Description and Evaluation of Groundwater Monitoring Activities in the Vicinity of the Witte Well Field

Prepared for

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1. Introduction and Summary of Results

1a. Introduction

This report describes the results of monitoring activities aimed at describing groundwater flow directions in the vicinity of the Witte well field in southeastern King County. The Witte well field is owned and operated by the Covington Water District and is located in Section 28, T. 22 N., R. 3 E., as shown on Figure 1. The monitoring activities described in this report were completed as part of an agreement between the Muckleshoot Indian Tribe and the Covington Water District. This agreement was aimed at resolving a dispute over a water permit that was granted by the Department of Ecology to the Covington Water District.

In July of 1987 Covington Water District applied for a groundwater right to use 1500 gallons per minute for municipal water supply from four wells in Section 28 of T. 22 N., R. 6 E., King County, Washington. These wells are known as the "Witte well field." The Department of Ecology issued an order granting a permit to the Water District in June of 1995. The Muckleshoots filed an appeal to the Pollution Control Hearing Board in which they challenged Ecology's approval of the permit. In November of 1996 the Muckleshoots and Covington Water District entered a Memorandum of Agreement aimed at resolving this dispute. The agreement includes the following conditions:

1) The Witte well field will not be operated between November 1 and May 15, except for routine maintenance and trouble shooting.
2) A set of clustered piezometers was to be installed within 100 feet of the Witte Well Field before September, 1996. A second clustered piezometer was to be installed within 300 feet of the well field before September, 1997. These piezometers were to be used to monitor water levels in the pumped aquifer, the confining unit above the pumped aquifer, and in the aquifer immediately above the confining unit.
3) A three-day, constant-rate pumping test was to be conducted as soon as feasible after installation of the piezometers to assess groundwater response.
4) A third clustered piezometer would be constructed within 1000 feet of the well field if either the Muckleshoots or the Water District deemed it necessary.
5) Two 30-day monitoring tests will completed each year. One test will be conducted immediately after the wells are turned on in May and the second will be conducted immediately after the wells are shutdown in November. These tests will be repeated for a minimum of five years.

The first two sets of clustered piezometers have been installed and data have been provided describing the water levels between June 3, 1997 and June 8, 1999. These data include two 30-day pumping tests (June, 1997 and June, 1998) and two 30-day recovery tests (November, 1997 and November, 1998).

This report presents the water level data that have been collected. It describes what these data directly show in terms of the effects of the Witte Well field on groundwater flow directions. It presents estimates of hydrogeological parameters based on the data, and uses these parameters to infer longer-term and more regional effects of the well field.

2. Background on the Basis and Objectives for the Monitoring Activities

The specific objectives for the groundwater monitoring program include the following: 1) collect data to better manage the Witte well field, 2) collect data that will allow a better understanding of well hydraulics and the effects of wells on flow systems in similar geologic environments, and 3) demonstrate what we believe is a useful approach for monitoring systems at all major water supply wells. Each of these objectives is described in the paragraphs below.

2a. Managing the Water Resources within the Soos Creek Basin

One of Covington Water District's stated objectives is to manage the water in the Soos Creek basin to better satisfy in-stream and public water supply needs. Good management decisions require good information on the seasonal and annual water balance within the basin. To develop this water balance, we need to know, as a minimum, the sources of the water that enter and leave the basin. The monitoring system provides information on the source of the water that leaves the basin via the Witte wells. This information represents one piece of the overall water balance for the basin.

We have argued, on the basis of studies published by the USGS and others, that the Soos Creek drainage basin is a relatively closed hydrologic system and that groundwater within this aquifer system originates primarily as recharge from precipitation (South King County Ground Water Management Plan, 1991; Woodward et al., 1995). We have further argued that the Witte wells draw water from these shallow aquifers, and thereby reduce the flow to streams within the basin. Covington's consultants have presented a different argument. They have suggested that the water that is extracted by the Witte Well field comes from deep inflow from outside of the basin. With regard to the source of the water from the Witte well field, Covington's consultants state the following: "We can, for certain, say it does not originate as leakage from the upper aquifer in the vicinity of the Witte well field. The evidence for this is the head relationship between the two aquifers. Downward leakage would require the upper aquifer to have the higher water level." (Joseph Becker, Robinson and Noble, letter dated March 27, 1996).

Questions regarding the source of the water for the Witte wells have important implications in terms of watershed management. If the Witte Well field derives its flow from the shallow aquifers in the vicinity of the wells, then the effects on shallow aquifers and streams would be relatively rapid. This should be considered in any future actions regarding groundwater development within the basin. If the Witte Well field derives its flow from outside of the basin, then the time lag for effects on the water balance for the shallow aquifers or streams would likely be longer and water management options might be adjusted accordingly.

As we pointed out when we initially asked for the monitoring system, additional monitoring wells are not going to eliminate all or even most of the uncertainties associated with the water balance within the Soos Creek basin. We are of the opinion that it is better to focus our monitoring to address specific questions related to the groundwater flow system in the vicinity of the Witte Wells. With this plan, we will at least be in a position to state, with some degree of certainty, whether the water that is extracted by the Witte wells should be included in a water balance aimed at protecting stream flow. Other monitoring activities would be required to address other segments or portions of the water balance.

The water right conditions specify that the Witte wells will be shut down or "rested" between November 1 and May 15 of each year. The intent of this period of rest is to allow the water levels in the pumped aquifer and adjacent aquifers to recover. The rate at which these levels recover was not known with the data that were previously available. The new monitoring system provides data that will allow these recovery times to be evaluated specifically for the geologic conditions at the Witte well site. The timing and duration of the periods of rest may be optimized or at least improved based on these data. The monitoring system also provides information that will be useful in evaluating groundwater recharge activities.

2b. The effects of wells on flow systems in similar geologic environments

The geologic and hydrologic characteristics of the Witte well field are similar to many sites in western Washington. The data that are collected at the Witte well field provides information that will allow a better understanding of the effects of water wells on the flow systems in these types of layered aquifer systems. This will in turn improve decisions that are made in the future at similar sites, including the potential benefits of aquifer recovery on streams. Of particular interest is whether resting wells in the winter can provide improvement in streamflow conditions and well performance for peak-season water supply.

2c. Demonstrating a standard for monitoring systems

We have argued that the data collected at the Witte well field will provide a tangible and recognizable benefit in terms of improved management decisions. We further believe these improvements will be recognized by regulators, by water purveyors, and by others interested in or affected by groundwater resource development. We hope that a new standard for monitoring activities will be set at the Witte well field and that all parties will conclude that a monitoring system similar to what has been installed would help improve and refine operations at all major water wells in layered geologic systems similar to what is found at the Witte well site.

3. A Conceptual Picture for the Aquifer System in Vicinity of the Witte Well Field

A conceptual picture that describes the aquifer system in the vicinity of the Witte well field can be developed from published geologic and hydrogeologic studies and from well logs. The primary sources of information include reports developed by the U.S. Geological Survey (Woodward et al, 1995; Dinicola, 1990), the South King County Groundwater Management Plan (1991), and well logs for the Witte well field. A conceptual and simplified geologic cross section in the vicinity of the Witte well field is shown in Figure 2. This section, which is part of cross section A-A' from Plate 1 of the 1995 USGS report (Woodward, et al., 1995), gives a generalized description of a geologic cross section drawn from the eastern part of the basin on the right toward the center of the basin on the left.

The hydrogeology at the Witte well site consists of a series of aquifers and confining units. The Witte well field extracts water from what is likely the Q(A)c aquifer. This aquifer is confined by the Q(A)f confining unit. Above the Q(A)f confining unit is the Qva aquifer, which is likely used for most of the domestic wells in the vicinity of the Witte well field. The Qva aquifer is confined by the Qvt confining unit. The Qvr deposits that are shown at the ground surface in much of Figure 2 may not be present at all locations in the vicinity of the Witte well field. It does appear to be present in the vicinity of monitoring well MW2 and may be the "water table" aquifer at this location.

The hydrogeological units in the vicinity of the Witte well field are also described in more local or specific terms in the reports prepared by Robinson and Noble. Table 1 compares the notation or terminology used by Robinson and Noble with what are likely the corresponding descriptors used by the USGS and others.

The Soos Creek basin has been described as "a relatively closed hydrologic system." (South King County Ground Water Management Plan, pp. D-9, 1991). Groundwater within this aquifer system originates as recharge from precipitation. About 40% of the precipitation on the Big Soos Creek Basin becomes ground-water recharge. This corresponds to approximately 21 inches of recharge per year. Estimates have been made that suggest 80 to 90 percent of this recharge (17 to 19 inches) stays in the shallow aquifers and is returned to streams within the basin. The remaining 10 to 20 percent (2 to 4 inches) moves downward into deeper aquifers (South King County Ground Water Management Plan, 1991; Woodward et al., 1995). The deeper groundwater in the vicinity of the Witte well fields does not likely discharge to the Cedar River, but may discharge to Big Soos Creek. This is due to an east-west trending bedrock ridge along the northern part of the basin. This ridge prevents groundwater discharge from the basin to the Cedar River.

The effect of the Witte wells on this flow system is to increase the amount of recharge which moves downward. This in turn decreases the amount of recharge that is returned to streams within the basin.

4. Summary of Monitoring Activities

4a. Pumping well installations

The four production wells that comprise the Witte well field were constructed between 1987 and 1992. These wells are described in a series of reports prepared by Robinson and Noble (1987; 1992a; 1992b; 1994). Appendix A provides a brief summary of these reports and includes the geologic logs, the construction details, the State of Washington water well reports, and the results of pumping and recovery tests. More details regarding well installation and testing are included in the original reports by Robinson and Noble.

4b. Monitoring well installations

The first monitoring well that was installed as part of the agreement between the Muckleshoot Indian Tribe and the Covington Water District was completed in December, 1996. This well is described in the January, 1997 report prepared by Robinson and Noble. Appendix B includes a map showing the well location and diagrams that describe the well construction and geologic log. The water well reports submitted to the Department of Ecology are also included. These materials were taken from the Robinson and Noble report (January, 1997). The well location is denoted MW1 and includes three piezometers. MW-1S is completed in the domestic or shallow aquifer, MW-1M is completed in the confining unit above the pumped aquifer, and MW-1D is completed in the pumped aquifer.

The second monitoring well, denoted MW2, was completed in April and May of 1997. This well is described in Robinson and Noble (June, 1997). Appendix B includes a map showing the well location and diagrams that describe the well construction and geologic log. The water well reports submitted to the Department of Ecology are also included. These materials were taken from the Robinson and Noble report (June, 1997). The well location includes four piezometers. MW-2WT is completed in what has been termed the "water table" aquifer, MW-2S is completed in the domestic or shallow aquifer, MW-2M is completed in the confining unit above the pumped aquifer, and MW-2D is completed in the pumped aquifer. Table 2 summarizes the construction of these piezometers.

4b. Pumping sequence and monitoring periods

The history of pumping at Witte well field from January, 1996 through June, 1999 is summarized in Table 3. Two full cycles of pumping and recovery have been monitored.

5. Responses of Water Levels to Pumping

The observed water levels in monitoring wells MW1and MW2 are shown in Figures 3 and 4. These figures include all of the data that have been collected at these wells between June 3, 1997 and June 8, 1999. This record can be divided into three types of periods: 1) recovery periods, 2) pumping periods, and 3) transition periods. Data during recovery periods (November to May) suggest that under natural or non-pumping conditions groundwater flow at the Witte well field is in the direction of the domestic aquifer. Figure 3 shows that water levels at MW1 are higher in the deep aquifer than in the shallow or domestic aquifer. Figure 4 shows that water levels at MW2 are higher in both the deep and the water table aquifer than in the domestic aquifer. The domestic aquifer is being recharged by the deep aquifer during these recovery periods. Data during pumping periods (May to November) show that when the pumps are operated groundwater flow is in the direction of the deep aquifer. This is most pronounced at MW1, which shows water levels in the deep aquifer approximately 10 feet below levels in the domestic aquifer.

The transition periods in May and November show that the flow directions switch over a relatively short period of time, on the order of several days. This is shown more clearly in Figures 5 and 6. The data shown on these figures were collected during the first 30-day pumping test in June of 1997. The pumping test began on June 3. Prior to pumping, the flow direction was upward in the direction of the domestic aquifer. Pumping causes the flow direction to be reversed. This reversal occurs after several hours at MW1 and after several days at MW2.

Figure 4 also includes data from what has been described as the water table aquifer. The elevation of this piezometer is approximately 405 feet. The effects of pumping on the water levels are not as obvious as for the deeper piezometers. The most direct response appears during the transition period in November of 1998. The water levels increase relatively rapidly after the wells are shutdown, but they do not show a clear drop when the wells are turned on.

Figure 7 shows water levels that were observed in a domestic well located approximately 200 feet from the pumping wells. The location of this well, which is termed the Dubigk well, is shown on the site location map in Figure 1. The well is reported to be 100 feet deep with a well screen at an approximate elevation of 395 feet MSL (Robinson and Noble, April 1997). This would place the well screen above MW2S and below MW2WT in what has been described as the domestic aquifer. Water levels in the Dubigk well drop at a relatively constant rate during pumping periods and recover at a relatively constant rate during recovery periods.

Table 4 summarizes the changes in water levels or drawdowns that result from pumping at the Witte well field. Table 5 compares the highest and lowest water levels observed in 1997 with the highest and lowest levels observed in 1998. The average change observed in these wells between 1997 and 1998 was -1.34 feet.

The groundwater flow directions can be determined by comparing water levels within the aquifers. Groundwater will flow in the direction of the hydraulic gradient. (The gradient is defined as the difference in water level between two points divided by the distance between these points). The gradients during pumping and non-pumping periods are summarized on Figure 8. During non-pumping or "natural" conditions, the flow is upward from the Witte aquifer to the domestic aquifer. This is shown by the data from April 8, 1997. The horizontal flow direction within both the domestic and Witte aquifers is away from the well field and toward the monitoring wells. During pumping conditions, the flow is reversed at MW1 so that it is downward from the domestic aquifer to the Witte aquifer. At MW2 the gradient remains upward during pumping, but the magnitude is reduced by a factor of 10, from 0.12 to 0.01. The horizontal flow direction is also reversed during pumping so that it is away from the monitoring wells and toward the well field.

6. Quantitative Analysis of Pumping Tests

Estimates of hydrogeological parameters can be developed from pumping tests conducted at the Witte well field. This section summarizes the results of the pumping tests that were conducted both prior to installation of the monitoring wells and tests that were conducted with the clustered piezometers.

6a. Parameter estimates from tests conducted prior to monitoring well installation

Pumping tests were conducted in each of the production wells at the time the wells were constructed. The data from these tests are included in the well construction reports prepared by Robinson and Noble (November, 1987; January, 1992; March, 1992; June, 1994).

Several of the tests were evaluated using the Theis and Hantush models for the aquifer system. These models can be used to provide estimates for the parameters that describe groundwater flow in the aquifer system. The Theis model neglects the effects of leakage from adjacent aquifers and assumes that all water is derived from the pumped aquifer. Estimates of the aquifer transmissivity, T, and storativity, S, can be obtained using the Theis solution. The Hantush models include the effects of leakage from adjacent aquifers and confining units. Two forms of the Hantush solution were used. The first form neglects the effects of storage in the confining unit. The second form includes this storage. The Hantush solutions provide estimates of the aquifer transmissivity, the aquifer storativity, the hydraulic conductivity of the confining unit, and the storage coefficient for the confining unit.

Descriptions of the Theis and Hantush solutions are available in most standard hydrogeology textbooks, including Freeze and Cherry (1979). Details of the methodologies for pumping test evaluations are included in Kruseman and de Ridder (1983). The pumping test software pacakge AQTESOLV was used to estimate the aquifer parameters. The results of the evaluations are included in Appendix C, and are summarized in Table 6. It should be noted that these tests were conducted over relatively short periods of time - between 4 and 24 hours.

6b. Parameter estimates from the 3-day pumping test and monitoring well MW1

A three-day pumping test completed in March, 1997 is described in Robinson and Noble (April, 1997). The response to pumping was monitored in MW1 and in several wells completed in the domestic aquifer. (MW2 had not been installed at the time this test was completed.) Production wells 2, 3, and 4 were operated during the test with a total pumping rate of approximately 870 gpm. A summary of the observed drawdowns after 3 days of pumping is given in Table 7.

Robinson and Noble conclude the following with regard to the drawdowns in MW1S and the Dubigk well (April 1997, page 15):

> *"Drawdown interference was observed in the Dubigk well and in MW-1S, both completed in a shallower confined aquifer. The reflection of pressure changes within confined systems is not unusual and can take place without the physical transfer of water. It is such a pressure reflection which most likely explains the observed response of the overlying confined aquifer. Observations of the water table during future start-up and shut-down events of the wellfield would help clarify this issue."*

The 3-day pumping test data were evaluated by Robinson and Noble using the Theis and Hantush models. The estimates they derived for the aquifer parameters are summarized in Table 8.

6c. Parameter estimates from 30-day pumping tests with monitoring wells MW1 and MW2

A 30-day pumping test was conducted at the Witte well field in June of 1997. With the exception of the three-day pumping test that was conducted from March 10 until March 13, 1997, the wellfield had been shutdown from January 16, 1997 until the pumping test began on June 3, 1997. The total pumping rate at the well field during the pumping test is shown in Appendix D. The stabilized pumping rate was approximately 850 gpm. The pumping rates at individual wells was approximately 465 gpm at Well 4B, 250 gpm at Well 2, and 135 gpm at Well 3.

The observed water levels in Production Well 1 and in Monitoring Wells 1 and 2 are included in Appendix D. The daily precipitation recorded at Seatac Airport during the 30-day test is also included in Appendix D.

The data that were collected at the deep monitoring wells MW1D and MW2D were evaluated with the Theis and Hantush models to estimate the transmissivity and storativity of the aquifer and the hydraulic conductivity of the confining unit. The results from this evaluation are summarized in Table 9. The curves used in the software package AQTESOLV to develop these estimates are included in Appendix D.

6d. Parameter estimates from 30-day pumping tests with monitoring wells MW1 and MW2 using MODFLOW and a three-layer model

The Theis and Hantush models are relatively simple models in terms of the assumed flow field and aquifer boundary conditions. For example, the Theis solution neglects vertical flow from adjacent aquifers and the Hantush solution neglects changes in water levels within adjacent aquifers. Both solutions assume static initial conditions prior to pumping.

The computer model MODLOW (MacDonald and Harbaugh,1988) can be used to allow more complex flow fields and boundary conditions. MODFLOW was used to simulate the 30-day pumping test conducted at the Witte well field. The objective behind this exercise was to develop estimates of aquifer parameters by comparing observed and calculated water levels.

A three layer model was used to simulate water levels in the Witte aquifer, the confining unit above the Witte aquifer, and the domestic aquifer. Table 10 summarizes the input parameters used in the model. Table 11 compares the observed and calculated water levels after 30 days of pumping for this set of input parameters. A comparison of observed and calculated water levels during the 30-day test is presented in Appendix D.

The differences between calculated and observed water levels during the early part of the test are due to non-equilibrium initial conditions in the model. The initial water levels in the deep aquifer were assigned values higher than in the shallow aquifer, to correspond to levels observed in the field. When the model is "turned on," the water levels adjust in response to this initial difference, as well as in response to the pumping. This fit could be improved by changing the boundary conditions along the lateral edges of the boundary. The goal, however, was to estimate aquifer parameters and not to get a "best fit" of observed water levels. The parameters estimated with the MODFLOW model are similar to the estimates developed with the Theis and Hantush solutions, as summarized in Table 12.

7. Effects of the Witte Wells on Leakage from Upper Aquifers and Streams

The geologic and topographic characteristics of the Soos Creek basin result in a system that is, for the most part, hydrogeologically self-contained. Groundwater within the basin originates from infiltration and not from groundwater inflow from outside of the basin. Groundwater leaves the basin in one of two ways: through stream flow, ultimately in Big Soos Creek, or through groundwater extraction wells. An increase in one of these end points necessarily results in a decrease in the other. As more water is removed through groundwater extraction wells, less water is available for stream flow. This conclusion is consistent with data and information included in published reports (e.g. Dinicola, 1990; South King County Ground Water Management Plan, 1991; Woodward et al., 1995).

7a. A Consideration of the effects on leakage from upper aquifers.

The Witte wells are completed in a semi-confined or "leaky" aquifer. 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. This behavior can be described with equations which represent well hydraulics (e.g. Hantush, 1964, pp. 326-338). The following expression gives, as a function of time, the percentage of the extracted water that originates as leakage in a leaky-aquifer system:

$$Q_L/Q_W = 1 - \exp(-K't/Sb')$$

In this expression Q_L is the volume of water that originates as leakage, Q_W is the volume of water that is extracted at the well, t is the time since pumping began, K' is the hydraulic conductivity of the confining layer, b' is the thickness of the confining layer, and S is the storage coefficient for the pumped aquifer. The storage coefficient is a measure of the compressibility of the aquifer.

The assumptions on which this expression is based are described in Appendix E. The geometry that is assumed is illustrated in Figure 9. The well is assumed to be completed in the lower aquifer and leakage is assumed to occur through the aquitard or confining unit above this aquifer. In terms of the Witte well field, Aquifer 1 in Figure 9 represents the Q(A)c unit, the aquitard represents the Q(A)f unit, and Aquifer 2 represents the Qva aquifer.

At early times, when pumping has just begun, the right hand side of this expression equals zero, which means that all the water that is extracted from the wells is derived from the pumped aquifer. After the well has been pumped for longer times, the right hand side approaches one, which means that all the water that is extracted is derived from leakage through confining layers. Although this equation only approximates the actual aquifer system in the Soos Creek basin, it can be used to give at least a sense of the time scales that are important in this problem.

The thickness of the confining unit, b', was assumed to be 50 feet. This is based on information from Woodward et al. (1995) (Plate 2) and on well logs for the Witte wells. The storage coefficient for the pumped aquifer, S, was assumed equal to $5x10^{-4}$. This estimate is based on compressibility values published in the literature for sand aquifers (p. 59, Freeze and Cherry, 1979).

The variable that is most important and uncertain in this expression is the hydraulic conductivity of the confining layer, K'. Figure 10 shows the contribution of leakage as a function of time for a range of values for K'. As the conductivity of the leakage layer increases, the contribution of leakage becomes more important more quickly. We believe that a value of K' = 10^{-7} ft/s (0.01 ft/day) represents a lower bound for this parameter and that a value of K'=10^{-5} ft/s (1 ft/day) is a reasonable estimate.

Figure 10 indicates that the impact of the Witte wells on shallow groundwater may occur quite rapidly. It is likely that after several days of pumping, the large majority of the water that is extracted from the Witte well field originated as leakage from more shallow aquifers.

7b. A Consideration of the Effects of the Witte Wells on Discharge to Streams

The calculations described in the previous section consider the effect of the Witte well field on shallow groundwater systems. In this section, we consider the effect of the wells on groundwater discharge to streams. Because there are no simple expressions that can be used to realistically address these effects, a numerical model for groundwater flow in the vicinity of the Witte well field was constructed using the MODFLOW computer program. MODFLOW was developed by the USGS (McDonald and Harbaugh, 1988) and is the groundwater flow model that is most commonly used in the United States.

The intent of the modeling exercise was to develop an estimate for how long it would take for groundwater extraction at the Witte well field to result in reduced stream flow in the Big Soos Creek basin. The geometry that was assumed is illustrated in Figure 11. In plan view, the flow field was assumed to extend from the bedrock outcrops along the eastern portion of the basin to Big Soos Creek on the west. The width of the flow field was assumed to be 12,000 feet. This width was chosen somewhat arbitrarily to reflect the area of influence for the Witte well field in a direction perpendicular to groundwater flow.

Three geologic layers were considered: the Q(A)c aquifer, the Q(A)f confining unit, and the Qva aquifer. These layers are assumed to dip from the east to the west, as shown in Figure 11. Groundwater flow within each of the aquifers is from the east to the west. This groundwater is assumed to be derived solely from infiltration due to precipitation. The western boundary of the flow field, which corresponds to Big Soos Creek, is treated as a constant head boundary. All other boundaries are no-flow boundaries.

Conditions prior to pumping were calculated by solving for the steady-state hydraulic heads assuming a uniform and constant infiltration rate. The following set of parameters was used in the steady-state analysis:

Hydraulic conductivity of the Qva aquifer: 350 ft/day (Woodward et al, 1995, p. 24)
Hydraulic conductivity of the Q(A)f confining unit: 0.1 ft/day (assumed)
Hydraulic conductivity of the Q(A)c aquifer: 80 ft/day (Woodward et al, 1995, p. 24)
Infiltration rate: 20 inches per year (Woodward et al, 1995, p. 30).

This set of parameters resulted in a distribution of hydraulic heads that was generally consistent with observed values. The calculated hydraulic head in the eastern part of the basin was approximately 600 feet and the head gradients dipped to the west in a manner consistent with field observations. Under steady conditions, approximately 80% of the discharge to Soos Creek comes from the Qva aquifer and the remaining 20% comes from the Q(A)c aquifer.

The steady-state heads were then used as initial conditions in a model that simulated the effect of the Witte well field. The well field was located as shown in Figure 11. The extraction rate at the well field was assumed to be 1500 gallons per minute. The effect of the well field is to reduce the flow or discharge to the constant head nodes that represent Big Soos Creek. Eventually, the flow to Big Soos Creek will be reduced by an amount equal to the pumping rate (1500 gallons per minute). Figure 12 presents the reduction in flow to Big Soos Creek. At time zero, which corresponds to beginning of pumping, no reductions in flow are seen and the discharge to Big Soos Creek is the same as the steady-state conditions prior to pumping. After the wells have been in operation for a period of time, the reduction of flow to Soos Creek will eventually equal the pumping rate at the wells.

The time that is required for the effect of the well field to be realized depends upon the storage coefficients for the aquifers. Lower values for storage coefficient result in more rapid response. Figure 12 shows the response at Big Soos Creek assuming two values of storage coefficients. These values are based on an aquifer thickness of 50 feet and an aquifer compressibility of 1×10^{-9} to 1×10^{-8} m^2/N. This range for compressibility is based on values reported in the literature for sand aquifers (Freeze and Cherry, 1979, p. 55).

The results shown in Figure 12 suggest that the well field may affect discharge in the streams several weeks to several months after the pumping is initiated. For example, after 10 days of pumping, the reduction in discharge to the stream equals 40% of the pumping rate if the storage coefficient is equal to $1x10^{-4}$. This corresponds to approximately 600 gallons per minute. If the storage coefficient is equal to $1x10^{-3}$, this 40% reduction occurs approximately 100 days after pumping is initiated.

The results presented in Figure 12 are aimed at gaining a sense of the time scales that are important for considering the effects of the Witte well field. The actual response time for the aquifer is dependent upon site-specific material properties. Although a relatively large amount of data is available concerning the Soos Creek basin, there are still uncertainties associated with this type of analysis are considerable. The results shown in Figure 12 are somewhat conservative in that they assume that the discharge location for the Qva and Q(A)c aquifers are located in the vicinity of Big Soos Creek. If these aquifers discharge to seeps or streams closer to the well field, then the effects of the well field will be realized more quickly than shown in Figure 12.

A more refined model of the Witte well field has been developed by Landauer (1998). This model incorporates 5 layers and includes more detailed geology and more representative boundary conditions for the flow system. The results of the more refined model, however, are similar in terms of the response times for groundwater extraction to affect water levels in adjacent aquifers and streams.

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Woodward, D.G., F.A. Packard, N.P. Dion, and S.S. Sumioka.Occurrence and Quality of Ground Water in Southwestern King County, Washington," USGS Water-Resources Investigations Report 92-4098, Tacoma, WA, 1995.

Table 1 - Comparison of descriptions for hydrogeologic units.

"Local" description in Robinson and Noble Reports	Possible correlation with units used in Woodward et al., USGS, 1995
Water table aquifer	Qvr - Vashon recessional outwash
Shallow aquitard	Qvt - Vashon till
Domestic or shallow aquifer	Qva - Vashon advance outwash
Middle or intermediate aquitard	Q(A)f - interglacial sediments
Witte Road wellfield aquifer	Q(A)c - outwash of drift sediments

Table 2 - Summary description of piezometer construction.

	Casing Elevation	Screen Depth	Screen Elevation	Static water 4/8/98	Static water Elevation
MW1D	496.4	200-205	292.8	57.07	439.3
MW1I		180-185	312.8	69.57	426.8
MW1S		125-135	365.3	72.10	424.3
MW2D	495.4	212-217	253.5	59.76	435.6
MW2I		190-195	302.5	71.50	423.9
MW2S		125-135	365.0	72.80	422.6
MW2WT		85-95	405.0	36.15	459.2

Table 3 - History of pumping at Witte Well field from January, 1996 through June, 1999

Beginning	Ending	Description
January, 1996	January, 1997	Wells operated with an average production rate of approximately 820 gpm.
January 16, 1997	March 10, 1997	All wells shutdown.
March 10, 1997	March 13, 1997	The first 3 day pumping test completed with MW1. Results are included in Robinson and Noble, April, 1997.
March 13, 1997	June 3, 1997	All wells shutdown.
June 3, 1997	November 20, 1997	Wells in operation. This period includes the first 30-day pumping test completed with MW1and MW2.
November 20, 1997	May 15, 1998	All wells shut down. This period includes the first 30-day recovery test completed with MW1and MW2
May 15, 1998	November 16, 1998	Wells in operation. This period includes the second 30-day pumping test completed with MW1and MW2. The average pumping rate was approximately 815 gpm.
November 16, 1998	May 18, 1999	All wells shut down. This period includes the second 30-day recovery test completed with MW1and MW2
May 18, 1999	June 8, 1999	Wells in operation. No data have been provided describing water levels or pumping rates after June 8, 1999.

Table 4 - Summary of the changes in water levels from pumping at the Witte well field.

			Drawdown	
		Distance to Well 4B	30 days 6/97-7/97	180 days 5/98-11/98
Well 1	Deep	45	35	47*
Well 2	Deep	70	70	81*
Well 4B	Deep	-	60	68*
MW1	Shallow	155	11	19
MW1	Intermediate	155	15	24
MW1	Deep	155	33	45
MW2	Water Table	380	1	3.2
MW2	Shallow	380	9	19
MW2	Intermediate	380	23	21
MW2	Deep	380	24	31
Dubigk	Shallow	200	7	15

* Drawdowns are for 150 days from 5/14/98 to 10/12/98. Data for 11/98 were not provided.

Table 5 - Low and high water levels in the vicinity of the Witte well field

		Low water levels			High water levels		
		11/19/97	11/15/98	Change	5/14/98	5/17/99	Change
MW2	Water Table	460.2	454.7	-5.5	457.9	457.9	0.0
MW1	Shallow	406.6	406.3	-0.2	425.2	424.1	-1.1
MW2	Shallow	407.3	404.8	-2.5	423.6	422.9	-0.7
MW1	Intermediate	404.6	403.6	-1.0	427.7	426.6	-1.1
MW2	Intermediate	405.4	403.8	-1.6	424.9	424.8	-0.1
MW1	Deep	396.1	394.9	-1.2	440.1	439.0	-1.1
MW2	Deep	407.7	405.9	-1.8	436.4	435.5	-0.9

Table 6 - Summary of aquifer parameters based on pumping tests conducted prior to installations of clustered piezometers.

Parameter	Range of Estimates
Aquifer transmissivity, T (ft^2/min)	1.3 to 2.1
Aquifer transmissivity, T (gpd/ft)	14,000 to 22,000
Aquifer hydraulic Conductivity, K (ft/min)	0.09 to 0.14
Aquifer storativity, S	1.2E-03 to 1.2E-02
Confining unit hydraulic conductivity, K' (ft/min)	2.2E-06 to 2.8E-03
Confining unit storativity, S'	9.8E-03 to 2.8E-04

Table 7- Summary of observed drawdowns during the 3-day pumping test.

Well Name	Distance from Well 4B (ft)	Approximate screen elevation (ft)	Drawdown after 3 days (ft)
Production Well 1	45	287-299	30.6
Production Well 2	70	290-302	66.2
Production Well 3	81	288-296	31.6
Production Well 4B	-	292-303	56.9
Monitoring Well 1D	155	290-295	29.6
Monitoring Well 1M	155	310-315	11.5
Monitoring Well 1S	155	360-370	7.0
Dubigk domestic	200	395	1.0

Table 8 - Summary of estimates for aquifer parameters from the 3-day pumping test (from Robinson and Noble, April 1997)

Parameter	Range of Estimates
Aquifer transmissivity, T (ft^2/min)	1.9 to 2.4
Aquifer transmissivity, T (gpd/ft)	20,000 to 26,000
Aquifer storativity, S	5.0E-04 to 1.0E-03
Confining unit hydraulic conductivity, K' (ft/min)	6.0E-04 to 5.0E-03

Table 9 - Summary of aquifer parameters from the 30-day pumping test with monitoring at MW1and MW2 using Hantush and Theis models.

Parameter	MW1D	MW2D
Aquifer transmissivity, T (ft^2/min)	2.2	1.3
Aquifer transmissivity, T (gpd/ft)	23,000	14,000
Aquifer storativity, S	$1.0x10^{-3}$	$6.3x10^{-3}$
Confining unit hydraulic conductivity, K' (ft/min)	$1x10^{-6}$	$3x10^{-5}$

Table 10 - Summary of the three-layer MODFLOW model used to simulate the 30-day pumping test.

Horizontal extent:	6300x6300 feet
Number of layers:	3
Thickness of pumped aquifer:	25 ft.
Thickness of confining unit:	30 ft.
Thickness of upper aquifer:	50 ft.
Boundary conditions in pumped aquifer:	no-flow
Boundary conditions in confining unit:	no-flow
Boundary conditions in upper aquifer:	constant head
Initial head in pumped aquifer:	437 ft.
Initial head in confining unit:	423 ft.
Initial head in upper aquifer:	420 ft.
Infiltration rate:	0
Pumping rate at Well 4B:	465 gpm
Pumping rate at Well 2:	250 gpm
Pumping rate at Well 3:	135 gpm
Hydraulic conductivity of pumped aquifer:	200 ft/day
Hydraulic conductivity of confining unit:	0.1 ft/day
Hydraulic conductivity of upper aquifer:	40 ft/day
Storage coefficient:	$5 x10^{-3}$

Table 11- Comparison of observed and calculated water levels for the 3-layer MODFLOW model

			Drawdown after 30 days	
	Unit	Distance from Extraction Wells	Observed	Calculated
Well 1	Witte aquifer	50 ft	35 ft	36 ft
MW1D	Witte aquifer	180	33	32
MW1I	Confining unit	180	15	16
MW1S	Domestic aquifer	180	11	10
MW2D	Witte aquifer	380	24	26
MW2I	Confining unit	380	23	22
MW2S	Domestic aquifer	380	9	7

Table 12 - Comparison of parameter estimates from Hantush/Theis models with estimates from 3-layer MODFLOW model

	Estimate from Hantush/Theis models	Estimate from 3-layer MODFLOW model
Aquifer transmissivity, T (ft^2/min)	1.3 to 2.4	3.5
Aquifer storativity, S (dimensionless)	$5x10^{-4}$ to $1x10^{-2}$	$5x10^{-3}$
Confining unit hydraulic conductivity, K' (ft/min)	$1x10^{-6}$ to $5x10^{-3}$	$2x10^{-3}$