IMPROVING THE QUALITY AND QUANTITY OF IN-STREAM HABITAT BY RESTING GROUNDWATER EXTRACTION WELLS

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By
Joel Massmann, Ph.D., P.E.
Keta Waters
6520 East Mercer Way
Mercer Island, WA 98040

In association with

Peter Bannister, Aspect Consulting

Steve Nelson, RH2 Engineering, Inc

Anne Savery, Consulting Hydrologist

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1. INTRODUCTION AND SUMMARY OF RESULTS AND CONCLUSIONS

Restoring groundwater contributions to streams has the potential to enhance both the quality and quantity of in-stream habitat and to mitigate trends toward warmer water temperatures in local watersheds. A methodology for restoring groundwater contributions to stream flow is to reduce groundwater extraction from wells at locations that are hydraulically connected to impaired streams and stream segments. “Resting” or “pausing” groundwater extraction from selected wells during selected time periods can result in significant increases in stream flow and significant decreases in stream temperature. The study described in this report was aimed at identifying the types of hydrogeological conditions or scenarios that may result in significant improvements to in-stream flow and temperature conditions through seasonal pausing of groundwater extraction from wells.

This study described in this report included four primary tasks, as summarized below. The percentage of the overall project assigned to each of these tasks is summarized in Table 1.1

Task 1 involved compiling and integrating recent studies and reports that describe or relate to benefits derived from resting or pausing groundwater extraction. Approximately sixty references were identified. Most of these references relate to analytical techniques or models and some have field data related to impacts. Relatively few explicitly consider resting wells and no references were identified that specifically considering resting wells in the Puget Sound region.

Task 2 involved compiling reports that describe pumping test data to help identify the site-specific characteristics that are important for quantifying the magnitude, timing, and distribution of stream flow impacts from groundwater extraction. Approximately 50 paper and electronic copies of available pumping test reports for WRIA 8 and WRIA 9 were compiled and were used to create a database of aquifer testing results for WRIA 8 and WRIA 9

Task 3 involved modifying the USGS steady-state groundwater model developed for simulating aquifer systems in the Puget Sound lowlands (Morgan and Jones, 1999) so that it can be used to simulate transient or time-varying effects of groundwater extraction.

Task 4 involved combining the results of the computer simulations developed in Task 3 with the well characterization data identified in Task 2 to evaluate potential improvements in in-stream flow conditions through seasonal pausing of specific groundwater extraction wells located in the Soos Creek drainage basin in southeastern King County.

A. Overview of groundwater/surface water interactions

Effects of resting wells and seasonal pumping have been considered in the peer-reviewed hydrogeologic literature. Recent studies that specifically consider the effects of resting wells and seasonal pumping on streamflow depletion include Chen and Shu (2006), Kendy and Bredehoeft (2006), Singh (2006), Darama (2001), Chen (2001), and Wallace et al. (1990).

Groundwater extraction from water supply wells can result in three general types of impacts to stream flow: 1) causing a loosing stream to loose more water 2) causing a gaining stream to gain less water, and 3) causing a gaining stream to become a loosing stream.[1] Most of the systems in WRIA's 8 and 9 fall into the second category – groundwater extraction causes a reduction in the rate of groundwater discharge to streams. Reducing groundwater extraction through temporary pausing or resting of wells can reduce these impacts by reducing the amount water loss from loosing streams or by increasing the amount of water gain to gaining streams. Examples of these general types of impacts are illustrated in Figure 1.1.

The potential benefits to stream flow that might be derived from resting water supply wells are dependent upon site-specific characteristics related to the size of the stream, geologic and hydrogeologic conditions, and the geometry of the well in terms of its depth and distance from effected streams. These site-specific characteristics control both the magnitude of the potential benefit and the timing of these potential benefits. The magnitude of the potential benefit relates to the ratio of the increase in stream flow relative to the volume of water that is not pumped during the resting period. This ratio might range from less than 10% for deep wells that are distant from streams to nearly 100% for more shallow wells located in close proximity to streams. The timing of the potential benefit relates to the lag between when a well is rested and when the potential benefit is realized in the stream. Lag times might range from several days or weeks for shallow wells located close to streams to years or even decades for deep wells located distant from streams.

Most of the water supply wells in WRIA 8 and 9 are completed in either shallow unconfined aquifers or in semi-confined or "leaky" aquifers. Shallow unconfined aquifers are often in most direct continuity with streams, particularly for smaller streams in the upper parts of a watershed. Wells in leaky aquifers may impact streams by drawing water from more shallow aquifers that are in direct connection to streams. In other cases, wells in leaky aquifers may directly impact streams at locations where the stream channel cuts into the pumped aquifer or into the confining layer above the pumped aquifer.

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[1] A loosing stream is one where water flows from the stream channel to the aquifer. A gaining stream is one where water flows from the aquifer into the stream channel. A given stream may be a gaining stream in some locations or at some times, and may be a loosing stream at other locations or at other times.

The rate of groundwater discharge to gaining streams or the rate of groundwater recharge from loosing streams is dependent upon water levels in the immediate vicinity of the stream. This is true for both the unconfined and confined scenarios. When a well is first rested, the initial impact is to cause an increase in aquifer water levels in the immediate vicinity of the well. Water levels at locations more distant from the well are not affected by the reduced groundwater extraction during this initial stage. Effects on discharge to streams are generally negligible during these early times. As time goes on, water levels may increase at more distant locations, including those locations in the vicinity of streams. Water level increases in the vicinity of streams result will eventually result in increased stream flow.

B. Factors that control the long-term benefit of resting wells

A large number of factors control the benefits that are derived from resting wells. These factors control both the long-term magnitude of the benefits and the shorter-term timing of these benefits, as defined above. In general terms, the long-term magnitude of the benefits to a particular stream are dependent upon the fraction of the pumped water that would otherwise reach the stream (for gaining streams) or stay in the stream (for loosing streams) if it were not extracted at the well. These long-term benefits are a function of large-scale characteristics of the site-specific hydrogeologic system.

The magnitude of the long-term benefits was considered in an earlier study completed by the U.S. Geological Survey (Morgan and Jones, 1999). This study, which was completed using a computer model, focused specifically on the effects of ground-water withdrawals on discharge to streams and springs in watersheds typical of the Puget Sound lowland.[2] The USGS model was loosely based on the Soos Creek drainage basin and was developed based on the following assumptions:

1. All groundwater within the basin is derived from groundwater recharge due to precipitation. Groundwater inflow from adjacent basins was assumed to be negligible.
2. All groundwater within the basin discharges either to small streams and springs in the upper part of the watershed or to a large river and associated springs in the lower valley part of the watershed.

The USGS model was used to evaluate the relative impact of groundwater extraction on the smaller streams and springs in the upper part of the watershed versus impacts on the river and springs in the lower part of the basin. Conclusions that were derived from this study include the following:

[2] The long-term impacts were considered in the USGS study by using a three-dimensional, steady-state or equilibrium groundwater model developed using the MODFLOW software package. This model does not consider the length of time that would be required for these impacts to be realized.

1. A well pumped from an unconfined outwash aquifer that is in contact with a streambed will capture nearly all of its discharge by diverting flow from the nearest reaches of the stream. Increasing the distance between the well and the stream allows the well to capture some discharge from other stream segments in the upper part of the basin, but it does not affect discharge to springs on the valley walls or to the river in the lower valley.
2. When a confining layer separates the nearest stream from the pumped aquifer, the effects of pumping spread over a much area. The low-permeability confining layer forces the influence area or capture zone for the well to extend to greater distances to divert the natural discharge required to offset pumping.
3. The presence of a confining layer between the well and the stream is more important than the distance between the well and the stream in determining the distribution of capture of natural discharge throughout the basin.

In very general terms, the USGS study showed that from 80% to over 95% of pumped water is derived from upper streams for shallow wells completed in aquifers that are directly connected to streams. The study also showed that 50% to 80% of pumped water is derived from upper streams for deeper wells completed in confined aquifers that are not directly connected to streams. The magnitude of the impacts from these deeper wells depended upon depth and distance to stream.

C. Factors that control the timing of benefits of resting wells

The USGS model described above considered long-term or equilibrium impacts of groundwater extraction. The time lag between changes in groundwater extraction and changes in stream was not considered. The USGS model was subsequently modified in the current study to evaluate the time-lag or transient effects. The sensitivity study that was originally completed by the USGS regarding the effects of well depth and well location on the relative impact to streams in the upper and lower parts of the watershed was revisited in the current study using the transient analyses. Conclusions that were derived from this study include the following:

1. The time lag for stream flow benefits from resting wells depends on the stream depletion factor defined as follows:

   $$\text{Stream depletion factor} = L^2S/T$$

   where L is the distance from the well to the stream, S is the specific storage for the aquifer (a factor related to porosity), and T is the aquifer transmissivity (a factor related to aquifer thickness and permeability). Large values for stream depletion factors correspond to slow response times.
2. Resting wells in unconfined aquifers that have stream depletion factors greater than approximately 300 days will generally result in benefits to stream flow, but these benefits will be spread over the year. The time lags associated with these

benefits are generally larger than seasonal. The season or time period that the wells are rested may not be critical for these types of scenarios – resting a well during the winter months may improve summertime flows about as much as resting a well during the summer months.

3. Resting wells in unconfined aquifers that have stream depletion factors less than approximately 300 days may provide some seasonal benefit to stream flow. For these types of systems, resting wells before or during periods with low stream flow may provide more benefit than resting wells during other times.
4. Resting wells in confined aquifers that are more than 3000 feet from streams may result in stream flow improvements spread over the year – the time lags associated with these impacts are generally larger than seasonal.
5. Benefits and time lags from resting wells near streams are sensitive to streambed characteristics. More data describing these characteristics would be useful to help quantify these benefits and time lags.

D. Conclusions regarding approaches for streamflow restoration

Wells that are located and designed to provide municipal water supply will not likely be optimal in terms of providing water for stream restoration. Wells that are explicitly designed and located for aquifer recharge and subsequent stream restoration would likely provide a significantly better return rate in terms of the amount of water that is returned to the stream as a percentage of the amount that is not used for municipal supply purposes. The transient USGS model described in Section 5 could be used to evaluate groundwater recharge features such as infiltration ponds or groundwater injection wells. These types of facilities may prove to be a more effective way to increase stream flows during low-flow periods.

Table 1.1 – Summary of tasks and percentages of effort

Task	Description		Percent effort
1	Compile and integrate recent studies and reports that describe or relate to benefits derived from resting or pausing groundwater extraction		6%
2	Identify characteristics of individual candidate wells		52%
3	Modify USGS steady-state groundwater model and complete simulations		33%
4	Categorize specific wells that provide opportunities for improving in-stream flow conditions		9%
TOTAL			100%

2. TASK 1: RECENT STUDIES AND REPORTS THAT DESCRIBE OR RELATE TO BENEFITS DERIVED FROM RESTING OR PAUSING GROUNDWATER EXTRACTION

A literature review was completed to identify studies, reports, and publications that describe or relate to benefits that may be derived from resting or pausing groundwater extraction. The references that were identified during this literature review are listed in Appendix B.

Approximately sixty references were identified. Most of these references relate to analytical techniques or models and some have field data related to impacts. Relatively few explicitly consider resting wells and no references were identified that specifically considering resting wells in the Puget Sound region.

A. Overview of literature related to the benefits of resting wells

Conclusions that can be derived from the literature review include the following:

- There is a relatively large and developed set of literature that describes the hydrogeological processes and factors that affect rates of stream flow depletion caused by groundwater extraction. This literature dates from the middle part of the last century. The references listed in Appendix A under the heading "**Seminal Papers**" include some of these earlier studies.
- Many of the more recent studies that are included in the peer-reviewed literature focus on analytical tools that can be used to quantify stream depletion rates. These analytical tools have been developed to evaluate a variety of hydrogeologic conditions. Some of these more recent studies include field data, but many do not. The references listed in Appendix A under the heading "**Stream Depletion**" include the recent studies that specifically relate to stream depletion due to groundwater extraction.
- Effects of resting wells and seasonal pumping have been considered in the peer-reviewed literature. Recent studies that specifically consider the effects of resting wells and seasonal pumping on streamflow depletion include Chen and Shu (2006), Kendy and (2006), Singh (2006), Darama (2001), Chen (2001), and Wallace et al. (1990).
- Important parameters that affect the timing of impacts from groundwater extraction include the permeability or hydraulic conductivity of stream channel deposits and the thickness of these deposits. The thickness and permeability of these stream channel deposits are quantified using a variable defined as the streambed conductance. References listed in Appendix A under the heading "**Streambed Conductance**" include recent peer-reviewed literature that describe estimates of streambed conductance values.

- The peer-reviewed literature contains numerous references that relate to groundwater/surface water interactions, including processes that occur in the "hyporheic zone" immediately adjacent to the stream channel. While these references are not focused specifically on impacts of groundwater extraction on stream depletion, they are relevant because they describe important physical, chemical, and biological processes that can be affected by groundwater extraction near streams. References listed in Appendix A under the heading "**Groundwater/Surface Water Interactions**" include recent peer-reviewed literature that describe these processes.
- One of the important physical characteristics of streams that are affected by streamflow depletion is temperature. References listed in Appendix A under the heading "**Temperature**" include recent peer-reviewed literature that describe thermal effects related to groundwater/surface water interactions. These references relate specifically to methods for using stream and groundwater temperatures to quantify groundwater/surface water interactions.
- Streamflow depletion due to groundwater extraction has been studied extensively in the Canterbury district of New Zealand. References listed in Appendix A under the heading "**Canterbury New Zealand**" include reports that describe field studies and management approaches adopted by the Canterbury Regional Council that relate to stream depletion.
- Several software packages have been developed that specifically address stream depletion from groundwater extraction. These packages include the program STRMDEPL developed by the U.S. Geological Survey and the program IGARF II developed by the Environmental Agency of the United Kingdom. Information related to these software packages is included in Appendix A under the heading "**Software.**"
- No studies have been identified in the peer-reviewed literature or the government agency literature that specifically consider benefits that may be derived from resting or pausing groundwater extraction in the Puget Sound region.

3. OVERVIEW OF PROCESSES THAT RELATE TO BENEFITS DERIVED FROM RESTING OR PAUSING GROUNDWATER EXTRACTION

This section presents a general overview of the important hydrogeologic characteristics and processes that relate to stream flow depletion and that control these interactions. The hydrogeological processes that control groundwater-surface water interactions and the impacts of groundwater withdrawals on stream flow are described in numerous textbooks and reports. The following general description is derived from excerpts taken from Morgan and Jones (1999).

When a well first begins to withdraw groundwater, water is removed from aquifer storage as the water level drops. This forms what is described as a "cone of depression." At this early stage, the withdrawal is balanced entirely by a reduction in the amount of water that is stored in the aquifer. Effects on discharge to streams are generally negligible during these early times. As pumping continues, the cone of depression will expand until it reaches an area where ground water naturally discharges, as to a stream or spring. The groundwater that is extracted during these intermediate times is derived from a combination of two main sources: 1) a reduction in the amount of water stored in the aquifer, and 2) a reduction in the rate of discharge to surface water systems.

As the cone of depression continues to expand, water is removed from storage until the cone has expanded into a large enough area to capture sufficient natural discharge to completely balance the withdrawal at the well. Once this new balance is achieved, the ground-water system is in a new state of equilibrium and the reduction in natural discharge plus withdrawals equals the rate of natural recharge. If the cone of depression expands into a recharge area rather than a discharge area, additional recharge to the aquifer may be induced. For example, groundwater inflow from wetlands in groundwater recharge areas may be increased due to downstream groundwater extraction. In cases where pumped wells are located near a stream or the cone of depression expands far enough, the hydraulic gradient can be reversed so that ground-water discharge to the stream stops entirely and water will be induced to move from the stream into the aquifer as additional recharge. A more typical effect, however, is that the groundwater extraction reduces the rate of discharge to the stream, rather than actually reversing flow out of the stream.

Most of the water supply wells in WRIA 8 and 9 are completed in either shallow unconfined aquifers or in semi-confined or "leaky" aquifers. Shallow unconfined aquifers are in most direct continuity with streams. The connection for wells in leaky, semi-confined aquifers is less direct, but not less important. In a leaky aquifer, a portion of the water extracted by the wells may originate from storage in the pumped aquifer and a portion may come from leakage through confining layers. When pumping first begins, the water comes primarily from storage in the pumped aquifer. As time goes on, more of the water that is extracted originates as leakage through the confining layer.

Analytical tools have been developed to estimate the response time for reductions in stream flow caused by groundwater extraction wells. Recent work includes Sophocleous et al., 1995, Hunt, 1999; Hunt et al, 2001; Hunt, 2003a; Hunt, 2003b; and Nyholm et al, 2003. A software package of analytical tools has also been recently developed by the Environment Agency of England. The objective of the software is "*to develop a reasoned, robust and technically supportable rationale for evaluating the effects of groundwater abstraction on river/groundwater interaction*" (IGARF1 v4 User Manual, Environment Agency, Science Group – Air, Land & Water, May 2004, p. 11).

In one of the more recent references regarding impacts of cyclically pumping at a well, Bredehoeft and Kendy (2006) examine the impact of a single well pumping, first located 0.3 km (0.2 mile) from the stream and then relocated 2.9 km (1.8 miles) from the stream. Their conclusion regarding impacts on streamflow provide a succinct summary of the benefits that may be derived from resting wells:

> *"In summary, the impact of pumping groundwater depends upon the aquifer properties and the distance of the well from the stream. The most important factor is the distance from the well to the stream. Moving the well away from the stream makes the impacts become more constant and decreases the annual fluctuation so that the impacts of a distant well on the stream are relatively constant through time."*

Resting wells that are close to streams result in stream flow benefits that vary with time – the benefits are more pronounced during periods of resting. Resting wells that are more distant from streams result in stream flow benefits, but these benefits are more constant and uniform. These phenomena and the characteristics that control them are discussed in more detail in the sections that follow.

A. Quantifying effects of groundwater extraction for wells in unconfined aquifers

Figure 3.1 illustrates effects of groundwater extraction on stream flow for wells in unconfined aquifers. The top figure illustrates an example flow scenario where a recharge area contributes groundwater that supports stream flow in an unconfined aquifer. The stream in this illustration is a gaining stream, which is typical for streams in WRIA 8 and 9.

The middle figure illustrates flow directions that may develop in the vicinity of an extraction well. In this middle scenario, the stream continues to receive groundwater inflow, but at a rate that is less than under the pre-pumping scenario. A groundwater divide is formed between the pumping well and the stream. Recharge between the well and divide flows to the well while recharge between the divide and the stream continues to flow to the stream.

The bottom figure illustrates flow directions that may develop in the vicinity of an extraction well under higher pumping rates or at later times than the middle scenario. In this bottom scenario, groundwater flow reverses direction in the vicinity of the stream.

The stream no long receives groundwater inflow, but rather becomes a “losing” stream that contributes flow to the groundwater system.

Groundwater wells in WRIA 8 and 9 typically do not result in losing streams (as shown in Figure 3.1B), but rather in streams where the rate of groundwater discharge is reduced (as shown in Figure 3.1A).

The timing of the effects of wells on stream flow can be quantified for relatively simple flow systems using analytical expressions. The timing of these effects depends in part on the “stream depletion factor” (sdf):

$$sdf = L^2S/T \qquad \text{(Equation 3.1)}$$

where

- L: distance from the well to stream
- S: specific storage (related to aquifer porosity)
- T: transmissivity (related to aquifer thickness and permeability)

The stream depletion factor has units of time. Large values correspond to slow response times.

For a fully-penetrating well in an aquifer that is also fully-penetrated by a stream, the stream depletion rate is given by (e.g., Jenkins, 1968)[3]:

$$\frac{q}{Q} = erfc(\sqrt{\frac{sdf}{t}}) \qquad \text{(Equation 3.2)}$$

where

- q: increase or reduction in stream flow (L^3/t)
- Q: pumping rate at the well (L^3/t)
- sdf: stream depletion factor (L)
- t: time after initiation of pumping

Equation 3.2 was developed assuming that the aquifer is homogeneous, isotropic, and semi-infinite in areal extent, the transmissivity is constant with time and space (i.e., that drawdown is negligible compared to the aquifer thickness), the water table is initially horizontal, and the pumping rate is constant with time. The expression can be used to quantify the impacts of stream depletion due to groundwater extraction well or the impacts of stream flow increased that result from resting wells that have been in operation for a long period of time.

[3] The notation “erfc” represents the complementary error function. This is a callable function in Excel and other spreadsheets and is used in much the same way as other callable functions such as “sine” or “cosine” or “logarithm.”

Stream depletion for wells that are operated on a cycle can be quantified using Equation 3.2 with super-position of recharge and discharge wells (Wallace et al., 1990). An example set of results is shown in Figure 3.2 for a flow system with stream depletion factor of 1 day. This example considers the effects of resting a well that has been in operation for a long enough period of time so the groundwater system is initially in equilibrium. The groundwater well is shut-off for four months beginning at time zero. The stream flow increases with time at a rate that is given by Equation 3.2. This is shown by the initial curve. After four months of resting, the stream flow rate has increase by an amount that is equal to approximately 90% of the steady-state pumping rate at the well. For example, if the well had been operated continuously at a rate of 1,000 gallons per minute (gpm), the stream flow would be increased by approximately 900 gpm after 4 months of resting.

If the well is then turned back on after four months of resting, the stream flow decreases and eventually the reduction in stream flow is approximately equal to the pumping rate (e.g., 1,000 gpm). The recharge that resulted from resting has effectively been reduced to zero at this point, as shown in Figure 3.2. The effects of repeated cycles of pumping are shown at later times on Figure 3.2.

The horizontal line shows the annual average impact of resting the well for four months each year. On an annual basis, the average stream flow is increased by 33% using this four months of resting. A comparison of the annual average impact (33%) with the time-varying impact (from 0% to approximately 90%) show that for a stream depletion factor of 1 day, seasonal impacts can result from resting wells.

Figure 3.3 compares the timing of impacts for system with different stream depletion factors. The larger the stream depletion factor, the smaller is the seasonal impact from resting wells. The results in Figure 3.3 also illustrate that substantial time may be required before the system reaches a "dynamic equilibrium" wherein the average impact to the stream is equal to the percentage of time the well is resting. For example, for a stream depletion factor of 500 days, the annual average stream recharge after four annual cycles of resting is approximaltey15%. The long-term impact, which is 33% for an annual resting cycle of 4 month each year, would eventually be achieved after a longer number of cycles.

The results shown in Figure 3.3 can be used to qualitatively evaluate the type of systems wherein there will likely be seasonal benefits to resting wells. For systems with stream depletion factors greater than approximately 300 days, there is little seasonal variation in the benefit from resting wells. The benefit in these systems will be approximately equal to the proportion of time the well is rested, regardless of the season in which the wells are rested. For example, the benefit during the summer from resting wells during the winter will be approximately equal to the benefit from resting the well during the summer months. This benefit will eventually be approximately equal to the proportion of time the well is rested. The results in Figure 3.3 also show that the benefits may not be realized until after several annual cycles in these systems with larger stream depletion factors.

Wallace et al. [1990] published a theoretical paper on stream depletion caused by cyclic pumping. They define a condition of dynamic equilibrium in which the stream depletion in one cycle is equal to the quantity of water pumped during that cycle. The time required for the system to reach this state of dynamic equilibrium depends upon the distance from the well to the stream and the hydraulic characteristics of the aquifer.

Wallace et al. [1990] presented an equation that describes the time needed for the impacts of a cyclically-pumped well to reach within 95% of dynamic equilibrium values:

$$t_e \approx 127(sdf) \qquad \text{(Equation 3.3)}$$

where t_e is the time to reach 95% of dynamic equilibrium and sdf is the stream depletion factor defined in Equation 3.1 Equation 3.3 is valid if the ratio of the pumping or resting cycle divided by the stream depletion factor is less than approximately 10. For systems with larger ratios, the well us close enough to the stream to reach equilibrium within the first pumping period so that the non-uniform pumping pattern is an accurate representation of the stream depletion pattern (Wallace et al, 1990). An example of this situation is shown in Figure 3.1.

Table 3.1 gives stream depletion factors for different combinations of distances between the well and the stream (L) and transmissivity, T. The results in Table 3.1 were derived using a specific yield, S, equal to 0.1. This is a typical value for unconfined aquifers.

Highlighted cells give combinations of distance to stream, L, and transmissivity, T, that result in stream depletion factors less than 300. These cells identify systems where there may be seasonal differences in the benefits derived from resting wells. For larger values of SDF, benefits to the stream are less dependent upon when wells are rested and will be approximately equal to the proportion of the time the well is rested, regardless of when this resting occurs.

B. Quantifying effects of groundwater extraction for wells in confined aquifers

Analytical expressions developed by Hunt (2003a, 2003b; 2005) can be used to quantify effects of resting wells in confined or semi-confined aquifers. Figure 3.4 illustrates the geometry assumed by Hunt. A groundwater extraction well located a distance, L, from a stream is pumped at a rate, Q, in a confined or semi-confined aquifer. The hydrogeologic properties of the aquifer include transmissivity, T, and storativity, S. The hydraulic properties of the confining unit include the hydraulic conductivity, K', the storage coefficient, S_s, and the porosity, σ. The EXCEL spreadsheet developed by Hunt (2005) is a useful tool simulating impacts.

The sensitivity of stream flow depletion rates to site-specific geometry and hydrogeology can be estimated using the following equation (from Hunt, 1999):

$$\frac{q}{Q} = erfc\left(\sqrt{\frac{SL^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda L}{2T}\right) erfc\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{Sl^2}{4Tt}}\right) \qquad \text{(Equation 3.4)}$$

where q, Q, S, L, t, and T are as described above. The parameter, λ, describes the conductance or "leakiness" of the streambed or confining aquitard:

$$\lambda = \frac{K'b}{B'} \qquad \text{(Equation 3.5)}$$

Where K' and B' is the hydraulic conductivity and the thickness of the streambed or the confining aquitard and b is the width of the stream.

Figure 3.5 presents solutions to Equation 3.5 for a system comprised of a well that is rested for 120 days after being pumped continuously. It is assumed that the well had been pumped for a long enough period of time prior to resting that equilibrium conditions had been achieved. The vertical axis in Figure 3.5 gives the stream recharge as a function of the pre-resting pumping rate. For example, if a well that is 1,000 feet from the stream had been pumped continuously at a rate of 1,000 gpm and is then rested, the increase in stream flow after 120 days would range from approximately 110 gpm (for a streambed conductivity of 0.1 ft/day) to approximately 850 gpm (for a streambed conductivity of 10 ft/day). These values are shown as a percentage of the pre-resting pumping rate in Figure 3.5a.

The example results described in Figure 3.5 show the sensitivity to distance from the stream and streambed hydraulic conductivity. Table 3.2 lists parameters that are common to all simulations. The results shown in Figure 3.5 illustrate that the magnitude and timing of the response to resting wells depends upon distance to the stream and streambed hydraulic conductivity. Because of difficulties in measuring streambed hydraulic conductivity, there will often be considerable uncertainties associated with the magnitude of impact.

Table 3.1. Stream depletion factors in days for different combinations of distances between the well and the stream (L) and transmissivity, T. Specific yield, S, is equal to 0.1.

	Transmissivity, T (ft2 per day/gpd per ft)				
Distance, L (ft)	**100/ 750**	**500/ 3750**	**1000/ 7500**	**3000/ 22500**	**10000/ 75000**
100	10	2	1	0.3	0.1
500	250	50	25	8	3
1000	1000	200	100	33	10
3000	9000	1800	900	300	90
5000	25000	5000	2500	833	250
10000	100000	20000	10000	3333	1000

Table 3.2. Variables used for examples shown in Figure 3.5:

Stream width	10 ft
Streambed conductance	0.1 to 10 ft/day
Thickness of streambed	5 ft
Saturated thickness of aquitard	15 ft
Aquitard conductivity	0.0025 ft/day
Thickness of aquifer	40 ft
Aquifer conductivity	100 ft/day

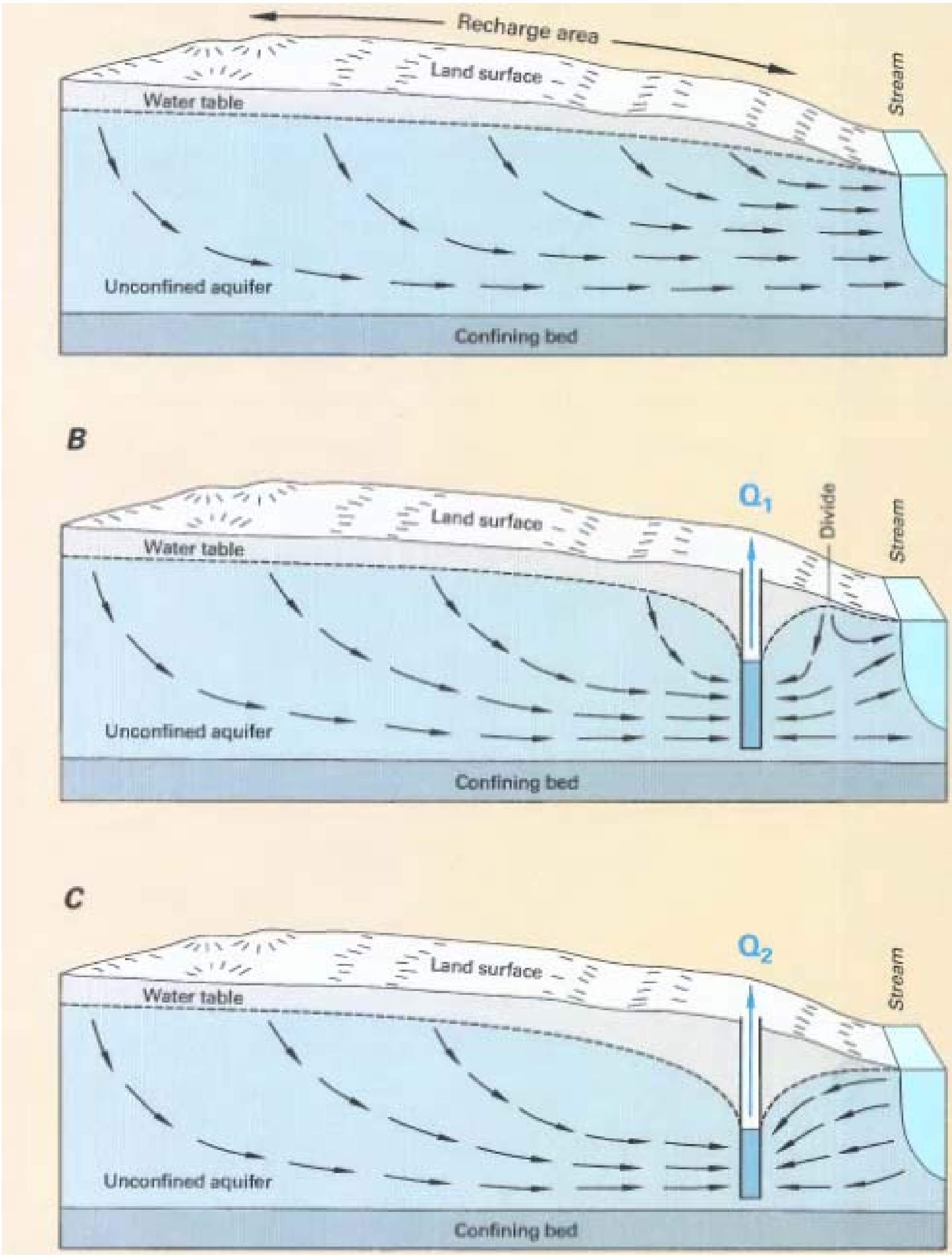


Figure 3.1. Groundwater extraction from wells in an unconfined aquifer.
From Winter et al. (1999)

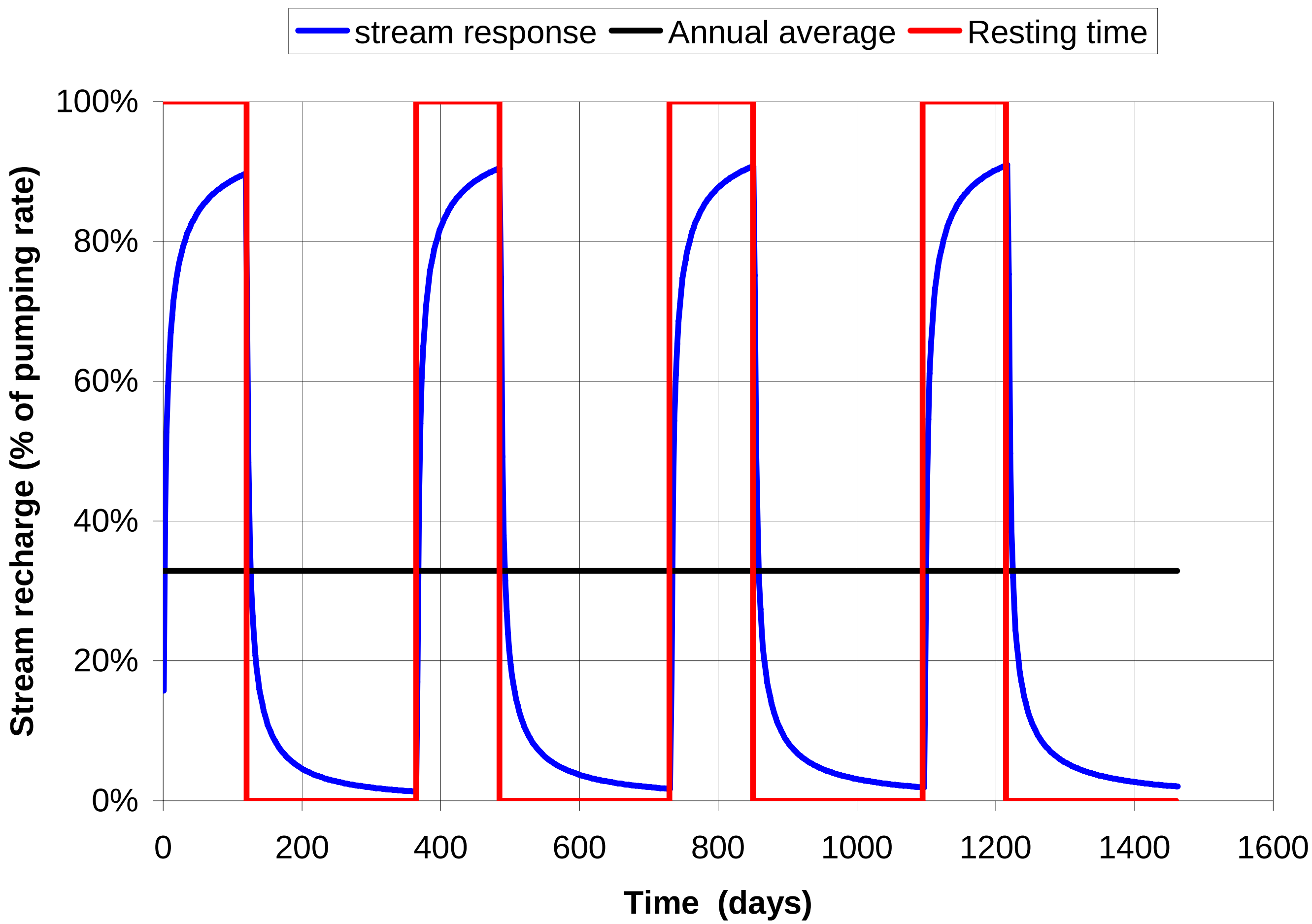


Figure 3.2. Stream depletion for a groundwater extraction well that is operated cyclically with 8 months of extraction followed by 4 months of resting

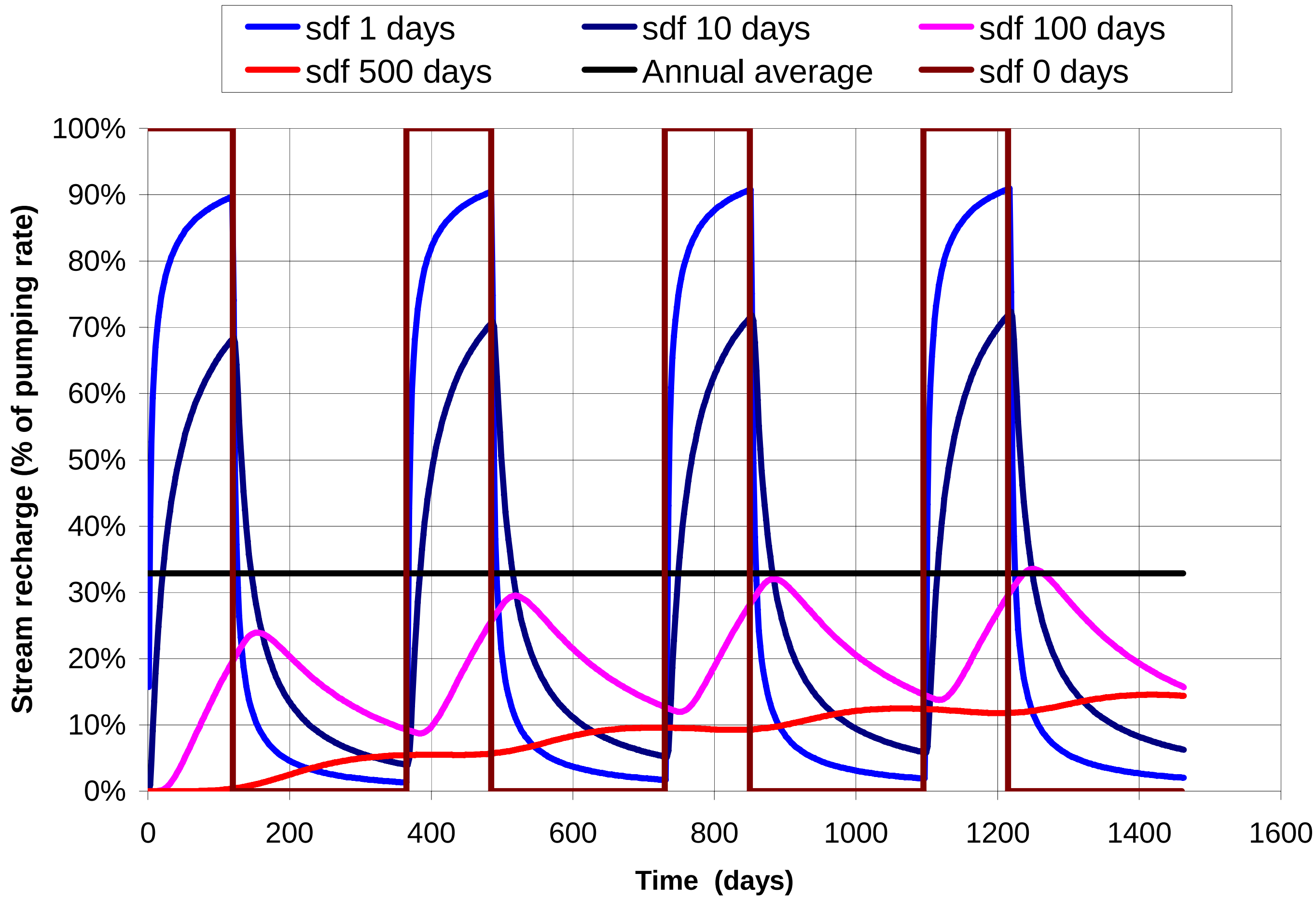


Figure 3.3. Response to resting wells depends on stream depletion factor (sdf) = L2S/T

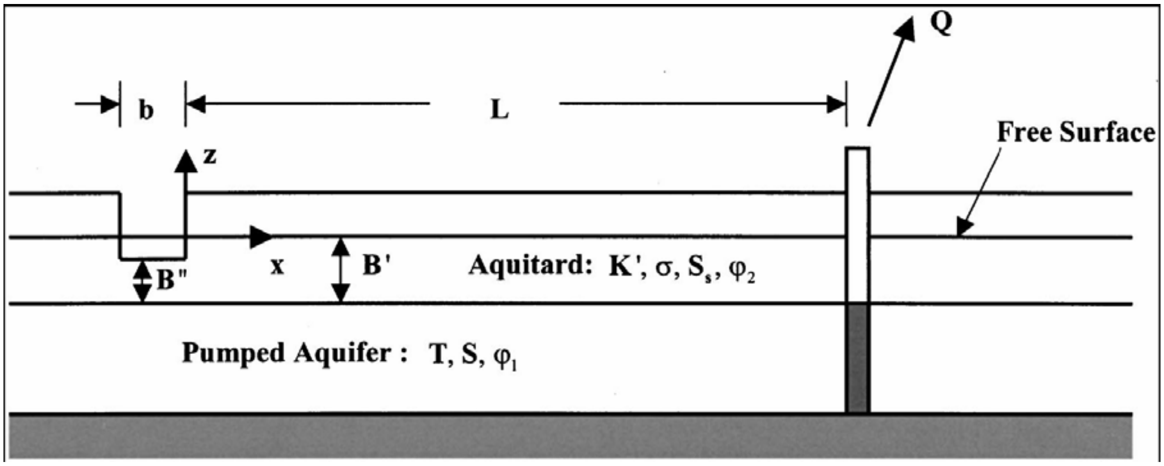


Figure 3.4. Definition of variables and geometry for analytical expressions used to estimate impacts in confined aquifers.
From Hunt (2003a)

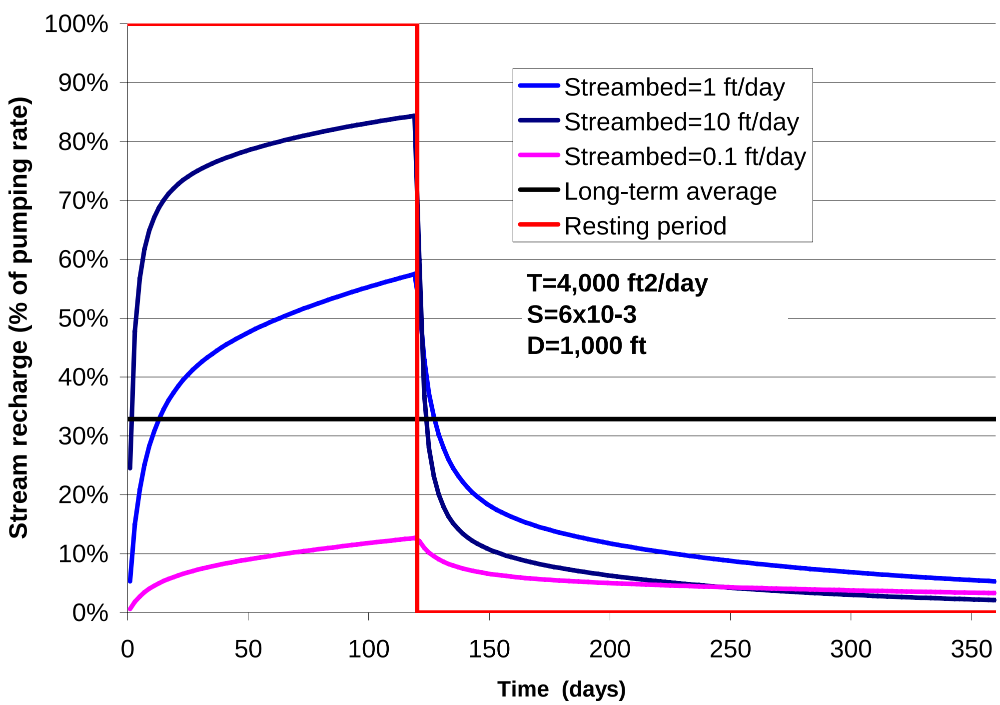


Figure 3.5a. Example results for a well 1,000 feet from stream

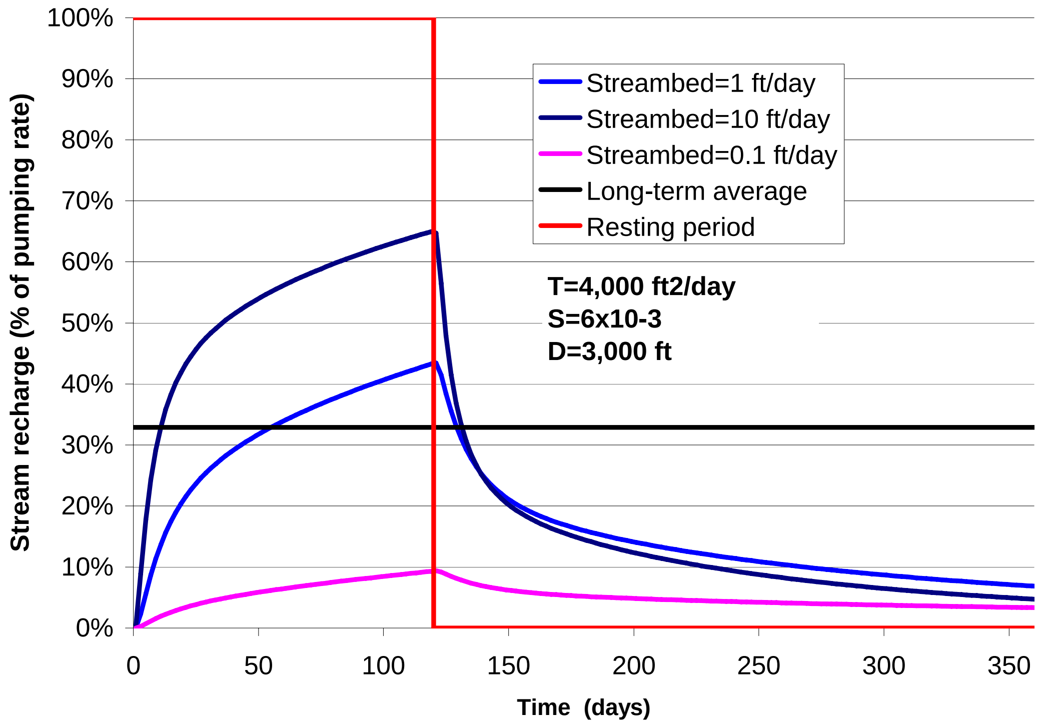


Figure 3.5b. Results for well 3,000 feet from stream

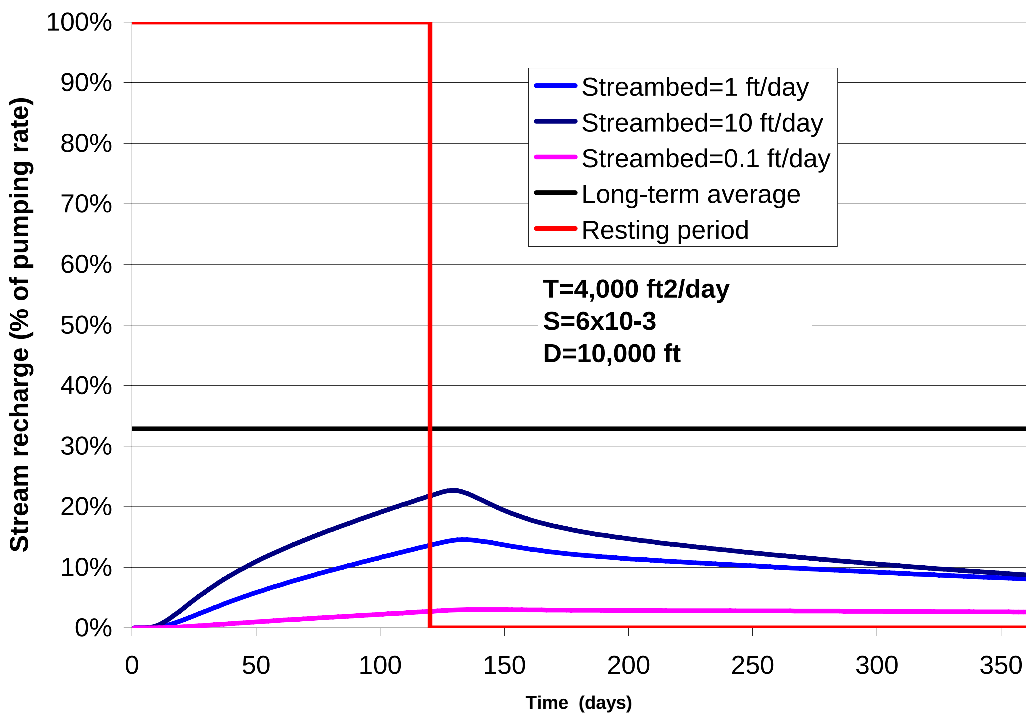


Figure 3.5c. Results for well 10,000 feet from stream

4. TASK 2: OVERVIEW OF GROUNDWATER WELLS IN WRIA 8 AND 9

Note: This task and description were completed by RH2 Engineering, Inc. Electronic files developed as part of this task are included on the data disk that accompanies this report. The figures and tables referenced below are included in Appendix C.

Task 2 involved a compilation of available hydrogeologic and/or water resource reports from water purveyors in WRIA 8 and 9 to extract data from the reports that would support the evaluation of the well pausing hypothesis as an option to meet source exchange objectives. In addition, this study reviewed available reports for data potentially useful for groundwater modeling of a conceptual groundwater system and/or modeling of an actual groundwater system to evaluate the well pausing hypothesis.

The locations of the groundwater sources described in the reports were compiled into a GIS database showing the locations of water systems and sources in WRIA 8 and 9.

A. Data Compilation

Approximately 90 paper and electronic copies of available pumping test reports and water resource summary reports for WRIA 8 and WRIA 9 were reviewed. Additional reporting data from water comprehensive plans, wellhead protection plans, and source information filed with the Department of Health were reviewed and compiled. Most of the reports were available for electronic reproduction and scanned and compiled onto two electronic data discs. Several reports were reviewed but available for scanning.

The summary of data extracted from the hydrogeologic reports includes general well conditions, location, ownership, and status (active, emergency, inactive); testing conditions; estimated aquifer properties and types; proximity to surface water; general surface water body conditions (depth, seasonal flow, sediment type); and a summary of the assumptions, findings, and utility of the reports. These summaries are presented in Table 1. Table 2 summarizes groundwater source data for larger supply wells in WRIA 8 and 9 which were obtained from public records at Washington Department of Health. Both Tables 1 and 2 are available in Excel worksheets on the CDs.

Attempts were made to use pumping test drawdown curves to estimate leakage factors using the Hantush method or similar approach. However, it was not possible to derive useful leakage factors from test curves, as the testing did not sufficiently document conditions necessary to evaluate the leakage factors. The testing typically was conducted to evaluate the specific yield of the well (withdrawal rate versus drawdown) to meet Washington Department of Health source approval requirements. To provide adequate data for estimating leakage factors, the well testing would have required longer pumping periods, analysis of stratigraphy and water level monitoring in various hydrostratigraphic units. Most tests were conducted without the use of observation monitoring wells.

To put the hydrogeologic and water resource reports in context with WRIA 8 and 9, a GIS map (Figure 1) was prepared showing the well locations and their position within their respective service areas, and their proximity to surface water bodies. Wellhead protection areas for the larger sources of groundwater supply for each purveyor in WRIA 8 and 9 were obtained from public records provided by Washington Department of Health and included to indicate the potential recharge area of larger supply wells in WRIA 8 and 9, to support the objectives of source exchange evaluation and the well resting hypothesis. The CD contains the shape files for Figure 1.

B. Findings and Conclusions

The general quality and utility of the reports was sufficient to compile an initial database that represents the range of aquifer characteristics for regionally important groundwater sources in WRIA 8 and 9. The general range of aquifer parameters is consistent with expected values for aquifers in lowland and upland areas, and aquifers that exhibit either confined or unconfined conditions.

Initial compilation supports understanding of regional aquifer characteristics and the potential application of the well pausing hypothesis. The summary of aquifer characteristics and geographic relationship between points of groundwater withdrawal and nearby surface water bodies may be used to develop a regional picture of the opportunities for source exchange. For example, the potential benefit of pausing a well on stream flow increases with decreasing depth, distance, and confinement of the well. Inspection of Tables 1 and 2 can indicate areas where greatest benefits of the well pausing approach may occur.

The database represents the initial compilation of a larger library of hydrogeologic, watershed, and water resource studies that contain data useful for evaluation the potential opportunities and benefits of the well pausing hypothesis. Many reports similar to those compiled in this study likely exist and their compilation and review would improve the understanding of WRIA 8 and 9 groundwater source characteristics and opportunities for well pausing.

5. TASKS 3: MODIFICATIONS TO THE MORGAN AND JONES MODEL FOR TRANSIENT SIMULATIONS

Task 3 involved modifying the USGS steady-state groundwater model developed for simulating aquifer systems in the Puget Sound lowlands (Morgan and Jones, 1999) so that it can be used to simulate transient or time-varying effects of groundwater extraction. The transient model was then used to help identify well characteristics and hydrogeologic conditions necessary to obtain significant flow improvements from seasonal resting. The revisions to the Morgan and Jones model are described in the sections that follow. Model applications are described in Chapter 6.

The Morgan and Jones model was revised in several iterations. These iterations were built from a common "base" model described in Morgan and Jones (1999). The transient models described in this chapter are directly based on that original model. Aspects of the model that were not changed are not generally described in the section below. The reader is referred to the original Morgan and Jones reference for details regarding their model. The multiple iterations or model revisions are included on the data disk so that interested parties can use a version that best suits their needs or objectives.

The model input files are included in the data disk that accompanies this report. The input files were developed using the Groundwater Vistas software (GW Vistas). This software is a graphical user interface that allows the MODFLOW input and output files to be more easily revised, viewed, and evaluated. The GW Vistas software package is one of the industry's standards for running MODFLOW models.

Groundwater modeling was conducted by Joel Massmann of Keta Waters, LLC and by Peter Bannister of Aspect Consulting, under the direction of and under subcontract to Joel Massmann of Keta Waters, LLC.

A. Overview of Model Iterations

Six model iterations are summarized in the paragraphs that follow. These iterations are described in very general terms in Table 5.1. The model used in all iterations is comprised of 70 rows, 50 columns, and 13 layers for a total of 45,500 cells. The number of active cells in the model is 29,760. This is the same as the original Morgan and Jones model.

With two exceptions, the hydrogeologic parameters were the same in all model iterations and were also equal to the Morgan and Jones values. These parameters are described in Table 5.2. The two exceptions relate to the vertical hydraulic conductivity value assigned to the glacial till layers and the storage coefficient. The vertical hydraulic conductivity of the till layers was changed for different iterations. These changes are summarized in

Table 5.3. The original Morgan and Jones model is a steady-state model and does not include storage coefficients.

Recharge rates for the different iterations are described in Table 5.3 for model iterations with constant recharge. Unique recharge rates are assigned to areas depending on whether the near-surface soils are glacial till or glacial outwash. Approximately 74% of the active model area is covered with glacial till and the remaining 26% is covered with outwash. This is the same as in the Morgan and Jones model. The recharge rates assigned to these two materials was 17.8 inches per year for till and 27 inches per year for outwash. This combination of rates results in a net recharge of approximately 20.1 inches.

Some of the model iterations include transient recharge rates that varied on monthly time steps. These rates are described in Table 5.4.

Other characteristics of the different model iterations are summarized below. Detailed information regarding the different iterations is also available from the GW Vistas model input files on the accompanying data disk.

Model CWA001. This is the first iteration of the model and represents the original Morgan and Jones model imported into the GW Vistas software. No changes were made to the basic input datasets. The advantage of this version over the original Morgan and Jones MODFLOW files is that the input and output files can be more readily changed and reviewed using the GW Vistas graphical interface.

Model CWA005. This is the first transient iteration of the model. It was noted that the calculated water levels from the original Morgan and Jones model were higher than expected and above ground surface throughout much of the model domain. In an attempt to reduce the water levels, a large number of drain cells were added to the upper layers of the model. These drains were added to all cells that were at the ground surface. The intent was for these drain cells to provide a “natural” way for the excess water to exit the model. The recharge rates assigned to the model were steady values. The rate was equal to 17.8 inches per year for till and 23.3 inches per year for outwash. This lower value for outwash (the value used by Morgan and Jones was 27.0 inches per year) was also an attempt to reduce the high calculated water levels. The net recharge for this scenario was 19.6 inches.

Model CWA015. The primary difference between this iteration and previous iterations relates to recharge rates. Previous iterations used constant recharge rates. Recharge rates were varied in this iteration on a monthly time step. The monthly values are listed in Table 5.4. The net recharge for this scenario was 20.3 inches. Relatively high recharge rates were required to keep cells from drying out during the summer months. Cells that alternate between wet and dry often cause instabilities in the MODFLOW software and higher recharge rates resulted in fewer instabilities.

Model CWA107. The SURFACT computer program was used in this iteration to address stability issues associated with wetting and drying cells.[4] This computer program, which is designed to better simulate saturation and de-saturation processes, allowed lower recharge rates, as listed in Table 5.4. The net recharge for this scenario was 12.8 inches. The water levels for this scenario were more reasonable with relatively few locations where levels exceeded the ground surface. The model requires significantly more computational time and effort and requires purchasing the additional SURFACT package. The model will not run using the MODFLOW software.

Model CWA110. The original Morgan and Jones model was loosely based on the hydrology and hydrogeology of the Soos Creek drainage basin. This is discussed in more detail in Chapter 6. The Soos Creek basin had been "re-scaled" in the Morgan and Jones model to make it approximately four times larger than the actual basin. The number and distribution of streams remained the same so that each stream effectively drained a much larger area than in the real world. This contributed to the unreasonably high water levels for reasonable recharge rates. Model geometry was restored to actual size and recharge rates were assigned accepted values. With the reduced basin size and the large number of drain cells used in this model iteration, relatively high recharge rates could be applied to the model with out causing unreasonably high water levels. A recharge rate of 48 inches per year, which is roughly equal to the annual precipitation rate, is applied to the model with this iteration. The excess water will "run-off" to the drains that represent the ground surface. This version of the model requires purchasing the additional SURFACT package. The model will not run using the MODFLOW software.

Model CWA311. Reducing the flow domain to a size that is more consistent with the actual drainage basin area for the Soos Creek basin resulted in reduced water levels, as compared to the model that was used in the Morgan and Jones report. The drain cells that had been added in earlier iterations to reduce water levels were therefore removed in this iteration. The number and location of river and drain cells in this iteration of the model are the same as what was used in the original Morgan and Jones model. This model was used for "generic" simulations aimed at evaluating transient effects of wells. Two sets of models were developed; one set uses a grid spacing of 500 feet (CWA311_500) and the second using a grid spacing of 750 feet (CWA311_750). Model file CWA311b is used for steady-state simulations and model file CWA311a is used for transient simulations.

[4] http://www.scisoftware.com/products/modflow_surfact_overview/modflow_surfact_overview.html

Table 5.1 – Summary of model iterations.

Model Iteration	Date Created	Summary Description	Cell size (ft)	Drain cells	River cells
CWA001	4/28/2007	Original Morgan and Jones, steady-state	1500	443	339
CWA005	5/2/2007	Incorporated surface drains, steady state	1500	3241	0
CWA015	5/3/2007	Transient model with transient recharge	1500	3241	0
CWA107	6/12/2007	SURFACT model with revised recharge matrix	1500	3238	0
CWA110	8/16/2007	MODFLOW, revised scale, transient recharge	**750**	3238	0
CWA311_500	10/10/2007	MODFLOW, steady recharge, generic simulations	**500**	443	330
CWA311_700	10/10/2007	MODFLOW, steady recharge, generic simulations	**750**	443	330

Table 5.2 – Summary of hydrogeologic parameters used in all model iterations.

		Model Layers	Layer Thickness (ft)		Hydraulic Conductivity (ft/d)		Specific Storage (1/ft)
Symbol	**Geologic Layer**		**Range**	**Mean**	**Horizontal**	**Vertical**	
Qal	Alluvium	9-13	10-500	400	50	5	1.0E-05
Qr	Recessional outwash	1,5,9	10-50	29	100	10	1.0E-05
Qt	Till	2,6,10	10-50	25	0.25	**varies**	1.0E-05
Qa	Advance outwash	3,7,11	10-115	36	100	10	1.0E-05
Qf	Interglacial sediments	4,8,12	10-150	60	1	0.005	1.0E-05
Qu	Undifferentiated deposits	13	10-480	275	25	0.167	1.0E-05
Tb	Bedrock	No-flow boundary					

Table 5.3 – Recharge rates for model iterations with constant recharge and vertical hydraulic conductivity for till layers.

Model	**Recharge for till**	**Recharge for outwash**	**Kv**
	(inches/year)		(ft/day)
CWA001	17.8	27.0	2.5×10^{-3}
CWA005	17.8	23.3	2.5×10^{-4}
CWA015	transient recharge		2.5×10^{-4}
CWA107	transient recharge		2.5×10^{-3}
CWA110	transient recharge		1.0×10^{-3}
CWA201	17.8	27.0	2.5×10^{-3}
CWA311	17.8	27.0	2.5×10^{-3}

Table 5.4 Recharge rates for model iterations with transient recharge.

	Recharge rates (inches/month)		
Month	**CWA015**	**CWA107**	**CWA110**
1	0.64	2.07	3.94
2	1.22	3.29	6.37
3	2.60	3.00	7.44
4	3.18	2.30	6.30
5	3.10	1.60	5.47
6	3.09	0.52	4.65
7	2.14	0.00	3.30
8	1.55	0.00	2.69
9	1.02	0.00	2.30
10	0.73	0.00	1.24
11	0.54	0.00	1.60
12	0.51	0.00	3.00
Annual average recharge (inches/year)			
	20.32	**12.77**	**48.29**

6. TASK 4 RESULTS

The objective of Task 4 was to evaluate potential improvements in in-stream flow conditions through seasonal pausing of groundwater extraction wells. This task included an assessment of the percent and timing of in-stream flow restored, the length of stream benefiting from flow restoration, and a recommendation on the period of time to pause withdrawals to maximize benefit to stream flow during the July – October low flow period.

A. Assessment of potential improvements through well resting

Potential improvements that may be derived through well resting were evaluated using the transient model described in Section 5. Results from simulations completed using model CWA311_750 are described below. Additional results are included in the spreadsheets "CWA30x_BRReport_750.xls" and "CWA30x_BRReport_500.xls" provided on the data disk that accompanies this report.

Table 6.1 summarizes the model simulations that were completed with the CWA311 model. The base model (Model CWA311) considers an extraction well located in the upper Qvr aquifer at a distance of 1500 feet from the stream. Other simulations were completed that consider wells at other locations and depths, as described in Table 6.1.

A description of the model input parameters including hydraulic conductivity values and stream characteristics are described in Morgan and Jones (1999). This reference is included in the disk that accompanies this report. The additional parameters that were added for the transient analyses were storage coefficients. The values that were used are described in Table 6.2

For each scenario, the model was first run to obtain a steady-state solution with a constant pumping rate of 1200 gpm. These steady-state solutions were used as initial conditions for transient simulation. The transient simulations were completed to evaluate the effects of the resting the well for the time period of July 1 to October 31. Six years of these cycles were simulated for each scenario.

Example results are included in Figures 6.1 through 6.16. The results shown in Figures 6.1 and 6.2 show the discharge rates for different stream and spring segments under a steady-state, no-pumping scenario. The locations of these stream and spring segments is the same as used in Morgan and Jones (see Figure 6, page 18, Morgan and Jones, 1999).

Figures 6.3 and 6.4 show the changes in flows to the different stream segments under a steady-state, constant pumping scenario for a well located in the upper Qvr aquifer. Results for three scenarios are included in Figures 6.3 and 6.4. The first scenario includes a well in the same model cell as the stream while the second and third scenarios consider a well 1500 and 3000 feet from the stream, respectively.

Figure 6.5 shows the results for a well near the stream completed at different depths. Figure 6.6 shows results for a well that is located 3,000 feet from the stream at different depths. Placing wells in deeper aquifers results in more impact to lower streams and less impact to upper streams, as expected.

The results described above and included in Figures 6.1 through 6.6 consider steady-state simulations similar to what is reported in Morgan and Jones (1999). The results of transient simulations are included in Figures 6.7 through 6.16. Figures 6.7 through 6.9 consider the effects of wells located in the Qvr aquifer at different distances from the stream. The vertical axis gives the differences in discharge to various stream and spring segments for the pump-resting scenarios, as compared to the constant pumping scenario.

The curves represent total or net impact. The top curve gives the combined effect on all four types of spring and stream segments. The impact to upper streams is given by the lower curve. The impact to upper springs is equal to the difference between the curve for upper springs and the curve for the upper streams. The impact to lower springs is equal to the difference between the curve for lower springs (the upper curve in Figures 6.7) and the curve for lower streams.

Figures 6.7 through 6.13 give the amount of flow that is returned to the streams and springs through pump-resting, as compared to a continuous-pumping scenario. The pump-resting scenarios, wherein the pump is rested for 4 months of the year and is operated at a rate of 1,200 gpm during the remaining 8 months, results in 0.9 cfs of additional flow on an annual basis. Some of this additional flow is returned to storage in the aquifer system and some is returned to spring and streams. The rate at which it is returned to the springs and streams is shown in Figures 6.7 through 6.13. Wells that are closer to the streams and more shallow cause more immediate increases in stream flow, as expected.

The results shown in Figures 6.7 through 6.13 are consistent with the analytical results described in Section 3. There is relatively little seasonal benefit from resting wells that are relatively deep and distant from the stream, similar to what is shown in Figure 6.13. It should be noted, however, that there is benefit from resting these types of wells, but the benefit is spread over the year and is less seasonally-dependent than benefits from shallow wells that are close to streams.

Figures 6.14 through 6.16 shows which areas or segments of the flow system are impacted most through resting of wells. The values givens in these figures represent annual averages over the 6 years simulations. For example, Figure 6.14 indicates that between 44% and 50% of the water that is not pumped through well resting results in increased stream flows, depending upon the distance from the stream. These results are for wells that are completed in the Qvr aquifer. Figure 6.15 compares the results for wells near the stream in different aquifers while Figure 6.16 compares results for wells distant from the stream. The minimum amount that is returned to upper streams is approximately 20% and occurs for wells that are completed in the deeper QAc aquifer.

B. Identification of wells with potential for flow restoration from seasonal pausing

The analytical modeling results included in Sections 3 and the numerical modeling results included in this section suggest that relatively shallow wells within approximately 3,000 feet of streams provide the best likelihood for seasonal benefits from well pausing. Wells that are more distance and more deep may result in benefits to streamflow, but these benefits will be spread over the year.

Table 6.3 gives examples of wells in WRIA 8 and 9 that are less than 3,000 feet from streams and that are relatively shallow. This table was developed based on the data set developed by RH2 Engineering, Inc, as described in Section 2.

It should be noted that the modeling results described above suggest that the benefit to nearby streams that may be derived from resting wells may be less than 50% of the water that is not pumped. This is shown, for example, in Figures 6.14 through 6.16.

Wells that are located and designed to provide municipal water supply will not likely be optimal in terms of providing water for stream restoration. Wells that are explicitly designed and located for aquifer recharge and subsequent stream restoration would likely provide a significantly better return rate in terms of the amount of water that is returned to the stream as a percentage of the amount that is not used for municipal supply purposes.

C. Recommendations for the modified USGS transient groundwater

The modified USGS model described in Section 5 could be improved through better data that describe stream conductance parameters. These parameters describe how easily water moves between the stream channel and the nearby aquifer materials. Spatially-detailed data that describe water levels in the stream, water levels in the aquifer, and the rates of streamflow gains or losses would be required to independently estimate these conductance values.

The sensitivity of the model results to aquifer storage characteristics may also be useful. There are relatively little data available to reliably estimate these storage characterics.

The USGS model does not include existing wells. In as much as the model reflects conditions in the Soos Creek basin, adding the additional municipal water supply wells may be a useful exercise.

The transient USGS model described in Section 5 could also be used to evaluate groundwater recharge features such as infiltration ponds or groundwater injection wells. These types of facilities may prove to be a more effective way to increase stream flows during low-flow periods.

Table 6.1 – Summary of scenarios used in model simulations

	Distance from Reach 4 (ft)		
	0	**1500**	**3000**
Unit of Well Completion	**Cell coordinates for well**		
	52,27	**51,29**	**51,31**
Qvr	CWA301	CWA311	CWA312
Qva	CWA302		CWA321
QAc	CWA303		CWA322

Table 6.2 – Aquifer storage parameters used in the modified USGS model

Layer	Storage coefficient	Specific yield
1	$1x10^{-3}$	$1x10^{-2}$
2-10	$1x10^{-4}$	$1x10^{-2}$

Table 6.3 Example wells less than 3,000 feet from surface water features.

SYSTEM NAME	SOURCE NAME	Depth of Well Boring	Aquifer Type	Region	Aquifer Name	Stream	Distance to Surface Water	T (gpd/ft) or Spec Cap (gpm/ft)
RENTON, CITY OF	WELL #1 (RW-1)	96	Unconf	Valley	Qal/Qvr	Cedar R	100	1,000,000
RENTON, CITY OF	WELL #2 (RW-2)	52	Unconf	Valley	Qal/Qvr	Cedar R	100	1,000,000
RENTON, CITY OF	WELL #3 (RW-3)	76	Unconf	Valley	Qal/Qvr	Cedar R	100	1,000,000
ISSAQUAH WATER SYSTEM	WELL # 1	107	Semi leaky	Valley	Qvr LIV	E Fk Iss C	200	500,000
ISSAQUAH WATER SYSTEM	WELL # 2	97	Semi leaky	Valley	Qvr LIV	E Fk Iss C	200	500,000
ISSAQUAH WATER SYSTEM	WELL #4	112	Semi leaky	Valley	Qvr LIV	E Fk Iss C	200	500,000
KENT WATER DEPARTMENT	ARMSTRONG SPRINGS A1	107	Spring	Upland	Qvr	Jenkins (Soos)	200	8.6
KENT WATER DEPARTMENT	ARMSTRONG SPRINGS A2	90	Spring	Upland	Qvr	Jenkins (Soos)	200	15.8
KENT WATER DEPARTMENT	OBRIEN WELL	192	Conf	Valley	preV	Springbrook (Green)	200	23.0
KENT WATER DEPARTMENT	WELL #1 - 212 ST	336	Conf	Valley	preV	Springbrook (Green)	200	39.1
KENT WATER DEPARTMENT	WELL #2 - 212 ST	248	Conf	Valley	preV	Springbrook (Green)	200	39.1
KENT WATER DEPARTMENT	WELL #3 - 212 ST	290	Conf	Valley	preV	Springbrook (Green)	200	39.1
KENT WATER DEPARTMENT	GARRISON WELL #2	435	Conf	Upland	preV	Harrison Cr (Springbrook)	200	26.3

SYSTEM NAME	SOURCE NAME	Depth of Well Boring	Aquifer Type	Region	Aquifer Name	Stream	Distance to Surface Water	T (gpd/ft) or Spec Cap (gpm/ft)
SAMMAMISH PLATEAU WATER & SEWER	WELL #7	83	Semi leaky	Valley	Qvr LIV	N Fk Iss	200	51.5
SAMMAMISH PLATEAU WATER & SEWER	WELL #8	105	Semi leaky	Valley	Qvr LIV	N Fk Iss	200	89.6
SAMMAMISH PLATEAU WATER & SEWER	WELL #9	194	Semi leaky	Valley	Qvr LIV	N Fk Iss	200	102.0
COVINGTON WATER DISTRICT	222ND PLACE A	81	Unconf	Upland	Qvr	Cranmar (Soos)	200	1,000,000
COVINGTON WATER DISTRICT	222ND PLACE E	87	Unconf	Upland	Qvr	Cranmar (Soos)	200	1,000,000
COVINGTON WATER DISTRICT	RAVENSDALE-FD#43	43	Unconf	Upland	Qvr/Qva	Ravensdale Cr	200	200,000
COVINGTON WATER DISTRICT	222ND PLACE C	85	Unconf	Upland	Qvr	Cranmar (Soos)	200	1,000,000
COVINGTON WATER DISTRICT	222ND PLACE D	83	Unconf	Upland	Qvr	Cranmar (Soos)	200	1,000,000
COVINGTON WATER DISTRICT	222ND PLACE F	75	Unconf	Upland	Qvr	Cranmar (Soos)	200	1,000,000
KING COUNTY WATER DISTRICT 111	WELL NO 9	443	Conf	Upland	preV	W Branch Big Soos	200	16.4
COVINGTON WATER DISTRICT	SE 264TH ST WELL	260	Conf	Upland	preV	Lucerne Lk	300	33.3
RENTON, CITY OF	WELL #8 (PW-8)	102	Unconf	Valley	Qal/Qvr	Cedar R	500	1,000,000
RENTON, CITY OF	WELL #12 (PW-12)	350	Leaky conf	Valley	Qal/Qvr	Cedar R	600	49,000 to 76,000
RENTON, CITY OF	WELL #11 (PW-11)	345	Leaky conf	Valley	Qal/Qvr	Cedar R	750	49,000 to 76,000
RENTON, CITY OF	WELL #17 (PW-17)	346	Leaky conf	Valley	Qal/Qvr	Cedar R	750	49,000 to 76,000

SYSTEM NAME	SOURCE NAME	Depth of Well Boring	Aquifer Type	Region	Aquifer Name	Stream	Distance to Surface Water	T (gpd/ft) or Spec Cap (gpm/ft)
REDMOND WATER SYSTEM, CITY OF	WELL NO. 3 (ABR043)	73	Unconf	Valley	Qvr	Bear	1,000	41.4
REDMOND WATER SYSTEM, CITY OF	WELL NO. 4 (ACJ523)	57	Unconf	Valley	Qvr	Sammamish	1,000	40.6
RENTON, CITY OF	WELL #9 (PW-9)	117	Unconf	Valley	Qal/Qvr	Cedar R	1,000	1,000,000
KING COUNTY WATER DISTRICT 111	WELL NO 3	84	Unconf	Upland	Qvr	Big Soos C	1,500	na
KING COUNTY WATER DISTRICT 111	WELL NO 4	159	Conf	Upland	preV	Big Soos C	1,500	na
KING COUNTY WATER DISTRICT 111	WELL NO 5	359	Conf	Upland	preV	Big Soos C	1,500	na
REDMOND WATER SYSTEM, CITY OF	WELL NO. 1 (ABR031)	56	Unconf	Valley	Qvr	Bear	1,500	100.0
REDMOND WATER SYSTEM, CITY OF	WELL NO. 2 (ABR042)	68	Unconf	Valley	Qvr	Bear	1,500	10.8
REDMOND WATER SYSTEM, CITY OF	WELL #5 (ABR041)	41	Unconf	Valley	Qvr	Bear	1,500	566.7
RENTON, CITY OF	WELL #5 (PW-5A)	410	Conf	Upland	preV	Lake Wash	1,500	20.0
NE SAMMAMISH SEWER & WATER DISTRICT	WELL #2-R	185	Leaky Conf	Upland	preVashon	Evans	1,500	10.7
NE SAMMAMISH SEWER & WATER DISTRICT	WELL #6	154	Leaky Conf	Upland	preVashon	Evans	1,500	12.9
NE SAMMAMISH SEWER & WATER DISTRICT	WELL #7	264	Leaky Conf	Upland	preVashon	Evans	1,500	10.6
AUBURN WATER DIVISION, CITY OF	WELL #3B	309	Conf	Valley	Qvrd	White R	2,000	100,000
AUBURN WATER DIVISION, CITY OF	WELL #2	242	Conf	Valley	Qvrd	Green R	2,500	2,000,000
AUBURN WATER DIVISION, CITY OF	WELL #6	237	Conf	Valley	Qvrd	Green R	2,500	2,000,000

SYSTEM NAME	SOURCE NAME	Depth of Well Boring	Aquifer Type	Region	Aquifer Name	Stream	Distance to Surface Water	T (gpd/ft) or Spec Cap (gpm/ft)
UNION HILL WATER ASSOCIATION INC	WELL #2	134	Conf	Upland	preVashon	Evans	2,500	6,000 to 50,000
PACIFIC, CITY OF	WELL #2 East Well (ABR 145)	47	Unconf	Valley	Qal	White R	3,000	110.7
PACIFIC, CITY OF	WELL #3 West Well (AFJ 034)	56	Unconf	Valley	Qal	White R	3,000	7.6
PACIFIC, CITY OF	*Pre-Active 01/04/2006 SOUTH WELL*	53	Unconf	Valley	Qal	White R	3,000	58.6
UNION HILL WATER ASSOCIATION INC	WELL #1	236	Conf	Upland	preVashon	Evans	3,000	30,000 to 50,000
UNION HILL WATER ASSOCIATION INC	WELL #1S	237	Conf	Upland	preVashon	Evans	3,000	30,000 to 50,000

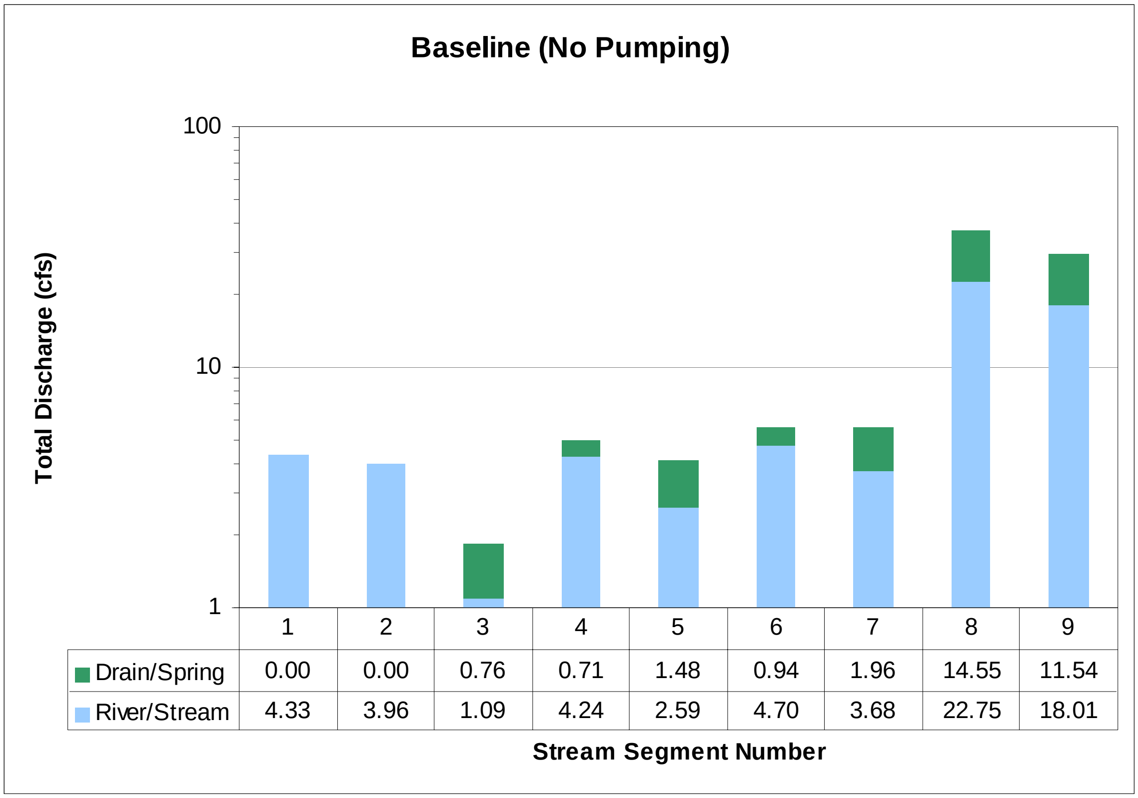


Figure 6.1. Total discharge for no-pumping scenario.

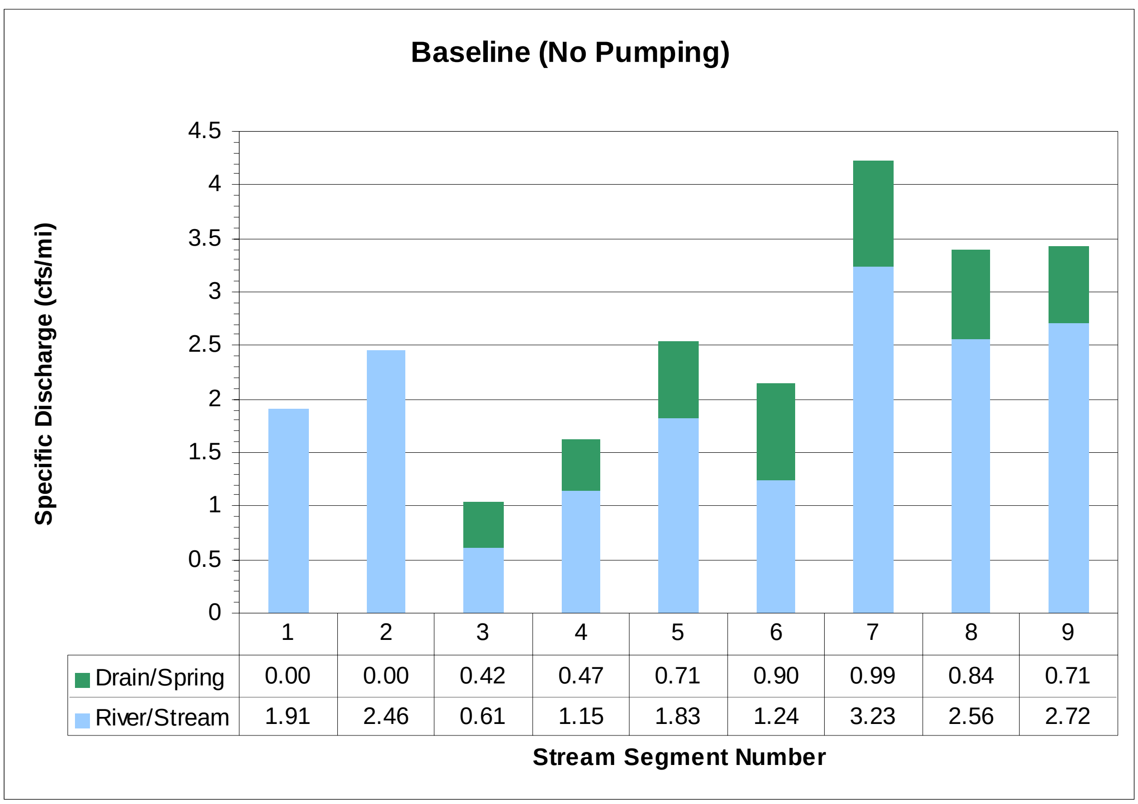
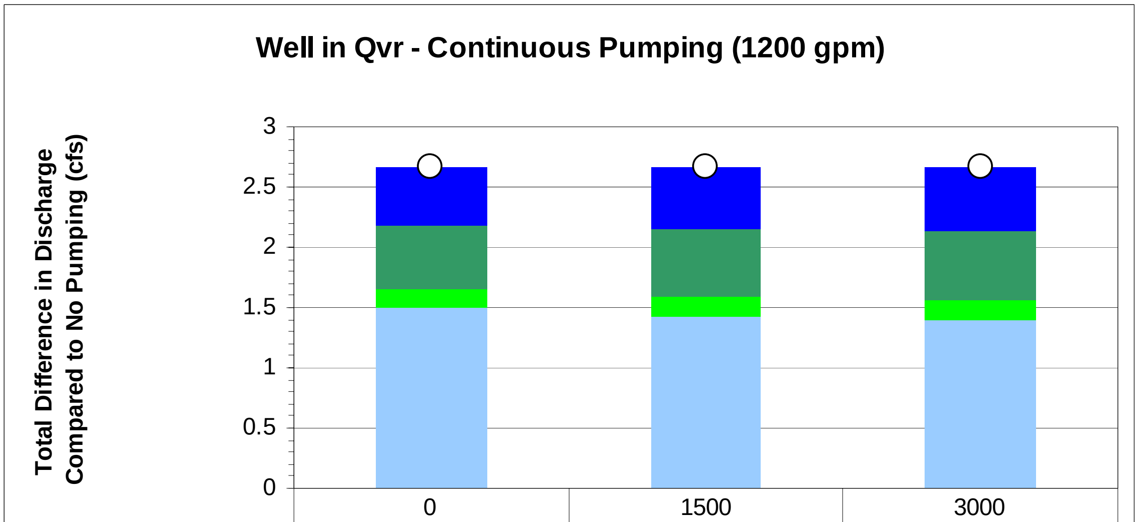


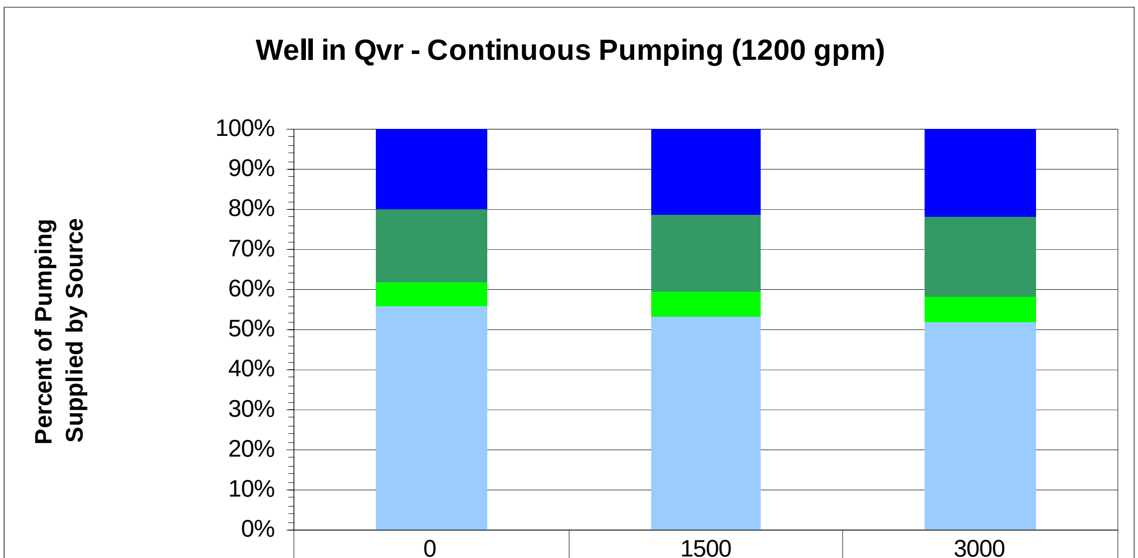
Figure 6.2. Specific discharge for no-pumping scenario.



	0	1500	3000
Lower Streams	0.486	0.516	0.534
Lower Springs	0.537	0.568	0.586
Upper Springs	0.152	0.161	0.167
Upper Streams	1.498	1.427	1.387
Pumping Rate	2.674	2.674	2.674

Distance Between Well and Stream (ft)

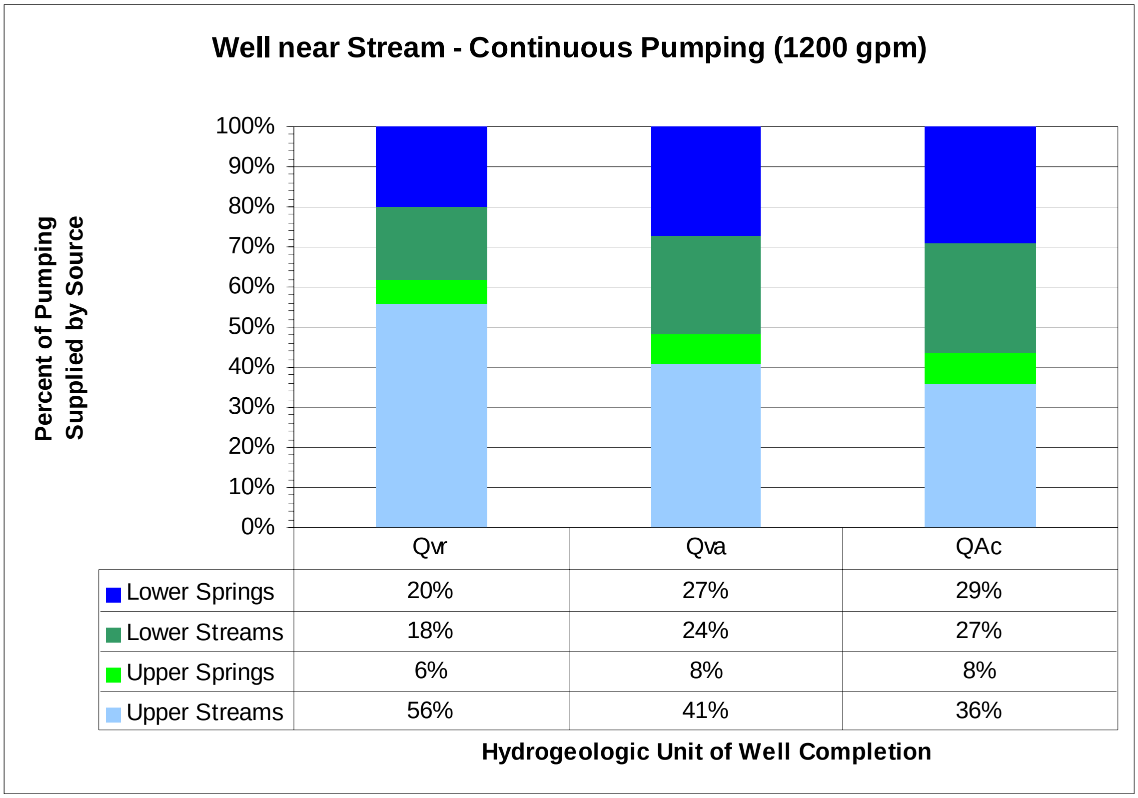
Figure 6.3. Difference in discharge compared to no-pumping scenario for Qvr wells



	0	1500	3000
Lower Springs	20%	21%	22%
Lower Streams	18%	19%	20%
Upper Springs	6%	6%	6%
Upper Streams	56%	53%	52%

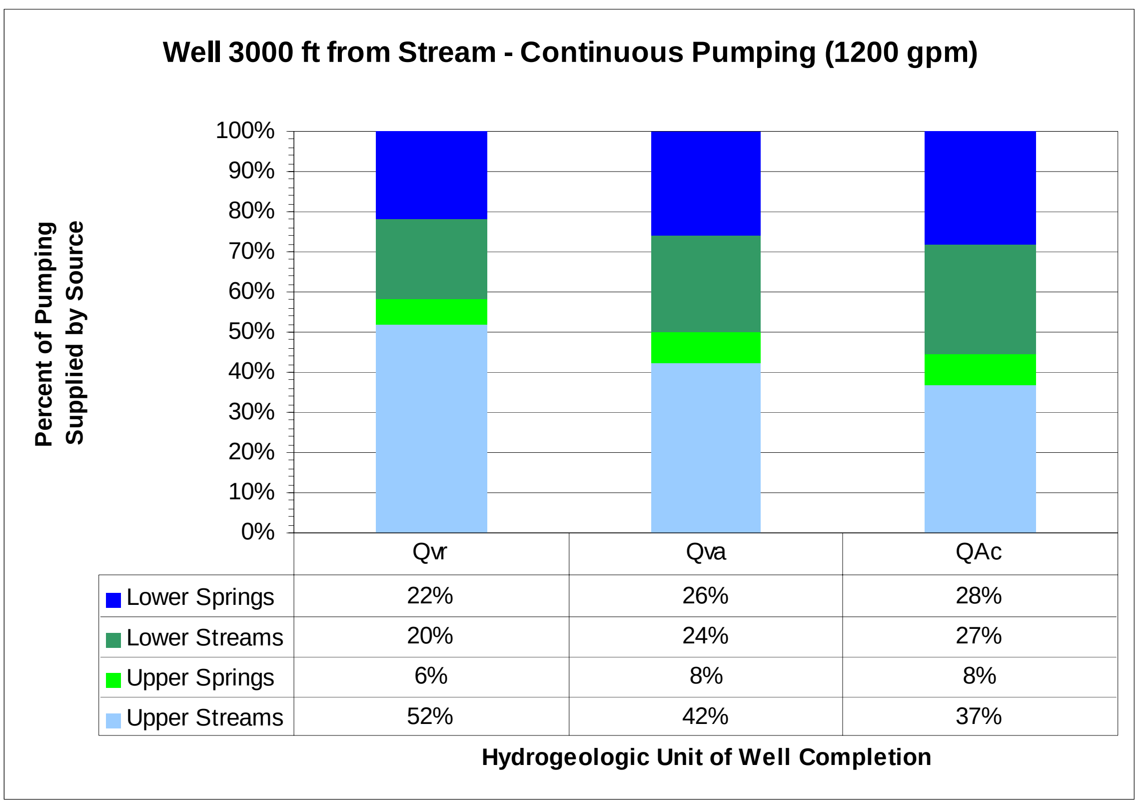
Distance Between Well and Stream (ft)

Figure 6.4. Percent of pumping supplied by source for Qvr wells



	Qvr	Qva	QAc
Lower Springs	20%	27%	29%
Lower Streams	18%	24%	27%
Upper Springs	6%	8%	8%
Upper Streams	56%	41%	36%

Figure 6.5. Percent of pumping supplied by source for wells near streams



	Qvr	Qva	QAc
Lower Springs	22%	26%	28%
Lower Streams	20%	24%	27%
Upper Springs	6%	8%	8%
Upper Streams	52%	42%	37%

Figure 6.6. Percent of pumping supplied by source for wells 3,000 feet from streams

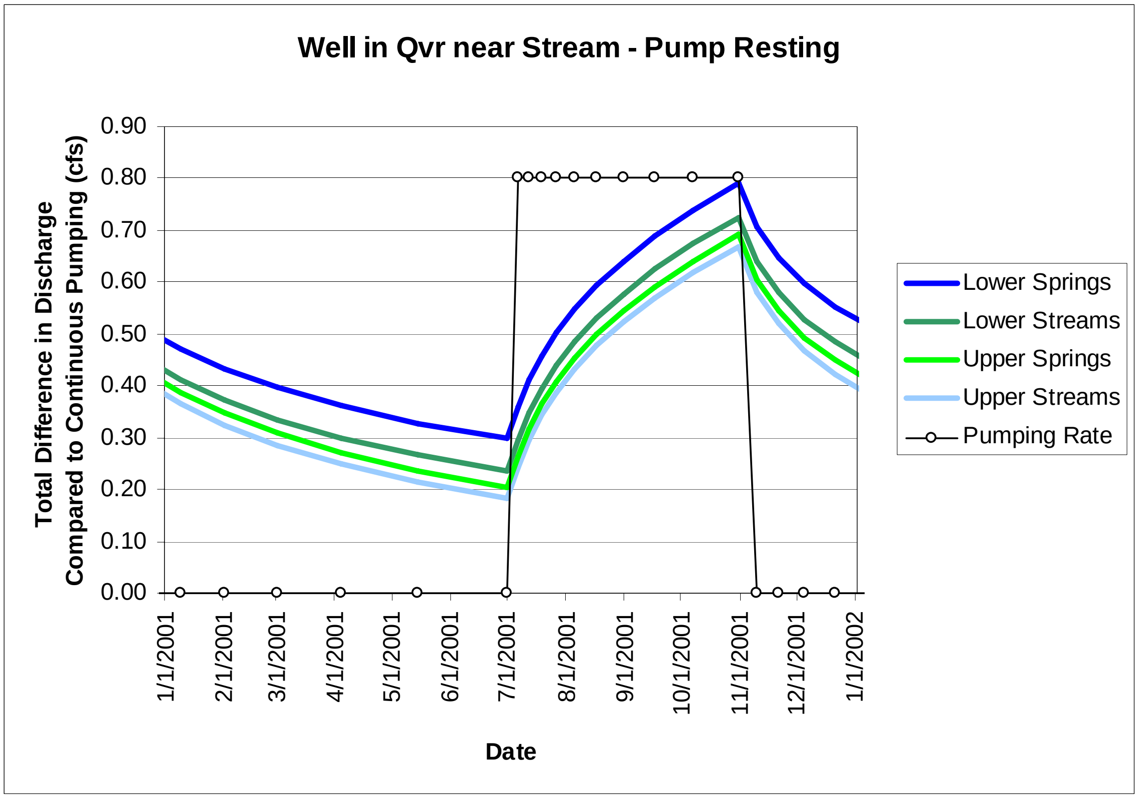


Figure 6.7. Transient results for well in Qvr near stream

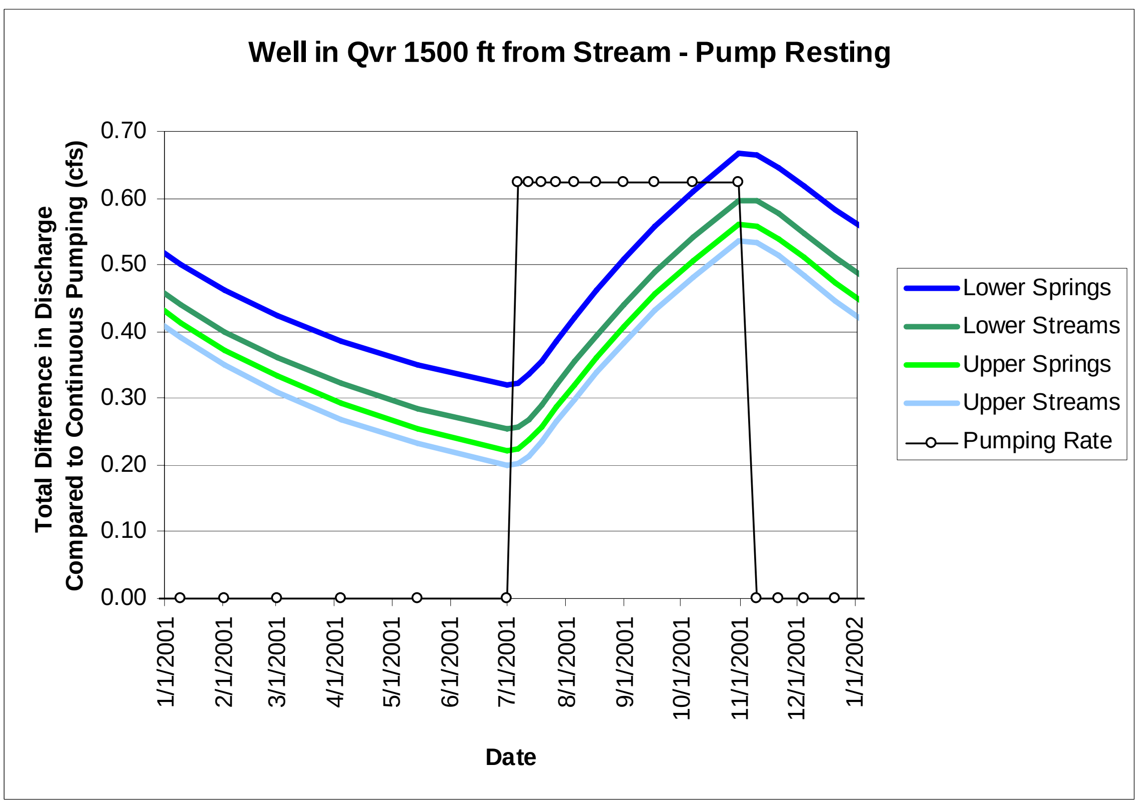


Figure 6.8. Transient results for well in Qvr 1500 feet from stream

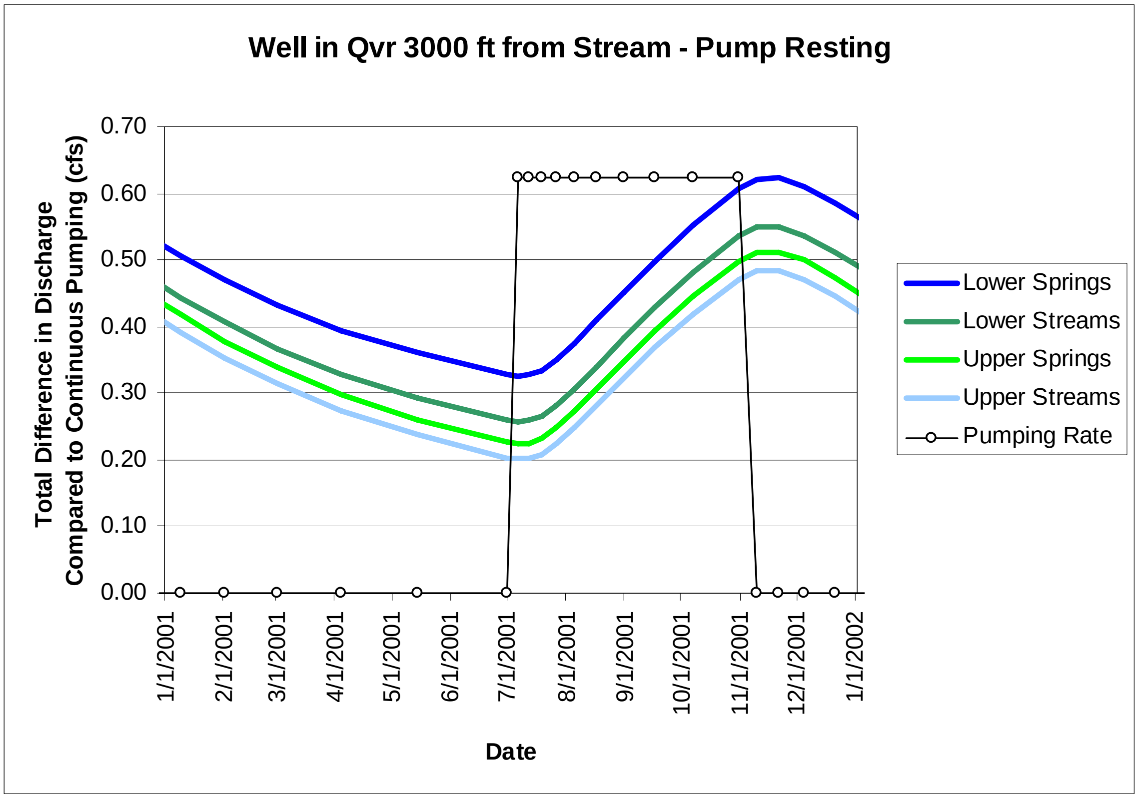


Figure 6.9. Transient results for well in Qvr 3,000 feet from stream

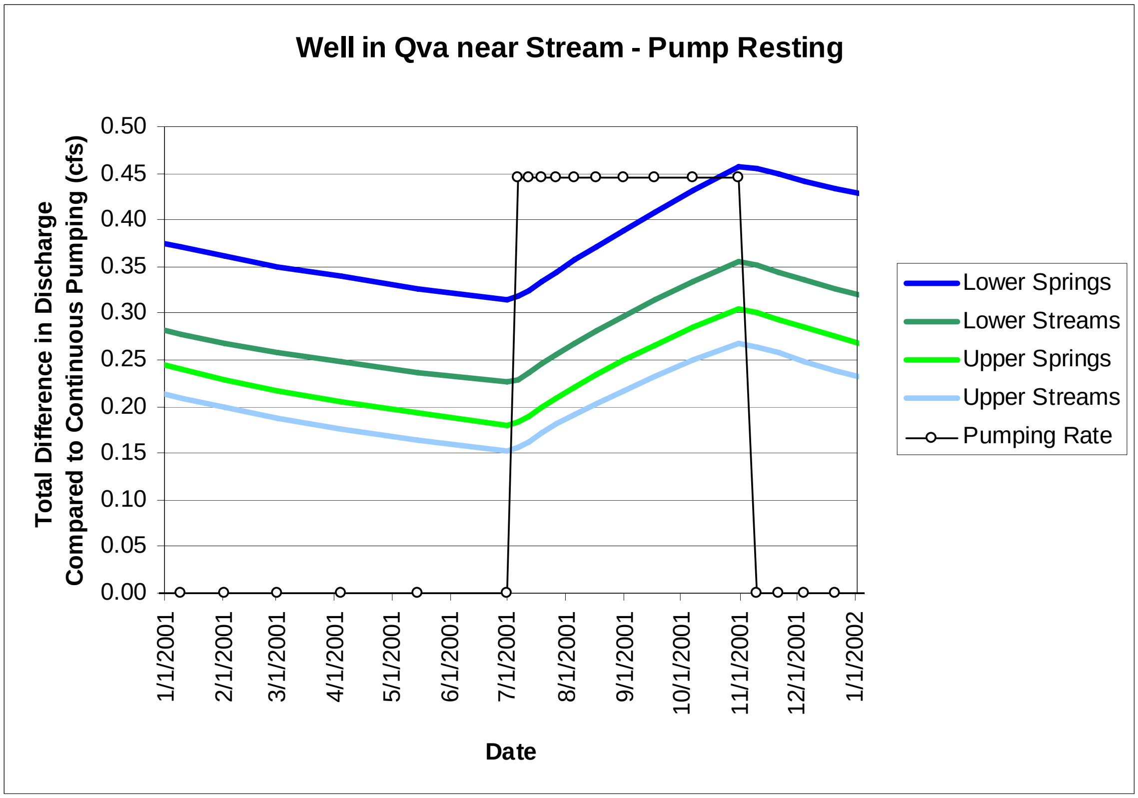


Figure 6.10. Transient results for well in Qva near the from stream

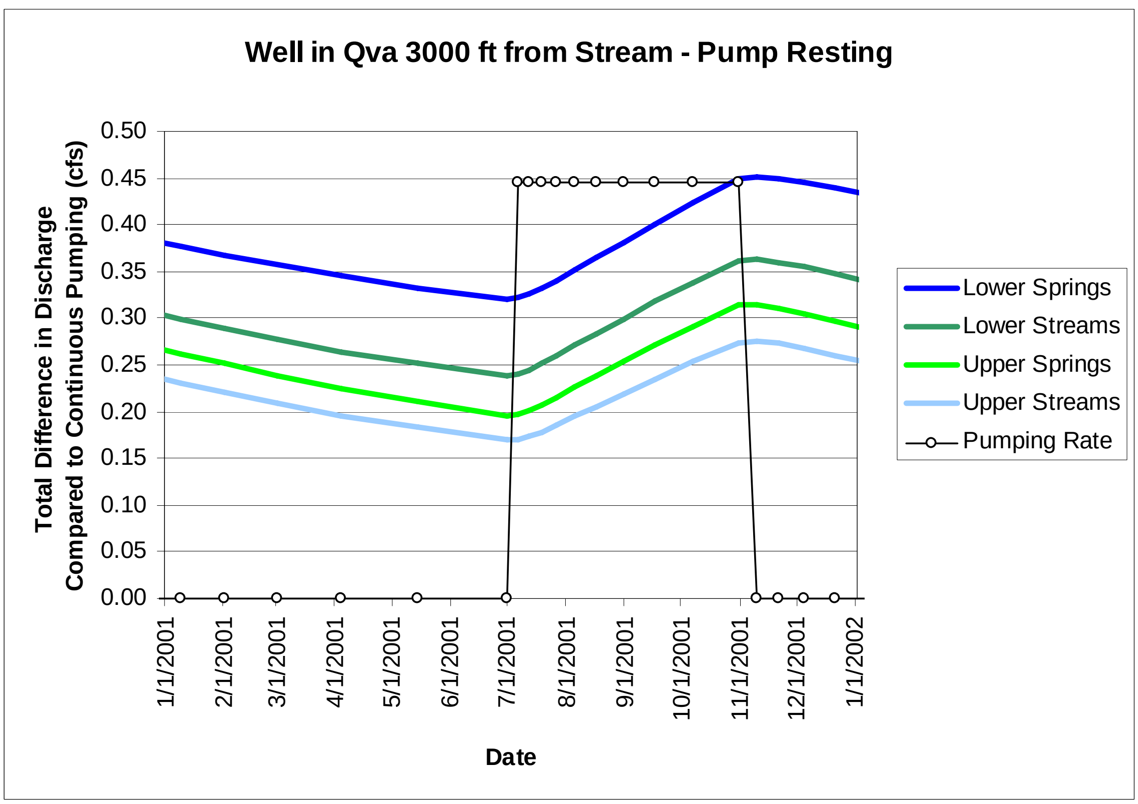


Figure 6.11. Transient results for well in Qva 3,000 feet from stream

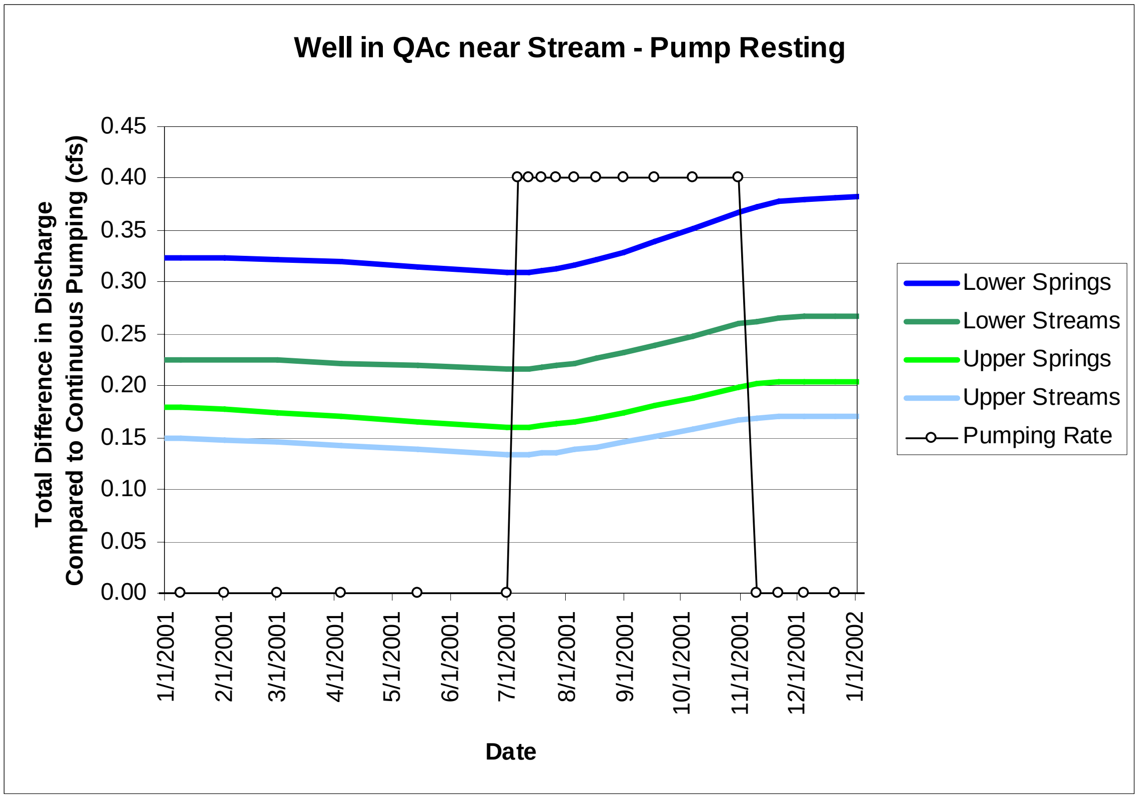


Figure 6.12. Transient results for well in QAc near stream

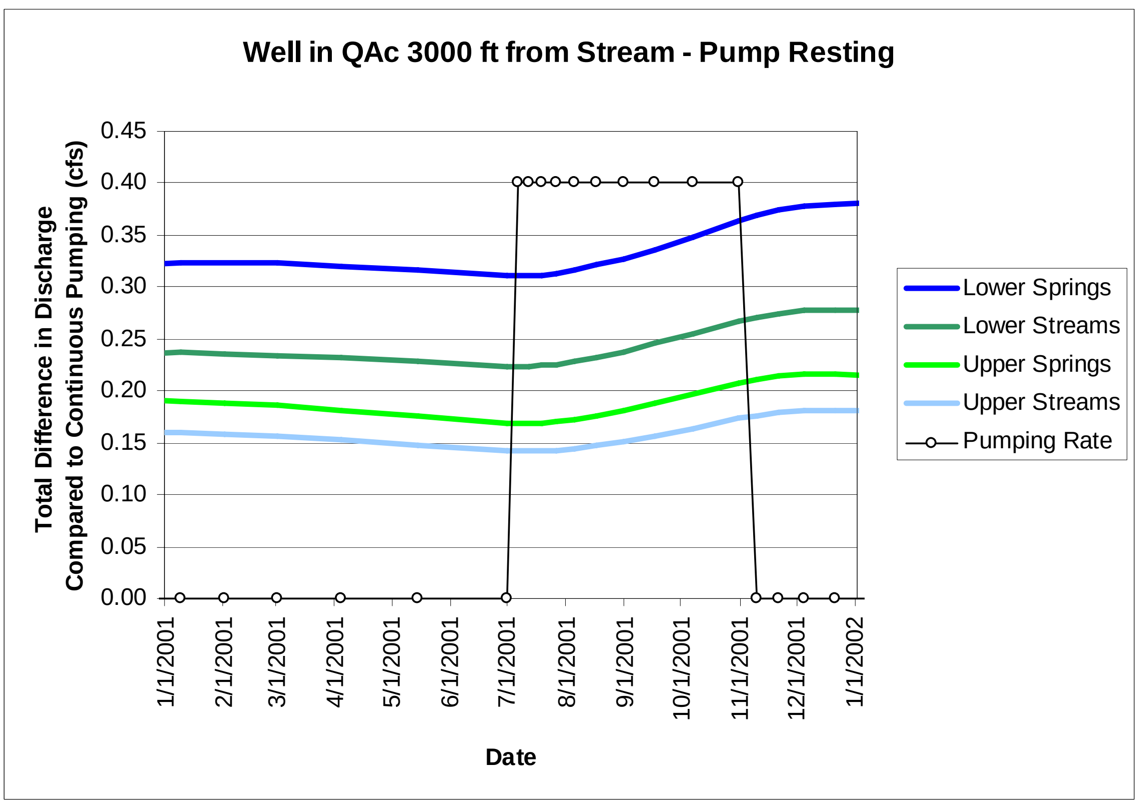
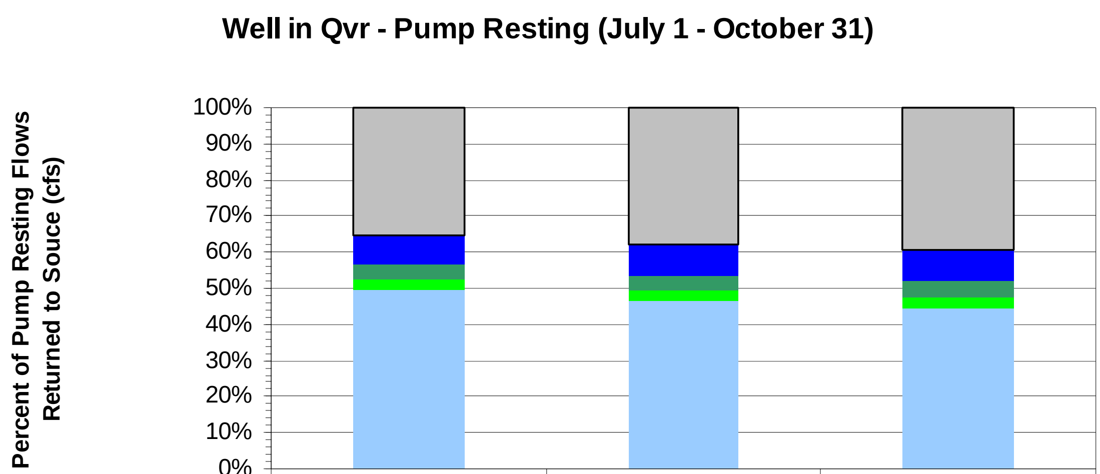
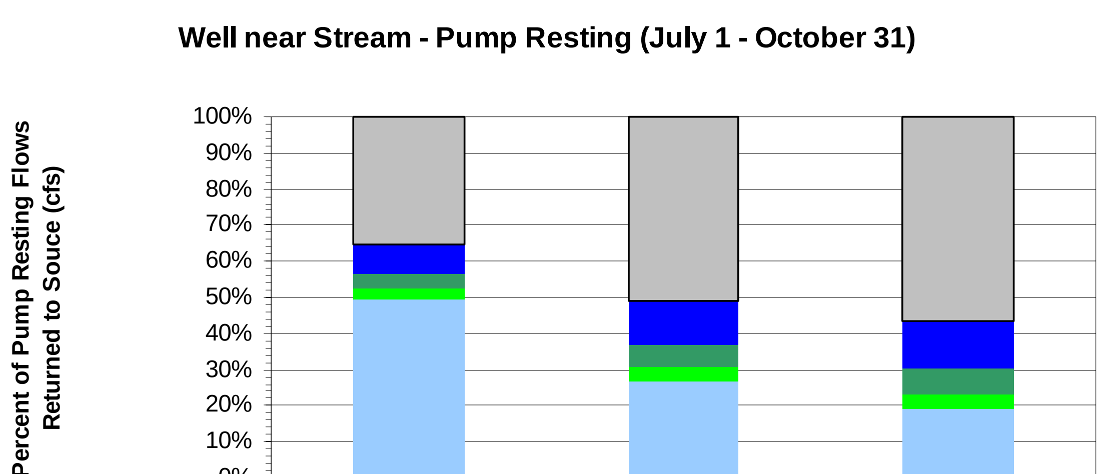


Figure 6.13. Transient results for well in QAc 3000 feet from stream



	0	1500	3000
Storage	35%	38%	39%
Lower Springs	8%	9%	9%
Lower Streams	4%	4%	4%
Upper Springs	3%	3%	3%
Upper Streams	50%	46%	44%

Figure 6.14. Percent returned to sources for well in Qvr



	Qvr	Qva	QAc
Storage	35%	51%	57%
Lower Springs	8%	12%	13%
Lower Streams	4%	6%	7%
Upper Springs	3%	4%	4%
Upper Streams	50%	27%	19%

Figure 6.15 Percent returned to sources for well near stream

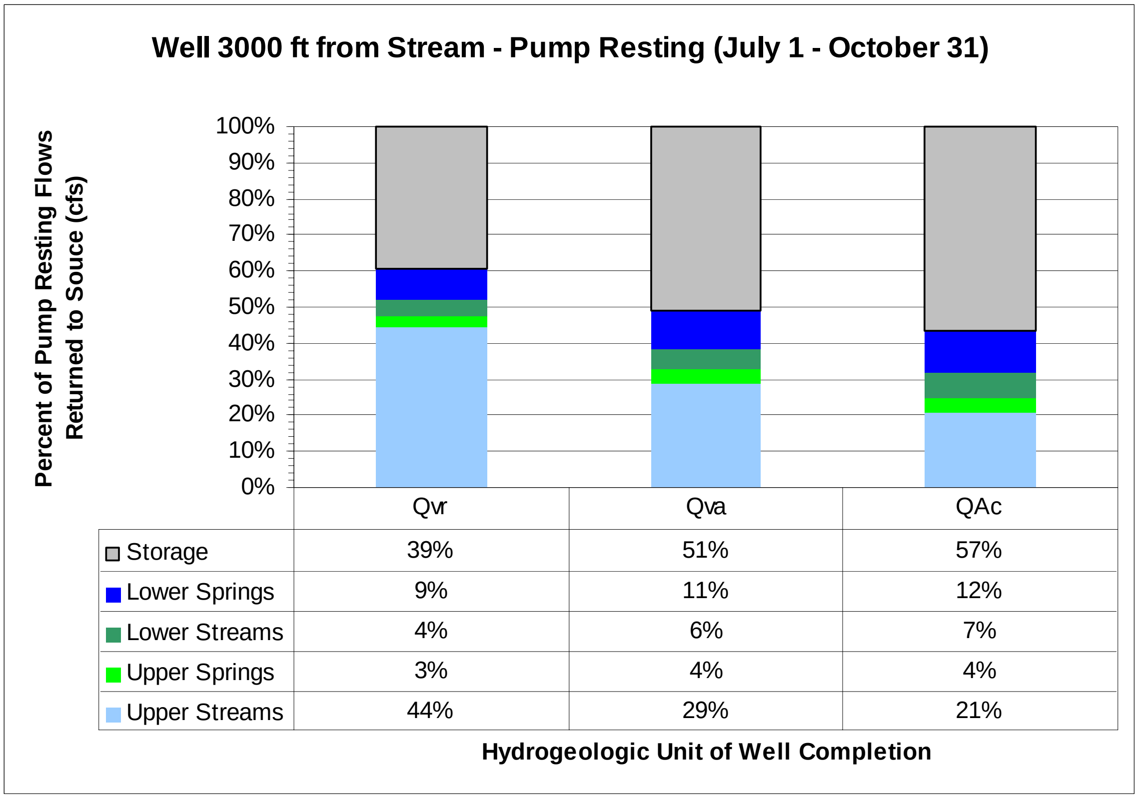


Figure 6.16. Percent returned to sources for wells 3,000 feet from stream

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Nyholm, T., S. Christensen, and K.R. Rasmussen, 2002. *Flow depletion in a small stream caused by groundwater abstraction from wells*, Ground Water, 40(4), 425-437.

Singh, S. K. 2006. Flow depletion of semipervious streams due to unsteady pumping discharge. Journal of Irrigation and Drainage Engineering, 132(4): 406-409.

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APPENDIX A

Listing of files on data disk

1. **Model files**
2. **Model results**
3. **Morgan and Jones (1999)**
4. **GIS files from RH2 Engineering, Inc**
5. **WRIA 8 and 9 source well database**
6. **Listing of WRIA 8 and 9 pumping test reports**

APPENDIX B

STUDIES, REPORTS, AND PUBLICATIONS THAT DESCRIBE OR RELATE TO BENEFITS THAT MAY BE DERIVED FROM RESTING OR PAUSING GROUNDWATER EXTRACTION

Seminal Papers

Glover, R. E. and C. G. Balmer. 1954. River depletion resulting from pumping a well near a river. American Geophysical Union Transactions, 35(3): 468-470

Hantush, M. S. 1965. Wells near streams with semipervious beds. Journal of Geophysical Research, 70(12): 2829-2838.

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Theis, C. V. 1941. The effect of a well on the flow of a nearby stream. American Geophyscial Union Transactions, 22(3): 734-738.

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Hunt, B. 1999. Unsteady stream depletion from ground water pumping Ground Water, 37(1): 98-102.

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Hunt, B. 2003. Field data analysis for stream depletion. Journal of Hydrologic Engineering, 8(4): 222-225.

Hunt, B. 2003. Unsteady stream depletion when pumping from semiconfined aquifer. Journal of Hydrologic Engineering, 8(1): 12-19.

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Knight, J. H., M. Gilfedder, and G. R. Walker. 2005. Impacts of irrigation and dryland development on groundwater discharge to rivers—a unit response approach to cumulative impacts analysis. Journal of Hydrology, 303: 79–91.

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Software

Barlow, P.M., 2000, Documentation of computer program STRMDEPL—A program to calculate streamflow depletion by wells using analytical solutions, *in* Zarriello, P.J., and Ries, K.G., III, A precipitation-runoff model for analysis of the effects of water withdrawals on streamflow, Ipswich basin, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 00-4029, p. 79–89.

> STRMDEPL is a FORTRAN program developed to calculate time-varying streamflow depletion caused by a pumped well. STRMDEPL is based on two analytical solutions that solve equations for ground-water flow to a well completed in a semi-infinite, homogeneous, and isotropic aquifer in direct hydraulic connection to a fully penetrating stream. One analytical method calculates unimpeded flow at the stream-aquifer boundary and the other method calculates the resistance to flow caused by semipervious streambed and streambank material. The principle of superposition is used with these analytical equations to calculate time-varying streamflow depletions due to daily pumping.
>
> Although STRMDEPL can be run independently, an extension was developed to run this program in tandem with the precipitation-runoff model HSPF. The HSPF model can readily incorporate streamflow depletions caused by a well or surface-water withdrawal, or by multiple wells or surface-water withdrawals, or both, as a combined time-varying outflow demand from affected channel reaches.

Parkin, G., S Birkinshaw, Z Rao, M Murray, P L Younger. Impact of Groundwater Abstractions on River Flows: Phase 2 – A Numerical Modelling Approach to the Estimation of Impact (IGARF II), R&D Project Record W6-046/PR, Environmental Agency of the United Kingdom, http://publications.environment-agency.gov.uk.

> The IGARF spreadsheet uses the method of Hunt (1999) to estimate the timing and magnitude of depletion on both forks of the river due to a single-day of pumping. Hunt's method calculates the effect of pumping a fully-penetrating well in a homogeneous, isotropic aquifer on a partially penetrating stream with a streambed permeability lower than the aquifer permeability. Because the Hunt equation is linear, it can be scaled to any operational ground water withdrawal rates and summed by superposition to calculate the depletion associated with any given pumping schedule.

APPENDIX C

Tables and Figure from Task 2
RH2 Engineering, Inc.
Included on Data Disk