3.0 WELLHEAD CAPTURE ZONE DELINEATIONS

The Washington State Department of Health Wellhead Protection Technical Advisory Committee has recommended four different methods that can be used to delineate wellhead capture zones, including (in increasing order of sophistication):

1. Calculated Fixed Radius
2. Analytical Methods
3. Hydrogeologic Mapping
4. Numerical Flow/Transport Models

Previous Wellhead Protection Areas were delineated using analytical methods, which are limited in their ability to simulate aquifers with variably hydraulic conductivity. Well transmissivities are known to vary between the City's Wellfields and both high and low transmissivities can be observed in both the Qal and Qga aquifers. The Qal aquifer supplying the Palermo and Brewery Wellfields is a channel feature that is limited in extent to the Deschutes River valley. It is, however, hydraulically connected to the Qga aquifer and there is regional groundwater flow from the Qga aquifer into the Qal aquifer.

The original capture zone delineations prepared for the 1997 WHPP were developed using a simplified analytical model (GFLOW) that is no longer in use. In order to capture the variable hydraulic properties of the aquifers supplying the wellfields, and to accommodate variations in recharge to these aquifers, a numerical groundwater flow model (MODFLOW) was chosen to generate capture zones for each wellfield. This section describes the modeling approach and parameters used to generate capture zones, which form the basis for delineating WHPA's that become subject to additional management activity, such as contaminant source inventories and City ordinance requirements.

Any model (numerical or analytical) is based on inputs for various aquifer parameters that are either measured or estimated based on data. The supporting data used for the model presented here is based on existing reports and wellhead completion records and no detailed field investigations were carried out to refine or confirm the model configuration or results. The modeling process (for both numerical and analytical models) involves using the model to calculate the groundwater flow field, and then comparing the model result to observed field conditions. This is called calibrating the model. Calibrating a model is typically undertaken in a "steady state" condition, where average water levels in the aquifer are used, and seasonal variations or year-to-year variations in groundwater flow system are not simulated. Models can produce similar depictions of observed field conditions using different combinations of model parameters and boundary conditions. This is referred to as the "non-uniqueness" problem in modeling. Despite these limitations, models are still the best method for delineating capture zones and defining wellhead protection areas. WHPA models would not, however, be considered applicable for a site scale transient contaminant transport analysis. The model created for the City is only intended to be used for wellhead protection planning purposes.

3.1 Model Codes and Datum

The groundwater model was developed using a public-domain US Geological Survey (USGS) software package called MODFLOW, which was originally released in 1988 (McDonald and Harbaugh 1988) and has had several updates over the years (Harbaugh and McDonald 1996; Harbaugh et al. 2000; Harbaugh 2005). MODFLOW was selected for this study because it is well suited to watershed-scale groundwater flow simulations and can account for the variability in conductivity. MODFLOW has been extensively tested and validated in a wide range of hydrogeologic environments for 25 years, and is generally accepted within the scientific and regulatory communities.

MODFLOW solves the three-dimensional groundwater flow equation for porous media using the finite-difference method. The graphical user interface (GUI) Groundwater Vistas was also used for pre- and post-processing of MODFLOW files. The GUI allows overlays of maps and can generate cross-sections to efficiently generate the aquifer geometry. It also allows processing of MODFLOW output to generate contour maps and compare modeled versus observed conditions.

After the MODFLOW simulation is completed, capture zones for the wellfields were delineated using the particle tracking software MODPATH (Pollock 1994) in GWV 6.44 (ESI 2011).

The North American Vertical Datum used for the model is NAVD 1988 (NAVD88).

3.2 Model Development and Calibration

Models are simplifications of the hydrogeologic setting being investigated, and the accuracy of model predictions depends on how well the model can reproduce the observed hydrogeologic setting. A model is produced by:

- Defining the model domain, layering, grid spacing and boundary conditions (Section 3.2.1). This is based on the conceptual hydrogeologic model and desired geographic accuracy of model predictions. Boundary conditions can be no flow boundaries, constant head boundaries, or constant flux boundaries.
- Assigning aquifer hydraulic properties throughout the model (Section 3.2.2). This is based on available reports and aquifer test data in City production wells.
- Assigning recharge rates and pumping rates for wells (Section 3.2.3). This is based on climate data, available reports and pumping data in City production wells. The pumping data includes both current pumping (for model calibration) and expected future pumping (for delineation of WHPA's).

- Calibrating the model (Section 3.2.4). As described previously, calibration involves comparing the model result to observed field conditions and then adjusting (if necessary) selected aquifer parameters until an adequate match is obtained. Calibrating a model is typically undertaken in a “steady state” condition, where average water levels in the aquifer are used. Once calibrated, the model can then be used to predict groundwater capture zones under future pumping conditions. The Tumwater model was calibrated to 1995 observed aquifer conditions and pumping rates.

3.2.1 Model Configuration and Boundaries

The model domain was selected to encompass the Palermo, Port, Bush Middle School and Southwest Wellfields. The model domain covers approximately a five-mile by five-mile area, to encompass bedrock outcrops of Tumwater Hill in the north to bedrock outcrops just outside of the City boundary to the south, and from the Black River drainage system to the west to the Deschutes River to the east. The model was discretized by a fixed-dimension finite difference grid spacing set to 200 feet by 200 feet. Model boundary conditions are used to assign flow into or out of the model domain (Figure 3-1).

The well locations were based on northing and eastings obtained from a georeferenced aerial map of the well houses in ArcView and confirmed by the City. The associated surface water drainage basins include parts of the Deschutes River and Black River drainage basins (Figure 3-1). The model domain boundaries were located to minimize boundary effects on the model flow field.

No-flow boundaries were assigned along the perimeter of the model active area (Figure 3-1). A no-flow boundary was also set along the bottom of the model. There is probably some degree of upward leakage from underlying strata, however, it is not considered sufficient to substantively affect the delineation of wellhead protection areas.

River boundary conditions were added in the model to represent the Black River (including Black Lake) and the Deschutes River (Figure 3-1). River elevations were taken from the 1997 WHPP (EES 1997). The river bottom was set 2 feet below the river stage throughout the model.

Stream survey data and measurements of the hydraulic properties of deposits data were not available for the modeling effort. The hydraulic conductivity of the riverbed sediment was taken as the calibrated hydraulic conductivity of the Qva aquifer (40 ft/day). The thickness of the riverbed sediments was estimated as 1 foot, making the river sediments essentially equivalent to aquifer sediments (e.g. full hydraulic connectivity). The width of the river channel was estimated as 10 feet, and the length of the river cell was set equal to the length of the model cell. During calibration, the model was found to not be sensitive to the river conductance.

3.2.2 Aquifer Properties

The model is constructed as a single layer model simulating two hydraulically continuous aquifer units (surficial aquifer and the advance outwash aquifer) with varying aquifer transmissivity zones. Transmissivity is the product of aquifer thickness (b) multiplied by hydraulic conductivity (k). Well tests can directly calculate aquifer transmissivity and these calculations are routinely performed to determine well yield. Table 3-1 shows observed and modeled aquifer transmissivity values at the Palermo wellfield, Port Wells 11 and 15, Bush Middle School Wells 12 and 14 and the Southwest Test Well (TW-04-01), based on the well completion tests (results of these tests are presented in well completion reports that are maintained in the City's files). Groundwater velocities and travel times, which are needed to delineate capture zones, must be determined using hydraulic conductivity, not aquifer transmissivity. Hydraulic conductivity was estimated by dividing the transmissivity by the aquifer thickness. The aquifer thickness in the model was assumed to be constant for the two aquifer units (surficial aquifer and advance outwash aquifer). Table 3-1 shows a single hydraulic conductivity value at each wellfield location that matched or slightly overestimated the observed transmissivity at each wellfield during calibration. In general, decreasing the transmissivity values within the model reduced the size of the wellhead capture zone, however during calibration to observed water levels, the models were found to not be overly sensitive to aquifer transmissivity.

Figure 3-2 shows the transmissivity distribution used in the model and a model cross-section of hydraulic conductivity is shown on Figure 3-3. Figure 3-4 shows the hydraulic conductivity distribution in map view. Figures 3-2 and 3-4 show interpolated aquifer transmissivity and hydraulic conductivity values across the model domain based on the point measurements at each wellfield (Table 3-1). Bedrock features in the interior of the model domain were assigned a very low transmissivity. The aquifer thicknesses and hydraulic properties are generally consistent with the geologic model developed in the 1997 WHPP (EES 1997), and evaluation of well logs and available aquifer test data.

Table 3-1: Observed and Modeled Aquifer Properties

	OBSERVED		**MODELED**			
	Transmissivity (Well Test)		**Transmissivity (k * b)**		**Thickness (b)**	**Hydraulic Conductivity**
	gpd/ft	**ft^2/day**	**gpd/ft**	**ft^2/day**	**ft**	**ft/day**
SW Test Well (TW-04-01)	112,000	15,000	134,649	18,000	60	300
Port #15	35,000 - 60,000	4,679 - 8,021	71,813	9,600	60	160
Port #11	11,800 - 13,100	1,577 - 1,751	13,465	1,800	60	30

Table 3-1: Observed and Modeled Aquifer Properties (continued)

	OBSERVED		MODELED			
	Transmissivity (Well Test)		Transmissivity (k * b)		Thickness (b)	Hydraulic Conductivity
	gpd/ft	ft^2/day	gpd/ft	ft^2/day	ft	ft/day
Palermo #2-6, #8	32,000 - 89,000	4,278 - 11,898	59,844	8,000	200	40
Bush Wells #12, #14	150,000 - 170,000	20,052 - 22,726	191,651	25,620	60	427

3.2.3 Recharge and Pumping Rates

Recharge was applied to each of the model cells. In the 1997 WHPP (PGG 1997), the recharge rate was estimated at 2 feet annually. During the model calibration process, recharge was adjusted to about 2.5 feet annually to match observed water levels in wells to within 5 feet of the 1995 water levels. Figure 3-5 shows the distribution of recharge over the groundwater model area domain.

Pumping rates for the City's wellfields were based initially on average 1995 pumping rates (coinciding with the time period for the most extensive spatially distributed water level measurements across the study area)The data was taken from the 1997 WHPP & 1998 WHPA modeling reports and presented in the 2010 Wellhead Protection Plan (Table 3-2).

Table 3-2: Pumping Rates (1995) Used for Model Calibration

Well	Wellfield	Pumping Rate* (gpm)
2	Palermo	59
3	Palermo	77
4	Palermo	128
5	Palermo	67
6	Palermo	120
7	Port	128
8	Palermo	88
9	Port	107
10	Port	130
11	Port	73
12	Bush Middle School	200
14	Bush Middle School	628
15	Port	214
20	Trails End	20
Total		**2,039** (2.9 mgd)

*mgd = million gallons per day

Pumping at the Southwest Wellfield was not included in the calibration simulation. The 1995 pumping rates were only used for the model calibration, as described below. For delineation of capture zones, different pumping rate scenarios were used for the model simulation to represent possible current pumping rates (Section 3.3), and the Southwest Wellfield was included as a pumping wellfield, but the aquifer properties were not changed.

3.2.4 Model Calibration

Using the boundary conditions, aquifer properties and recharge distribution described above the model simulated groundwater flow pattern in the area. The calibration simulation was performed under steady-state conditions. In a steady-state simulation, temporal variations (i.e. daily recharge values, pumping schedules, etc.) are not considered. The water levels produced from the groundwater model using 1995 pumping rates were compared to the December 1995 water levels as presented by EES (1997). December water levels represent an average between the seasonal high water levels that are typically seen in March and the seasonal low water levels that are typically seen in September. The annual water level fluctuations are on the order of 10 feet, so the target tolerance for model calibration was +/- 5 feet of the observed December 1995 water levels. Figure 3-6 shows the resulting head contours with 1995 water level data.

3.3 Delineation of Capture Zones

To delineate capture zones, a particle tracking code was used to simulate the time-of-travel for groundwater to reach the City's pumping wells under future pumping conditions. Future conditions are typically used in wellhead protection planning since they are usually higher than current conditions and reflect a conservative and forward-looking approach to aquifer protection and management. No other changes to aquifer properties or model configuration were made from the calibrated model "baseline simulation".

3.3.1 Particle Tracking Code

Capture zones for the wellfields were delineated using the particle tracking software MODPATH (Pollock 1994) in GWV 6.44 (ESI 2011). MODPATH Particle tracking is a method of determining time-of-travel along groundwater flowpaths defined from a MODFLOW distribution of steady state water-levels (hydraulic heads). Particles are placed at user defined locations and MODPATH is run for a specified period of time. The density and distribution of particles at any point in time can then be output from MODPATH. For capture zone delineation, particles are placed in close proximity to a well and then reverse tracked from the well to define zones of contribution to the well at a given point in time.

Particles were placed around each of the Palermo, Port, BMS and SW wells and the MODPATH simulation was run for 10 years with reverse particle tracking to delineate the capture zones for the wellfields. Time of travel markers were placed along the particle paths indicating the six-months, one-year, five-year, and ten-year time-of-travel zones.

3.3.2 Effective Porosity Estimate

Effective porosity is a measure of the open space in a granular material and is expressed as a percentage of open space that can transmit groundwater flow. Effective porosity does not affect the groundwater heads or steady state flow field, but it is necessary to compute groundwater velocity and travel time. Generally speaking, the size of a modeled capture zones is inversely proportional to effective porosity. A larger effective porosity means that a greater volume of groundwater is present closer to the well, which creates a smaller capture area. A smaller effective porosity means that the same volume of water will have to be pulled from further away which creates a larger capture area.

No direct measurements of effective porosity are available for the aquifer materials at the City's Wellfields. For unconsolidated glacial materials effective porosity generally ranges from 0.2 to 0.4 (Anderson and Woessner 1992). A value of 0.25 is typically used in many Wellhead Protection applications (New Jersey Geologic Survey Open File Report 03-1, 2003), and was used in previous WHPA delineations for Tumwater. This is the value used in the model.

3.3.3 Pumping Rates

Three pumping rate scenarios were simulated to delineate capture zones. The "Water Right" simulation is based on converting the Qa for the water rights to a continuous pumping rate in gallons per minute. An "Installed Capacity" model simulation was using also run using the maximum pumping capacity for each of the City's wells.

- **1995 Baseline Simulation:** This is the calibration simulation and represents 1995 pumping conditions. Pumping at the Southwest Wellfield was not included in the calibration simulation. Observed water levels in 1995 matched the model result to within 5 feet, and are considered an acceptable calibration to simulate capture zones (section 3.2.5).
- **Water Right Simulation:** Pumping rates were input based on the water rights maximum annual volume (Appendix B). Where multiple water rights applied to the same well, pumping rates were combined as explained in the comments in Appendix B. For example, water right "GWP 7278" applies to Port Wells 9, 10, 11, and 15 and Bush Well 14; in this case the maximum rate was split among the associated wells based on the capacity listed in the 1997 WHPP. Water right "G2-00271C" applies to Port wells 11, 13 and 15. Well 13 is no longer in operation, and in this case the total pumping rate was evenly distributed between Well 11 and 15. Pumping rates for the Southwest wellfield was taken from the maximum instantaneous pumping rated on the pending water right application.
- **Installed Capacity Simulation:** For this model scenario, the installed well capacities listed in the 1997 and 2010 WHPP plans were used as the modeled pumping rates. Pumping rates for the Southwest wellfield was taken from the maximum instantaneous pumping rated on the pending water right application.

The pumping rates used for the two scenarios are shown in Table 3-3.

Table 3-3: Pumping Rates Used for Capture Zone Delineation

Wellfield	Well ID	Modeled Pumping Rates (gpm)		
		1995 Baseline Simulation	**Water Right Simulation**	**Maximum Installed Capacity Simulation**
Palermo	3-6, 8, 16	Simulated as two wells of equal capacity.		
	TOTAL	**1,530** (2.2 mgd)	**1,868** (2.7 mgd)[1]	**2,000** (2.9 mgd)
Port	9	107	175	400
	10	130	192	485
	11	73	127	275
	15	214	335	800
	TOTAL	**524** (0.8 mgd)	**830** (1.2 mgd)	**1,960** (2.8 mgd)
Bush Middle School	12	200	139	750
	14	628	1,211	2,350
	TOTAL	**828** (1.2 mgd)	**1,350** (1.9 mgd)	**3,100** (4.4 mgd)
Southwest	SW	0	1,335	2,226
	TOTAL	**0**	**1,335** (1.9 mgd)	**2,226** (3.2 mgd)
TOTAL		**1,832** (2.9 mgd)	**5,383** (7.7 mgd)	**9,286** (13.3 mgd)

Notes: [1] Represents total of all Palermo Wellfield water rights

3.4 Capture Zone Results and Discussion

3.4.1 Overview

The results of the capture zone delineations are summarized below:

- **1995 Baseline Simulation:** Figure 3-6 shows the simulated groundwater flow field for the 1995 Baseline of 2.9 mgd total pumping.
- **Water Right Simulation:** Figure 3-7 shows the capture zones for the Water Rights simulation at 7.7 mgd total pumping. This represents a reasonable approximation of full exercise of the City's water rights in the future. The results shown in Figure 3-7 include an additional "factor of safety", which was applied on the GIS maps as a 10% spatial increase in the modeled capture zones. In Figure 3-7, the shaded areas represent the modeled capture zone and the 10% "safety factor" is shown as a solid line.
- **Installed Capacity Simulation:** Figure 3-8 shows the capture zones for the Installed Capacity Simulation at 13.3 mgd total pumping. This represents a physical maximum approximation of potential capture zones and represents the largest capture zones that the existing wells could create. The possibility of obtaining additional water rights beyond what is already administratively issued and applied for that might allow pumping of wells to their full installed capacity is unknown. This simulation demonstrates the overall extent of the aquifer that could deliver groundwater to the City's wells and is an appropriate scenario for delineating WHPAs.

3.4.2 Discussion

This section provides a discussion of the capture zone at each wellfield, including how the current capture zone delineations compares to previous delineations.

- **Palermo Wellfield:** The capture zone for the Palermo wellfield is generally shorter and squatter than the 1997 analysis and incorporates a larger area southeast of the wellfield (including an additional 3,000 feet along Interstate 5) Figure 3-9 is a comparison of the 1997 and 2014 captured zones. The 1997 modeling analysis was based on an analytical model (QuickFlow) that produced a long narrow capture zone. The QuickFlow parameters differed in thickness, hydraulic conductivity, and hydraulic gradient compared to the MODFLOW parameters. The MODFLOW simulation is better able to simulate the interpreted aquifer thickness, the change in aquifer properties between the Deschutes Channel fill sediments and the upland glacial stratigraphy, and the northerly component of groundwater flow. In the current delineation, the calibrated flow field closely matched observed ambient conditions, and no manual adjustment of the simulated capture zones was needed. Most of the previous 1997 capture zone that extended over Trosper Lake has been eliminated in the MODFLOW simulation. This is consistent with groundwater mapping that shows groundwater flow in this area to the north along Percival Creek (Figure 3-9). Therefore, we think that the MODFLOW delineation of capture zone for the Palermo Wellfield is accurate and should be adopted for the revised delineation of WHPAs.
- **Port Wellfield:** Although the capture zone for the Port wells extends upgradient further to the southeast than the previous 1997 capture zone, the overall capture zone areas are similar. As in the 1997 WHPP, the 10-year capture zones of the Port and Bush Wells aggregate into a larger single area. The additional capture area to the west of the Port wells is primarily attributed to the larger pumping rate simulated in the MODFLOW model (0.75 mgd in the 1997 model versus 1.2 mgd in the MODFLOW model). The 1997 modeling also produced a noticeable deflection extending east that was not produced in the MODFLOW simulation. The flat hydraulic gradient in the area introduces some uncertainty on the direction of groundwater flow and associated extension of capture zones (Figure 3-8). We think the deflection produced in the 1997 models is produced from a combination of flat hydraulic gradients and interference effects from Bush wells that forces the capture area for the Port wells to move east.
- **Bush Wellfield:** The MODFLOW model extends the capture area of the Bush Wellfield to the southeast, whereas the 1997 capture area extended almost directly south. Again, the flat hydraulic gradient in the area introduces some uncertainty on the direction of groundwater flow, but we interpret a northwesterly gradient in this area, which would be consistent with a southeasterly trending capture zone. Regardless, the inclusion of the Southwest Wellfield produces capture zones in parts of the areas previously delineated due south of the Bush Wellfield, thus maintaining most of the capture zone defined in the 1997 WHPP.
- **Southwest Wellfield:** This capture zone extends southeast, adjacent to the Bush Wellfield capture zone. The delineation is consistent with the northwesterly gradient. Notably, the capture zone for the Southwest Wellfield includes an additional 5,000 feet of Interstate 5, which is a potential source of contamination.

3.4.3 Recommended Wellhead Protection Area (WHPA)

We recommend that the Maximum Installed Capacity Simulation shown in Figure 3-8 (with the 10% “safety factor”) be used to delineate Wellhead Protection Areas for the City’s Wellfields. The following sections (Contaminant Source Inventory and Management Strategies) are focused on these areas.