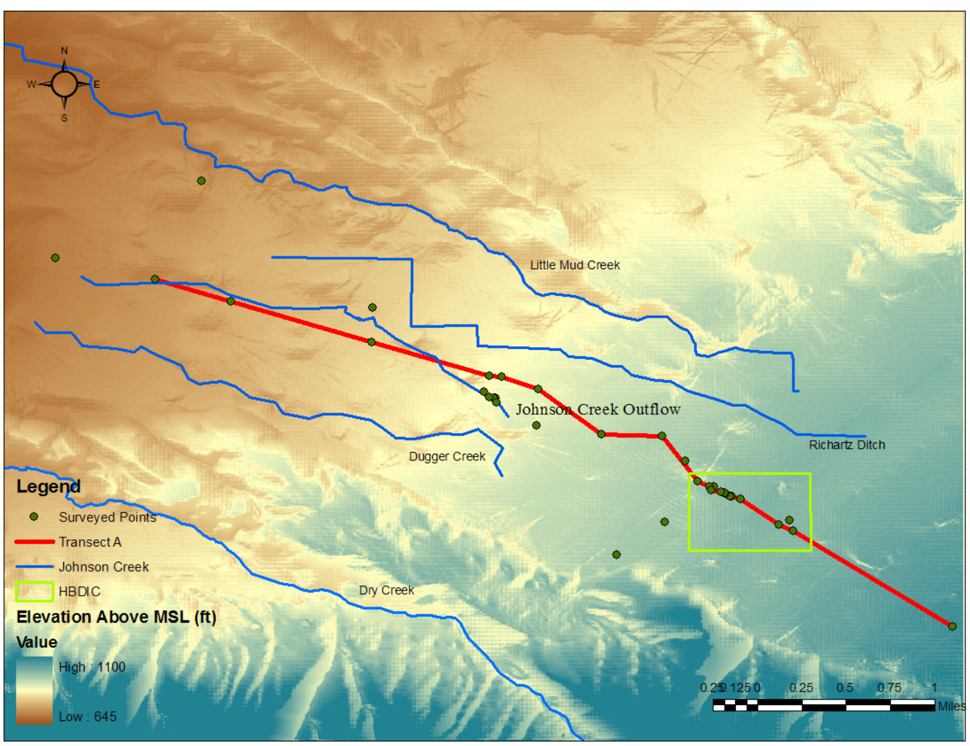

Figure 4. Johnson Creek Study Area Transect A

For the purposes of the cross sections along the transects the geologic layers are assumed to be both continuous and uniform – that is they do not abruptly end, so an interpolation between the discrete transect points is an accurate model of the strata beneath the ground surface. To create the geologic cross sections beneath the transect lines, ground surface elevations, structure contour and isopach maps (Lindsey, 2003) of the alluvial gravels and top of the Mio-Pliocene conglomerate formation were used to develop estimates of the thicknesses and contact elevations of the strata (See Figure 4 and 5). For geologic units below ground surface point elevations (amsl) and thicknesses were interpolated by a method of minimizing total interval distance.

Each surveyed point that was used to define the transects was displayed using ESRI ArcView 9.1 Geographic Information Systems software, and the distance between points was calculated using the measuring tool to obtain total distance. The elevations of geologic contacts were determined using both isopach maps and structure contour maps. When elevations of contacts determined by isopach maps differed from those determined by structure contour maps the mean value was used.

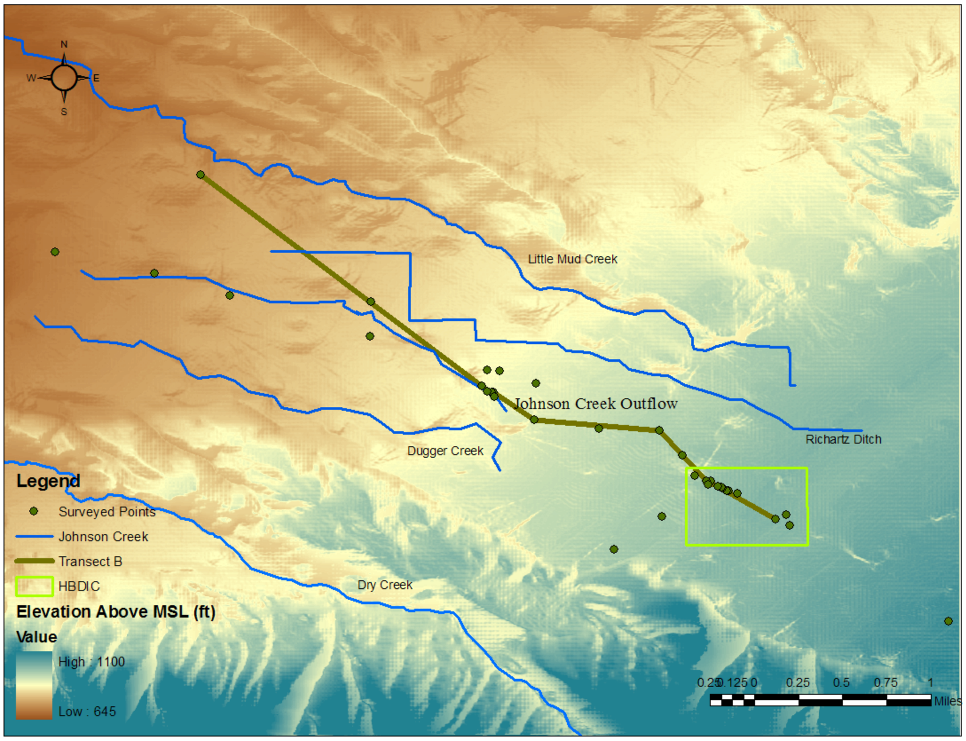

Figure 5. Johnson Creek Study Area Transect B

Water Table Modeling:

Well level data is available for most months between June 2003 and July 2006 from the WWBWC monitoring network (WWBWC, 2007). The static water levels were collected at regular time intervals since 2003 by WWBWC staff. Continuous water level data is available for certain time intervals for wells at survey points GW-45 (B2), GW-35 (A14/B5), GW-17 (A15/B-6), GW-58 (B-9), GW-31 (B-12). Static water level data are available for the following wells (with closest transect point in parentheses) GW-43 (point A2/B1), GW-45 (A4), GW-16 (A16), GW-34 (A21) (WWBWC Wellnet Data, 2007).

Tables 1 and 2 show the estimated water table elevations for available wells in Transect A and B. In Table 2, the column labeled Grabner corresponds to the measured stage elevations of the springs at the headwaters of the South Fork of Johnson Creek, measured at WWBWC streamflow Gauge at Grabner Lane.

The project faced significant data gaps. Of 33 months of data that were analyzed, only 1 well (GW-35) provided a complete data set. The number of actual well data observations ranged from four (GW-34) to 16 (GW-17). In order to complete the data sets, each individual series was regressed using Ordinary Least Squares against GW-35, and the resulting linear equation was used to interpolate the remaining points. Primary data was used wherever it existed. R^2 values for the regressions and the functions used are tabulated in Table 3. Notice that GW-43 is not included in this analysis. GW-43 had only one static water level recorded during the time this survey details (during June 2004). The data in bold-face type are modeled data, while the normal type are observed static water levels.

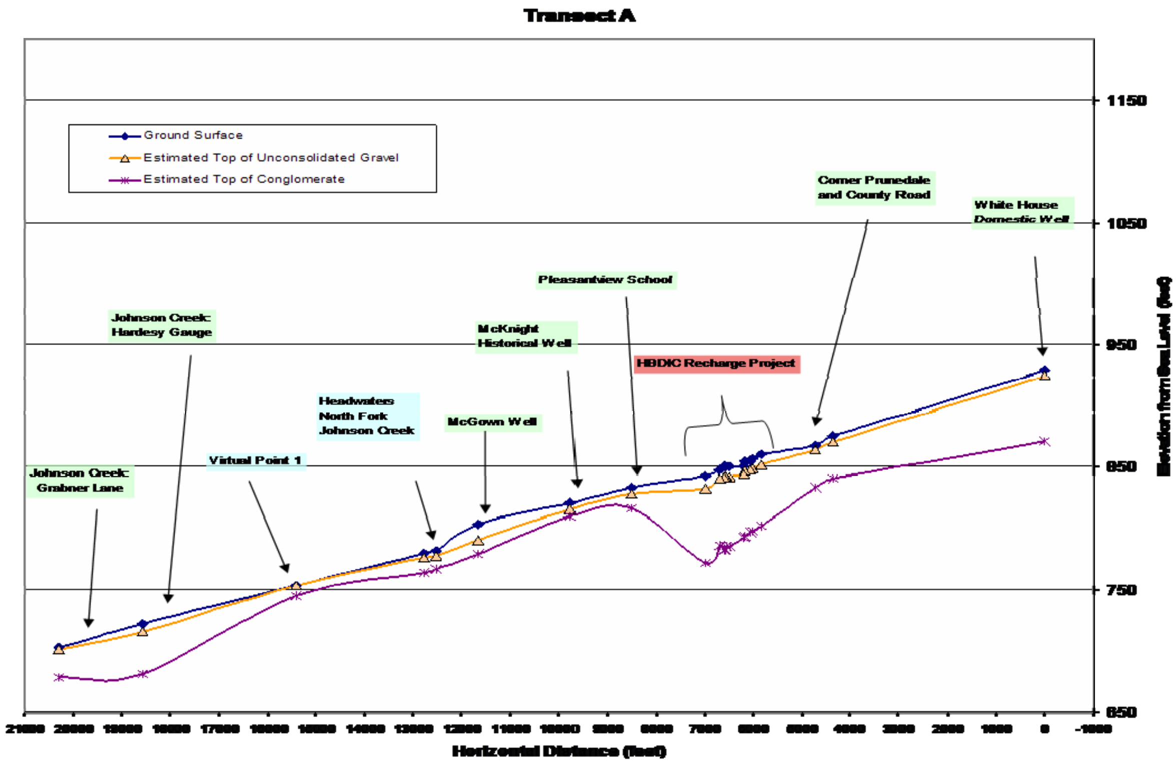

Figure 6. Cross-section for Transect A

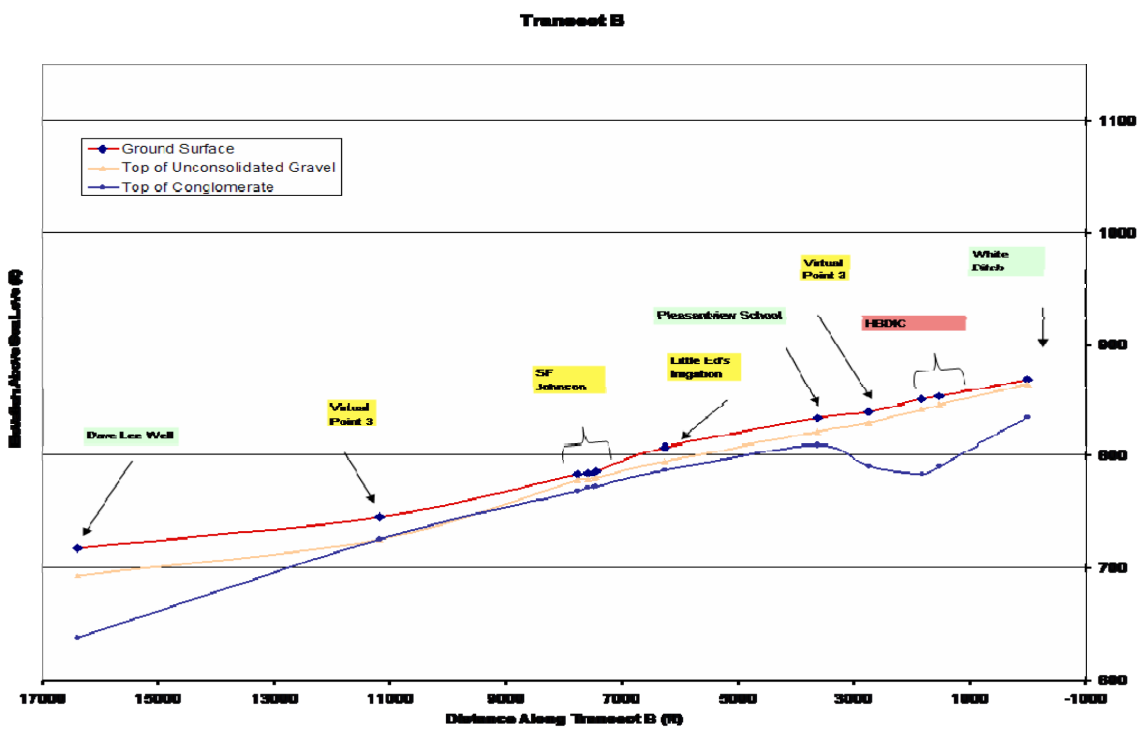

Figure 7. Cross-section for Transect B

Table 1. Water Table Values at Well Sites along Transect A

Date	GW-43	GW-45	OBS 2	OBS 1	GW-35	GW-17	GW-58	GW-34
Jul-03	**794**	**817**	**807**	**807**	806	**802**	**780**	**673**
Oct-03	**803**	**830**	**819**	**818**	815	812	**786**	**671**
Dec-03	**802**	**828**	**816**	**816**	814	**807**	789	666
Jan-04	**796**	**820**	**809**	**809**	808	**804**	**782**	**673**
Feb-04	**794**	**817**	**807**	**807**	806	**802**	**780**	**673**
Mar-04	**792**	810	**805**	**805**	802	**801**	**779**	**673**
Apr-04	**805**	**830**	824	823	815	809	**787**	**671**
May-04	**808**	**835**	824	824	819	814	**789**	**670**
Jun-04	832	824	814	814	814	807	**786**	676
Jul-04	**798**	**818**	812	811	807	811	**780**	**673**
Aug-04	**797**	**821**	808	808	809	**804**	**782**	**672**
Nov-04	**803**	**831**	816	816	816	807	789	**671**
Dec-04	**807**	833	828	823	817	808	789	**674**
Jan-05	**795**	**820**	804	804	808	799	787	**673**
Feb-05	**791**	**813**	799	799	804	**800**	782	**674**
Mar-05	**795**	**814**	808	807	806	**802**	781	**673**
Apr-05	**814**	**841**	839	836	822	**814**	789	**669**
May-05	**805**	**834**	818	818	818	809	789	**670**
Jun-05	**799**	**826**	811	810	812	803	784	**672**
Jul-05	**791**	813	807	807	801	792	772	**674**
Aug-05	**789**	811	**800**	**800**	802	**798**	774	**674**
Sep-05	**793**	814	**8067**	**807**	806	797	778	**673**
Oct-05	**802**	827	**819**	**819**	815	806	783	**665**
Nov-05	**806**	829	**822**	**823**	818	**811**	**789**	**670**
Dec-05	**803**	828	**817**	**817**	814	**808**	**786**	**671**
Jan-06	**811**	844	**827**	**827**	821	**813**	**791**	**670**
Feb-06	**800**	820	**815**	**815**	813	**807**	**785**	**672**
Mar-06	**807**	841	**821**	**821**	817	**810**	**788**	**671**
Apr-06	**810**	838	**826**	**826**	820	817	**790**	**670**
May-06	**810**	843	**825**	**825**	820	814	**790**	**670**
Jun-06	**799**	821	**811**	**811**	810	806	**782**	677
Jul-06	**793**	817	**799**	**799**	801	806	**776**	673

Table 2. Water Table Values at Well Site along Transect B

Date	GW-45	GW-35	GW-17	Grabner	GW-58	GW-31
Jul-03	**804**	797	**795**	**785**	**773**	657
Oct-03	**816**	806	786	**786**	**779**	**665**
Dec-03	**814**	804	**800**	**786**	767	649
Jan-04	**807**	799	**796**	**786**	**775**	662
Feb-04	**804**	797	**795**	**785**	**773**	667
Mar-04	803	796	**794**	**785**	**772**	667
Apr-04	**816**	806	**801**	**786**	**780**	666
May-04	**822**	809	788	**787**	**782**	667
Jun-04	816	805	782	**786**	**779**	668
Jul-04	**804**	797	785	**785**	**773**	664
Aug-04	**808**	800	**797**	**786**	**775**	659
Nov-04	**818**	807	785	**787**	769	**666**
Dec-04	825	808	785	**787**	769	671
Jan-05	**806**	799	783	**786**	767	671
Feb-05	**800**	794	**793**	**785**	762	669
Mar-05	**804**	797	**795**	**785**	761	666
Apr-05	**827**	813	**807**	787	769	**666**
May-05	**821**	809	788	787	769	669
Jun-05	**813**	803	781	785	778	**665**
Jul-05	806	792	750	785	769	664
Aug-05	803	792	**791**	**785**	770	**664**
Sep-05	807	797	789	**785**	773	**664**
Oct-05	819	806	781	**786**	780	**665**
Nov-05	821	809	**801**	**787**	**782**	**665**
Dec-05	820	805	**801**	**786**	**779**	**665**
Jan-06	836	812	**806**	**787**	**784**	**666**
Feb-06	812	804	**800**	**786**	**778**	**665**
Mar-06	833	807	**801**	786	**781**	**665**
Apr-06	830	811	791	788	**784**	**666**
May-06	836	811	788	787	**783**	**666**
Jun-06	813	800	780	787	**776**	665
Jul-06	809	792	780	786	**769**	664

A linear function was created for that month that related all the other well levels to GW-43 and extrapolated to estimate levels for all other months; it should be noted that all results are preliminary, and all data for GW-43 except for June, 2004 are extrapolated. Also, Recharge wells 1 and 2 have a correlation coefficient of 0.996 – the difference in their estimated static water levels is smaller than the significant figures associated with the equations used to estimate the water levels – for the purposes of this paper, Recharge 1 and Recharge 2 have identical water table elevations. Table 3 shows the results of the linear regressions and their associated R^2 values.

For continuous water level data, the monthly mean of the water level were used. If complete water level data for the month were not available, the limited data were used to calculate the mean static water level. To calculate year to year rises in the water table, the mean water level for the month was used. Monthly data were used because of the seasonal variability of flow required greater temporal resolution than simple yearly data. Weekly data were often unavailable, and the resulting increase in uncertainty was unwarranted, since we are interested in long term variation.

Table 3. Interpolation Statistics

Well	Function	R^2
Grabner	(Grabner) = 0.1143(GW-35) + 694.33	0.64
Recharge 1	(WELL 1) = 1.3533(GW-35) – 284.63	0.77
Recharge 2	(WELL 2) = 1.3533(GW-35) - 284.63	0.77
GW-17	GW-17 = 0.7611(GW-35) + 188.22	0.55
GW-31	GW-31= 0.1051(GW-35) + 580.47	0.01
GW-34	GW-34= -0.2285(GW-35) + 857.31	0.07
GW-45	GW-45 = 1.4533(GW-35) - 354.58	0.82
GW-58	GW-58 = 0.7436(GW-35) + 180.48	0.75

Results:

Water table impacts:

The following is a discussion of the changes in the water table over both the transects surveyed. Between the four quarters following July 2003 and four quarters preceding July 2006 the mean static water level (SWL) as measured along the whole transect increased, on average, 2.35 (±1.43) feet for Transect A and 2.96 (±3.87) ft for Transect B. However each well saw different changes in water levels. The maximum increase for the interval considered Transect A is where the recharge occurs 4.75 ft (GW-45), the only negative change -0.26 ft occurred at GW-34, the furthest downstream from the recharge basin. The standard deviation of the changes in water level for Transect A was only 1.43 ft. It is highly likely then that the increase in the SWL along Transect A is indicative of a significant trend, and the water table along the South Fork Johnson Creek is rising. For Transect B, however, standard deviation was 3.87 feet, which is larger than the observed change implying that the decrease is statistically insignificant. However, if we remove the outlier, GW-17 which is an active irrigation well, the mean water table increase is 3.79 ft, with a standard deviation of 3.69 ft; this omission would make the increase in water along Transect B statistically significant.

Tables 4 and 5 detail the year-to-year changes by season in the static water levels for transects A and B respectively. The column labeled "Total" refers to the average change over the season across the whole transect: the green boxes refer to average increases, the red boxes to decreases. We notice that the water table shows consistent growth across seasons except during the fall of 2004, and the first half of 2005. The row labeled "Δ from mean of first 4 quarters to last 4 quarters" shows the total change over the time period for that specific well. We notice that all wells have seen a net increase in static water levels since measuring began in 2003. We can see that there is a clear trend towards increasing static water levels at most wells over time.

Table 4. Transect A Individual Well Head Changes (ft)

Δ SWL	GW-43	GW-45	OBS 2	OBS 1	GW-35	GW-17	GW-58	GW-34	Total
Summer '03-04	13.96	3.66	4.96	4.49	3.70	5.45	2.75	0.76	4.97
Fall '03-'04	-15.60	-4.32	-5.52	-5.21	-5.07	-9.71	-6.38	-0.45	-6.53
Winter '03-'04	3.12	2.03	-0.89	-0.73	0.30	8.23	2.84	1.56	2.06
Spring '04-'05	-0.69	1.59	-1.95	-2.15	1.09	-5.21	2.50	-0.25	-0.63
Summer '04-05	-2.91	-7.88	-0.21	-0.01	-2.69	-2.00	-5.43	-1.52	-2.83
Fall '04-'05	-0.20	0.11	-0.45	-2.03	0.06	-2.23	2.34	2.82	0.05
Winter '04-'05	6.86	8.59	9.40	10.98	6.55	7.26	1.55	-2.59	6.07
Spring '05-06	2.75	5.57	3.92	3.29	2.68	0.64	1.38	-0.61	2.45
Summer '05-06	4.16	9.69	2.09	3.35	3.40	5.13	3.14	-0.78	3.77
Δ from mean of first 4 quarters to last 4 quarters	2.87	4.76	2.84	2.99	2.51	1.89	1.17	-0.27	2.35

Table 5. Transect B Individual Well Head Changes (ft)

Δ SWL	GW-45	GW-35	GW-17	Grabner	GW-58	GW-31	Total
Summer '03-04	5.62	3.70	-6.94	0.42	2.75	6.93	5.62
Fall '03-'04	1.59	1.09	-1.60	0.13	-10.58	0.11	1.59
Winter '03-'04	2.07	0.06	-10.30	0.01	-6.39	11.00	2.07
Spring '04-'05	3.61	2.68	2.13	0.18	-11.70	0.20	3.61
Summer '04-05	-2.36	-5.07	-13.67	-0.89	-3.77	0.66	-2.36
Fall '04-'05	-1.99	-2.69	6.87	-0.31	9.39	-0.28	-1.99
Winter '04-'05	12.52	6.55	15.33	0.75	14.64	-5.03	12.52
Spring '05-06	15.58	3.40	-2.55	0.69	16.23	-1.30	15.58
Summer '05-06	3.99	0.30	6.00	1.10	0.23	0.03	3.99
Δ from mean of first 4 quarters - last 4 quarters	10.16	2.51	-1.18	0.52	2.70	3.08	2.96

Over the long term, we observe increases in water table levels, particularly close to the recharge project. For Transect A, the overall change in water level decreases as the well moves away from the HBDIC recharge point. A linear model for the decrease is $\Delta SWL = -0.00025 * D + 4.55966$ where D is the distance (in feet) from the HBDIC recharge project, the R^2 is 0.75. Transect B also shows a decline with distance from the recharge project. The model for Transect B is specified by $\Delta SWL = -0.00027 * D + 4.87954$ where

D is the distance (in feet) from the HBDIC recharge basin. It has an R^2 of 0.12. In both cases, the t-statistics imply that distance from the recharge site is a significant variable at the 1% level (for Transect A, the probability that there is no correlation between the distance from the recharge basin and the rise in static water levels is 0.09%; for Transect B, it is 0.94%). Since the static water level changes are higher closer to the recharge basin, we suspect that the recharge project is positively affecting the local water table, however other influences of aquifer levels include ditch operations, application of irrigation waters, pumping of aquifers varies year by year, and drought conditions (particularly 2005) (Bower, 2007).

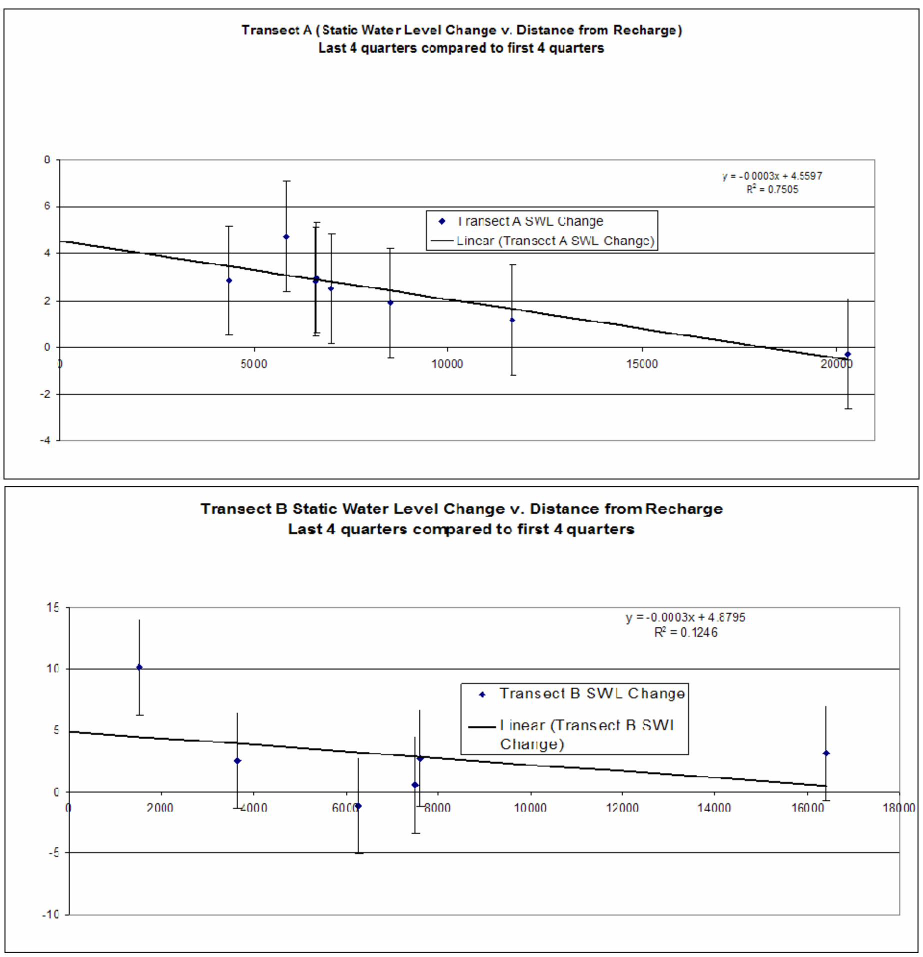

Figure 8. The effect of distance from recharge site on well levels.

Darcy's Law Calculation:

In order to establish whether the empirical water table increases discussed above have a causal effect on the discharge increases we use Darcy's Law to predict the time required from the recharge point to both the North fork and the South fork of Johnson Creek. Since Darcy's Law holds for saturated and unsaturated flow, for steady state and transient flow, for both homogenous and heterogeneous systems, and in both rocks and granular media (Freeze and Cherry, 1979), and because the system described consists of unconsolidated gravels atop consolidated gravels, the model is applicable.

We begin with the discharge statement of Darcy's Law (units in parentheses):

$$\vec{Q}(L^3T^{-1}) = K(LT^{-1}) \bullet A(L^2) \bullet \frac{\partial \vec{H}}{\partial \vec{L}},$$

where *Q* is the discharge in volume per unit time, *K* is the horizontal hydraulic conductivity, $\partial H/\partial L$ is the gradient vector of the ground, and A is the cross-sectional area.

We reduce this to a one-dimensional problem by first considering the velocity through a constant area (the outflow of the spring), which allows us to divide through by A, and then to further treat the partial derivative $\partial H/\partial L$ as constant from the recharge basin to the spring, meaning that we assume the flow of water is along a line of constant slope. This reduces the problem to

$$v(LT^{-1}) = K(LT^{-1}) \bullet \frac{\Delta H}{L},$$

where *v* is the Darcy velocity, and $\Delta H/L$ and *K* are both defined as above. The Darcy transit time (T) is the total distance traveled divided by the velocity. The actual Darcy velocity is proportional to the permeability of the given soil. The distance has two components, the vertical distance, H and the horizontal distance, L. The total distance is then:

$$T = \frac{\sqrt{L^2 + H^2}}{v/n} = \frac{\sqrt{L^2 + H^2}(n)}{K \bullet (\Delta H / L)}.$$

Using the calculated water table data, the head gradient between the stream (in Transect A, the North Fork: Point 16, in Transect B the South Fork: Point 8 and the water table at the recharge point which was approximated at the surveyed elevation of GW-45. Over the range of the data in this project the static water table shifted only slightly (between 2.35 and 2.96 feet). However the gradient of the water table for the two transects is quite similar. For Transect A, the mean head between the recharge basin and the North Fork of Johnson Creek was ΔH=43.1 (± 9.7) ft. For Transect B between the recharge project and the termination at South Fork of Johnson Creek the mean head was only ΔH=30 (±10.3) ft. The horizontal distance (*L)* for Transect A was significantly longer (6156 ft) than that of Transect B (5509 ft)[2], which implies that the gradient (defined as ΔH/L) is significantly smaller. Since the transit times are inversely related to gradient, the smaller gradient for Transect B explains the longer estimated Darcy transit times for that Transect A.

Because the water table elevation over the time studied varies widely, so does the pressure on each individual water particle. Since the velocity of a dynamic fluid is defined as

$$v = \sqrt{2(\frac{p}{\rho} - gH)}$$

(where *v* is velocity *p* is pressure, ρ is density, g is the gravitational constant and H is the head) the changing head varies the pressure exerted on the individual water particles dramatically. It is intuitive then, that the velocities of the individual water particles express

[2] These values were calculated in ArcGIS. They were "snapped" and thus are only as uncertain as the GIS survey which accurate to sub-centimeter resolutions. For the purposes of this project, these are exact values.

large variances. Indeed, the calculated Darcy transit times vary from 2103 days to 4592 days with a mean of 3155 days and 710-day standard deviation for Transect A. For Transect B the mean transit time is 4039 days, varying between 2015 and 6947 days. The standard deviation is 1277 days. The results are summarized in Table 6.

As the water table increases with the continued recharge from the HBDIC recharge project, so will the difference between the water table and the spring outflows. Since head and velocity are inversely related, we expect that further monitoring will find that the effective transit times will decrease as recharge continues.

Conclusions:

Since November 2004, when the HBDIC recharge project began operation, the water table has shown increases along both transects. The transit times calculated using Darcy's Law imply that long-term increases in flow at the North Fork of Johnson Creek are expected to occur in November 2009. We expect that the increase in stream discharges found from 2005 to 2006 will increase as the water particles continue to reach the outflow.

Calculating the transit times from the recharge basin to GW-35, we see that they are approximately 1.5 years, and indeed, we see a spike from the autumn of 2005 to the summer of 2006 consistent with the general time that the recharge project is active. Figure 8 also details that the increases in water table over the time period we observe are largest close to the recharge project.

Table 6. Calculated Darcy Transit Times from Recharge Basin to Johnson Spring

	North Fork Time (days)	North Fork Time (years)	South Fork Time (days)	South Fork Time (years)
Date				
July-03	3691	10.11	5437	14.90
October-03	2730	7.48	3301	9.04
December-03	2840	7.78	3506	9.61
January-04	3395	9.30	4686	12.84
February-04	3698	10.13	5456	14.95
March-04	4595	12.59	5739	15.72
April-04	2716	7.44	3275	8.97
May-04	2436	6.67	2791	7.65
June-04	3108	8.52	3287	9.01
July-04	3658	10.02	5350	14.66
August-04	3306	9.06	4477	12.27
November-04	2642	7.24	3142	8.61
December-04	2568	7.04	2573	7.05
January-05	3433	9.41	4777	13.09
February-05	4186	11.47	6947	19.03
March-05	3677	10.07	5400	14.79
April-05	2216	6.07	2445	6.70
May-05	2484	6.81	2872	7.87
June-05	2954	8.09	3727	10.21
July-05	4168	11.42	4950	13.56
August-05	4568	12.51	5687	15.58
September-05	4020	11.01	4693	12.86
October-05	2915	7.99	3023	8.28
November-05	2770	7.59	2831	7.76
December-05	2843	7.79	2927	8.02
January-06	2103	5.76	2015	5.52
February-06	3427	9.39	3748	10.27
March-06	2219	6.08	2150	5.89
April-06	2338	6.41	2291	6.28
May-06	2119	5.80	2033	5.57
June-06	3354	9.19	3639	9.97
July-06	3777	10.35	4291	11.76
Mean	3155	8.64	4039	11.07
Median	3031	8.30	3727	10.21
Min	2103	5.76	2015	5.52
Max	4595	12.59	6947	19.03
σ	710.9822	1.947896	1277	3.50

This analysis suggests that there is likely a connection between the increase in water level at both forks of Johnson Creek (shown in Table 5) and the rises in the water table demonstrated here. It is also likely that the HBDIC recharge project does show positive, long term impacts on the aquifer underlying Johnson Creek evidenced by the changes in SWL in Transect A and Transect B. It is expected that as the Darcy flows of the HBDIC recharge project reach the headwaters of the South Fork of Johnson Creek, the flows will increase proportional to the average head change across the whole aquifer.

At this time, however, the increases in stream flow can not yet be shown to be directly related to static water level changes in the alluvial aquifer. The observed increases in flow detailed in Figure 6 are not consistent with a Darcy flow explanation.

The short term variation in flows may be better explained by a transverse pressure wave moving through the aquifer. This variation was modeled by Newcomb in (1965) and Bower in (2005), who calculated the pressure wave velocity to be approximately 0.9-1 mile/week. More data is required to further establish the short term impact of the HBDIC recharge project and increase in stream flow at Johnson Creek.

Future work to extend this project might include collecting long-term continuous discharge data from Johnson Creek, and correcting for well draw-downs during the irrigation season. Since we expect that the long-term impacts of the HBDIC recharge project will be seen in the current (2007) summer season, it would be useful to be able to correlate actual discharge values to historic HBDIC recharge volumes. This would also serve as a good checking method for the Darcy's Law calculations. It is possible that GW-17 showed a net decrease in SWL due in part to agricultural use; this is the only well where the SWL decreased, it is unlikely to be representative. Some other cause must be responsible for the change.

It is expected that refinements to the measurements of the permeability factors of the unconsolidated gravels and conglomerate will yield lower transit times consistent with those observed.

This project continues the pattern of work showing that artificial aquifer recharge has long-term environmental benefits. Increased stream-flows have benefits for species using riparian habitats, including lower summer water temperatures, and increased water availability for flora. Further, the long term effects of raising the water table imply increased water availability for irrigation, and lower pumping costs. The work done here suggests that the HBDIC project may be an effective way to raise local water tables over an extended period of time and restore the historical decline of water in the Walla Walla Basin.

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