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TAX 91-075 State Wellhead Protection Program [illegible]
Clark Co. Dept. of Community Development [illegible]

METHODS TO DETERMINE WELLHEAD PROTECTION AREAS FOR PUBLIC SUPPLY WELLS IN CLARK COUNTY, WASHINGTON

APPENDICES

Intergovernmental Resource Center

February 1992

WRIA # 27-28

Appendix A

WELLHEAD PROTECTION AREA DELINEATION REPORT

BATTLE GROUND WELLS 1 AND 2

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix A
Wellhead Protection Area Delineation Report

Well: Battle Ground Wells 1 and 2

Setting: The Battle Ground wells are in the town of Battle Ground on gentle west sloping land near the base of the Cascade Mountains foothills in north central Clark County. The East Fork of the Lewis River forms a 100 to 170 foot (30 to 52 meters) deep east-west valley about one to two miles north of Battle Ground. Weaver Creek flows around the west base of Tukes Mountain less than a mile east of the well.

There are four wells at two sites used by Battle Ground. Wells 1 and 2 are close together and produce about two thirds of the water used by the city. The two remaining wells, 4 and 5, are about one half mile south, down gradient of well 1. Well 5 produces the balance of the city supply with well 4 as a standby well (Dietrich, 1982). The delineated wells, 1 and 2, are 144 feet 44 (meters) and 152 feet (46 meters) deep and are completed in the upper member of the Troutdale Formation.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Aquifer extent was identified from geologic mapping of the upper member of the Troutdale Formation (Mundorff, 1964; Swanson and others, 1991) and lithology descriptions from water well reports. In addition to the upper Troutdale Formation sandy gravel, the aquifer includes sand at the top of the fine grained lower Troutdale Formation. Aquifer water levels are near the top of the upper Troutdale Formation, making saturated thickness about equivalent to the thickness of the upper Troutdale Formation and underlying sand bed, about 200 feet (64 meters). The aquifer is underlain by fine grained lower member Troutdale Formation deposits comprised of silt, sandy silt, sand, and clay. Insufficient well data exists to accurately characterize these deposits.

A northeast-southwest tending ground water divide between the East Fork of the Lewis River and the well acts as a partial upgradient boundary. The ground water divide is about 2,000 feet (600 meters) northwest of the well. However, two dimensional flow paths can extend up gradient along the divide. Weaver Creek, about 2,500 feet (780 meters) southeast of the well does not cut into the aquifer, lying on younger fine grained material (sandy silt with some sand and gravel). Tukes Mountain, about 4,800 feet (1,450 meters) east of the well, is a hill of volcanic rocks predating the Troutdale Formation that locally forms a boundary for Troutdale Formation deposition. Tukes Mountain appears to act as an isolated barrier to ground water flow incorporated into the local ground water flow pattern.

Gradient and Flow Direction: Gradient and flow direction were taken from an aquifer water level map for the upper Troutdale Formation drawn using spring 1988 water levels measured by the USGS. Gradient is about 0.003 at the well and steepens to about 0.007 one mile up gradient. Flow direction is to the southwest at the well but becomes more westerly north of Tukes Mountain. Well records from the Battle Ground area show deeper water levels with increasing well depth indicating a downward gradient between and sometimes within aquifer units.

Aquifer Properties:

Transmissivity: A transmissivity of 20,000 gallons/day/foot (250 meters^2/day) was estimated from specific capacity (8 gallons/minute/foot drawdown) and an estimated storage coefficient (0.001) using a graphic method described by Theis and others (1964). Available single well recovery tests gave transmissivities of 10,000 to 20,000 gallons/day/foot.

Porosity: Well record and field observation descriptions of aquifer lithology were used to estimate a porosity of .2 from tabulated aquifer porosity estimates (Heath, 1983).

Pumping Rate: An average pumping rate of 348,000 gallons/day (1,300 meters^3/day) was calculated from reported peak year pumping totals for wells 1 and 2 of 127,000,000 gallons in 1988 (Written communication, 1989, US Geological Survey).

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to determine aquifer geometry, aquifer properties, and water level surface. Basic data included geologic maps, regional hydrogeologic maps, and information from water wells (water level, lithology, and pump tests).

Zones of contribution for 1, 5, 10, 20, and 50 years were delineated using a simple combination of two dimensional flow line mapping and time of travel delineations from EPA MWCAP model (EPA, March, 1991) (Figure BG-1-1). MWCAP time of travel delineations were calculated using gradients measured from the potentiometric surface map. The MWCAP calculated zone of contribution width at the well and zone of contribution length, and aquifer water level map flow lines were combined to make two dimensional flow based delineations reflecting information describing non-uniform gradient, a ground water divide, barrier effects, and near well pumping effects on gradient.

Analytical Models: The WHPA Version 2 MWCAP model (EPA, March, 1991) was used to delineate zones of contribution for 1, 5, 10, 20, 50 years. A barrier boundary was used to simulate the ground water divide between the well and the East Fork of the Lewis River. Analysis was based on data generated by hydrogeologic mapping. The same parameters were used for each time of travel calculation. Figure BG-1-2 shows the results.

Values selected were:

Transmissivity: 250 meters^2/day
Pumping rate: 1,300 meters^3/day
Gradient: 0.004 for 1, 5, 10 years, and 0.006 for 20, 50 years time

of travel
Flow angle: -126° (216° compass bearing)
Porosity: 0.2
Aquifer thickness: 64 meters
Time of travel: 1, 5, 10, 20, and 50 years

The barrier boundary was 600 meters from the well with an angle of 300 degrees.

An additional model was constructed to include the south well site, well 5, in the delineations. The EPA RESSQC model (EPA, March, 1991) was used to delineate 1, 5, and 10 years zones of contribution for Battle Ground wells 1, 2 and 5 (Figure BG-1-3).

Values selected were:

Transmissivity: 250 meters^2/day
Pumping rate: 1,300 meters^3/day for wells 1 and 2, and 360 meters^3/day for well 5
Gradient: 0.004
Flow angle: -126° (216° compass bearing)
Porosity: 0.2
Time of travel: 1, 5, and 10 years

Calculated Fixed Radius: Calculated fixed radii delineations were made using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulation volumetric flow equation. Figure BG-1-4 shows these delineations.

Values selected were:

Pumping rate: 17,045,000 feet^3/year (127.5 mg/y)
Porosity: 0.2
Length of well screen: 42 feet
Times of travel: 1, 5, 10, 20, and 50 years

Fixed Radius: Figure BG-1-5 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: Refer to USGS map report.

References Cited:

Dietrich, W.L., March, 1982, Ten Year Water System Plan for the City of Battle Ground, Washington: Draft Report, Battle Ground, Washington.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: United States Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

Mundorff, M.J., 1964, Geology and Ground-Water Conditions of Clark County, Washington, with a Description of a Major Alluvial Aquifer Along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268p., 3 pls.

Swanson, R.D., W.D. McFarland, J.B. Gonthier, and J.W. Wilkinson, 1991, A Description of Hydrogeologic Units in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90-4196.

Theis, C.V., R.H. Brown, and R.R. Meyer, 1963, Estimating the Transmissivity of Aquifers from the Specific Capacity of Wells: U.S. Geological Survey Water Supply Paper 1536-I, pp. 331-341.

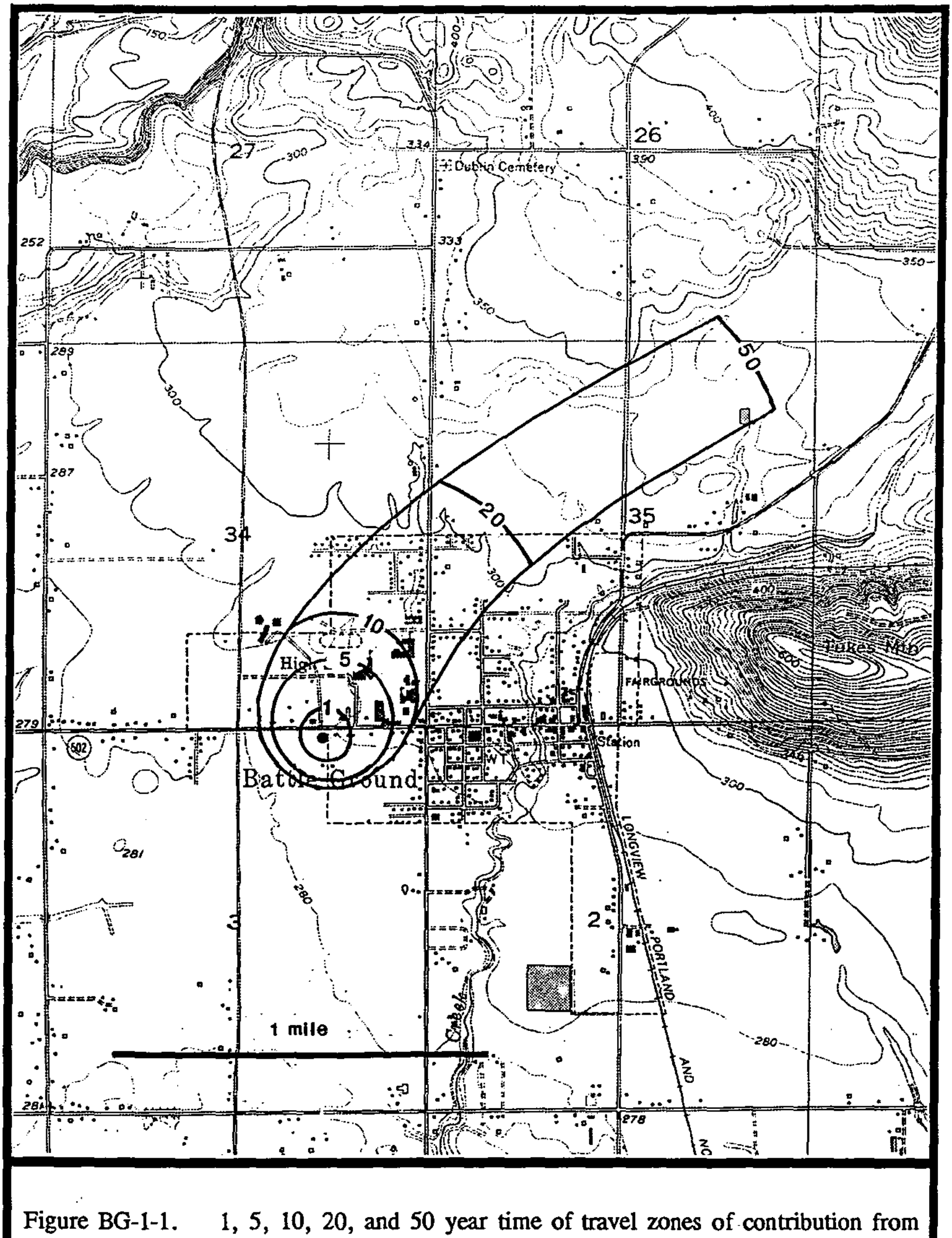

Figure BG-1-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution from hydrogeologic mapping and analytical method for Battle Ground wells 1 and 2.

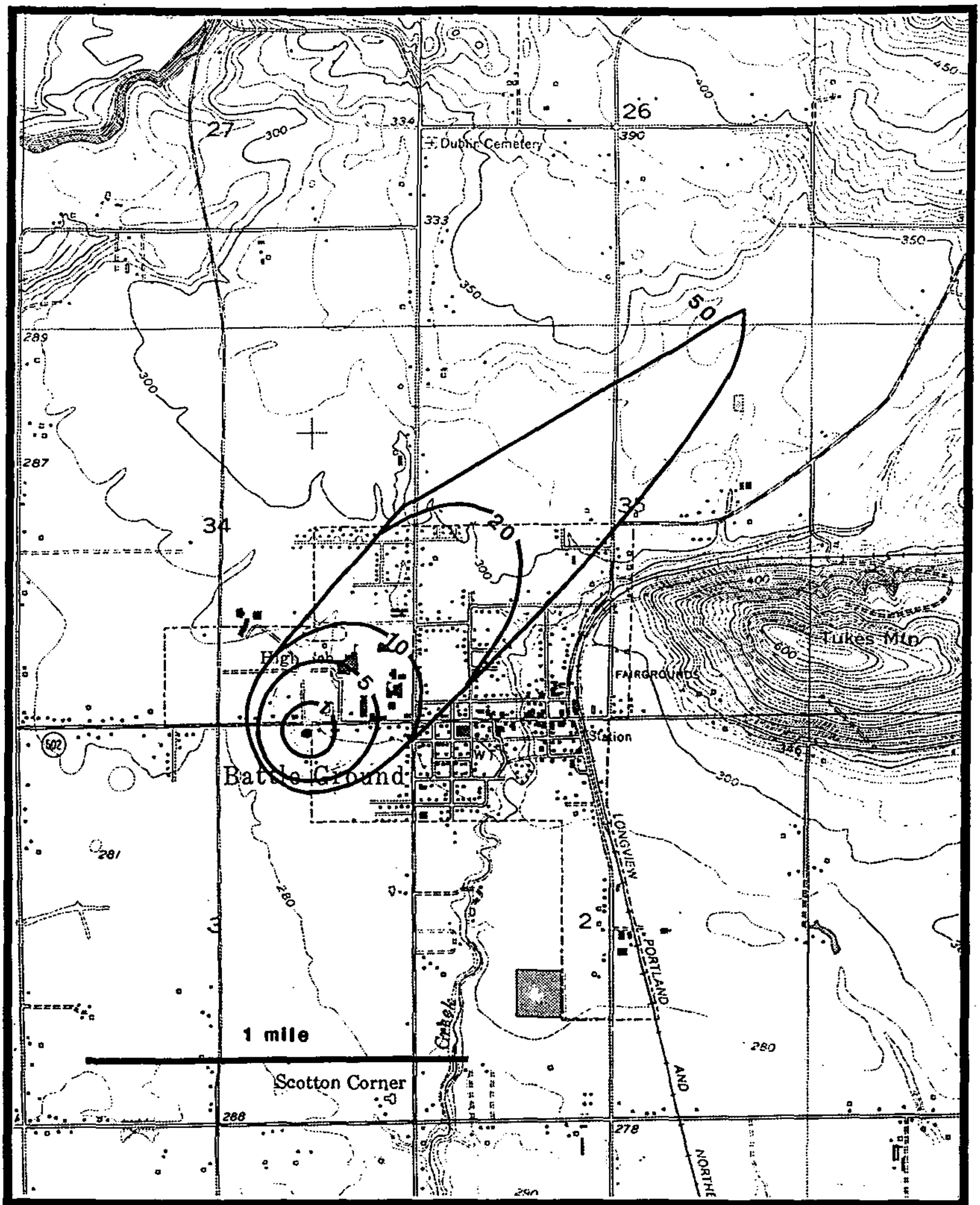

Figure BG-1-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the EPA WHPA MWCAP model for Battle Ground wells 1 and 2.

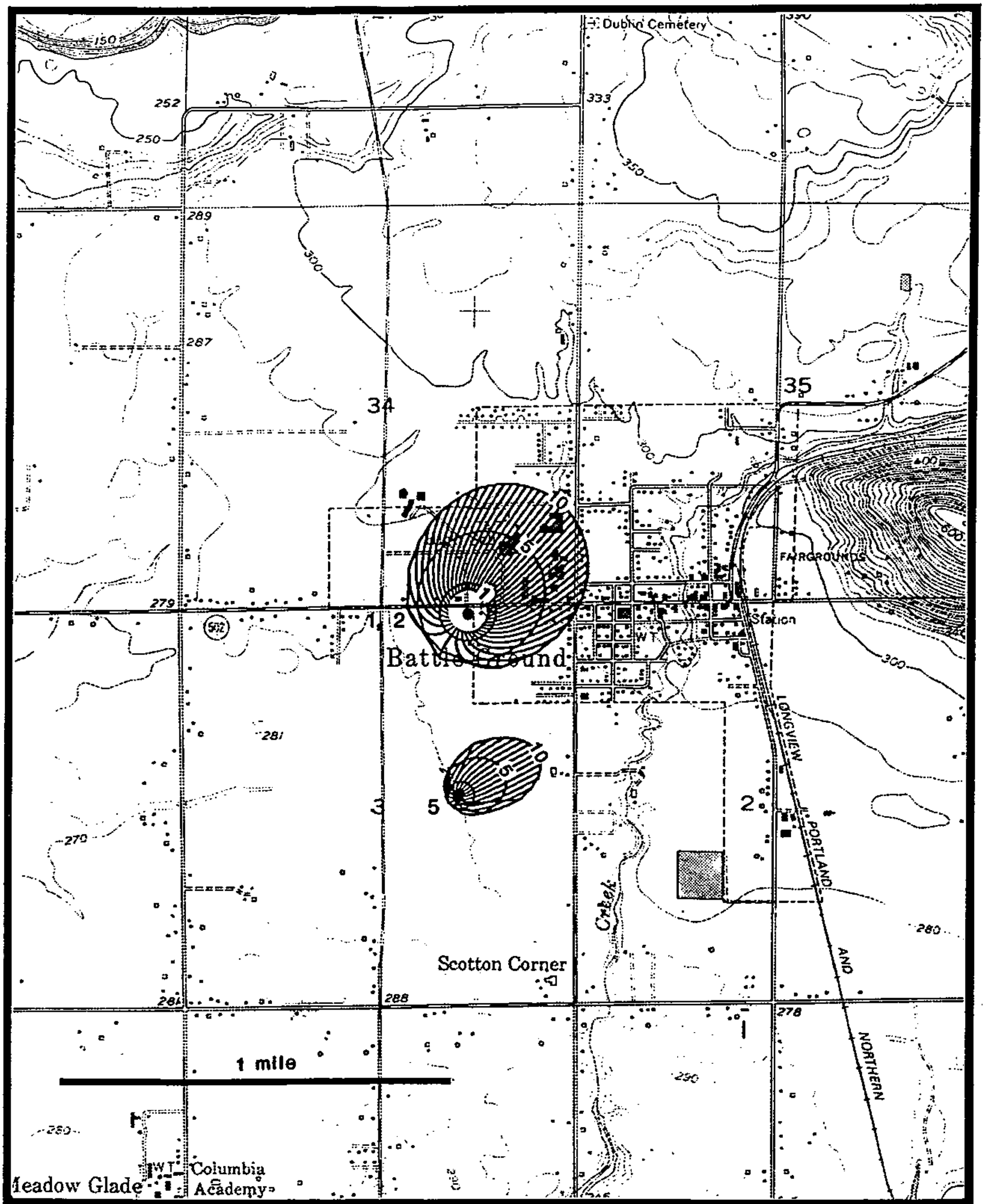

Figure BG-1-3. 1, 5, and 10 year time of travel zones of contribution using the EPA RESSQC WHPA model for Battle Ground wells 1, 2 and 5.

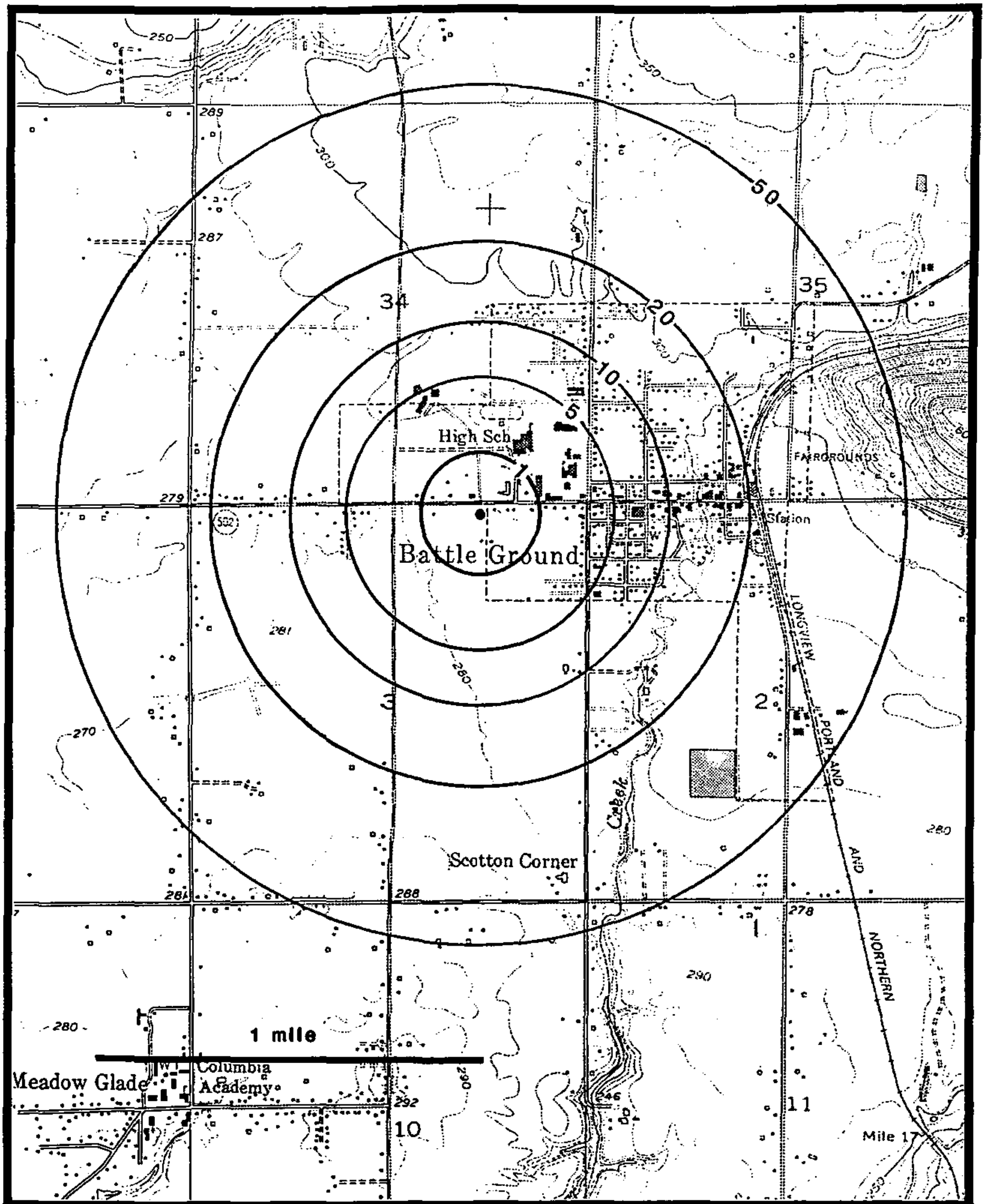

Figure BG-1-4. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

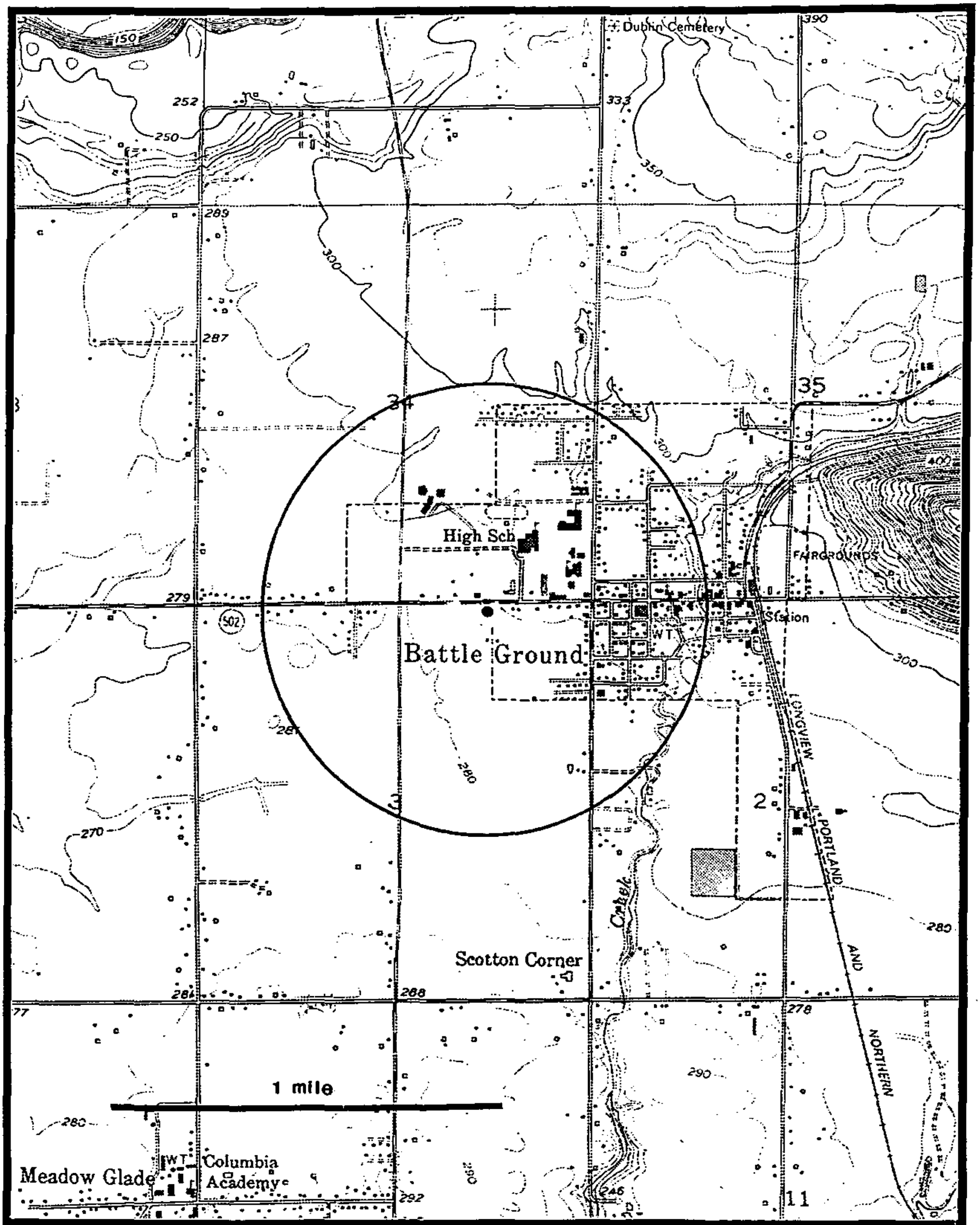

Figure BG-1-5. 3000 foot fixed radius delineation for Battle Ground wells.

Appendix B

WELLHEAD PROTECTION AREA DELINEATION REPORT

CAMAS AND WASHOUGAL SUPPLY WELLS

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix B
Wellhead Protection Area Delineation Report

Well: Camas and Washougal Municipal Wells

Setting: Camas municipal wells 5, 6, and 7; and Washougal municipal wells 5, 6, 7, 10, and 11 are on a low ridge of unconsolidated gravel between the Washougal River and Columbia River. All wells, except Washougal well 10 are within about 3000 feet of each other near the border between Camas and Washougal. Washougal well 10 is located about 9600 feet east of the other wells near the shore of the Washougal River.

The wells all tap a shallow permeable gravel aquifer less than 100 feet thick. Dense volcanic rocks form an east-west valley wall just north of the Washougal River. The aquifer is underlain by these rocks and semi-consolidated silty sand and gravel at about 40 to 50 feet below sea level and about 80 to 110 feet below land surface.

Camas well 7 is the principal ground water source for the City of Camas. Wells 5 and 6 are used primarily as backups. Older wells, 1, 2, 3, and 4 are essentially unused at this time. Washougal wells 5, 6, 7, and 11 are the principal supply wells for the town. Well 10 is used to a lesser degree and older intermittently used wells near well 10 are grouped with well 10 for delineation.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Geologic mapping and water well records were used to map the extent of the unconsolidated gravel aquifer. Trimble (1963) mapped the extent of these gravels as a part of a distinct geologic unit, the Quaternary lacustrine gravel on his 1:62,500 scale map of Portland area geology. Lithology descriptions from water well records collected from WDOE files as well as Camas and Washougal Water System Plan reports were used to describe aquifer thickness. Where no lithology descriptions were included for older wells, aquifer depth and thickness were inferred from reported screened interval. Based on wells records, saturated aquifer thickness is about 50-60 feet (15-19 meters). The total thickness of the gravel is 80 to 110 feet (24-33 meters).

The Columbia River is likely to approximate a fully penetrating stream boundary with an infinite source of water. Recent mapping by the US Geological Survey in the Portland Well Field and greater Portland Basin (Swanson and others, 1991) identifies a 250 to 300 foot (75 meter to 90 meter) thick sediment filled paleo Columbia River canyon which cuts through the late Pleistocene deposits that include the unconsolidated gravel aquifer in Camas. The present Columbia River channel depth on USGS 1:24,000 scale topographic maps is 30 to 40 feet (9 to 12 meters).

The Washougal River is only about 300 feet (90 meters) from Camas well 7. Washougal well 10 is slightly less than 200 feet from the Washougal River channel. Some connection between the river and the gravel aquifer is assumed based on water level data and a pump test at Washougal Station 10 showing a transmissivity of over 1,000,000 gallons/day/foot, Wells away from the river have transmissivity values about one quarter this. The river lies on bouldery sandy, gravel near these wells.

Water levels recorded by the USGS and Camas city employees show that the well water levels generally are below the Washougal River at well 7. Water level data for the area of Washougal well 10 suggests that there may also be flow from the river toward the well. Washougal public works reports that well 1, an old well near well 10 is unusable due to bacterial contamination during periods of high water in the Washougal River.

A valley wall barrier is formed by the older volcanic rocks just north of the Washougal River. The gravel aquifer is underlain by older volcanic rocks and Troutdale Formation semi-consolidated sandy gravel, sand, and silt forming a relatively low permeability lower boundary.

Wells at the James River paper mill, about 750 meters west of the Camas wells (Figure CAWA-1) pump huge amounts of water (about 0.9 m^3/second or 14,000 gallons/minute according to industrial pumpage estimates for the area made by the USGS) from shallow gravel aquifers adjacent to the Columbia River and mouth of the Washougal River. These wells are reported to have been used at a constant rate for many years.

Gradient and Flow Direction: Two water level maps were made from WDOE water well records, USGS and water purveyor water level measurements from Camas and Washougal public supply wells, and stream elevations from USGS 1:24,000 scale topographic maps with 10 foot contours. Head Map A was drawn to show a water table high along the central axis of the gravel area between the Washougal and Columbia Rivers. This setting allows flow to the Washougal River from the south. Head Map B is more generalized and does not attempt to map this feature. Map B was used for delineations. The accuracy of the resulting water level maps is questionable due to the lack of well data, local effects of supply wells, and poor control on stream surface elevation. Generally, ground water flows from east to west and toward the Columbia River. Based on map B, gradient varies from 0.0016 to 0.005 in the vicinity of the western wells.

Aquifer Properties:

Transmissivity: According to city reports, aquifer transmissivity was calculated for several wells and varies from 225,600 gallons/day/foot to 1,240,000 gallons/day/foot. The highest transmissivity value is for Washougal well 10, and may be influenced by a recharge boundary at the Washougal River.

A transmissivity of about 225,600 gallons/day/feet (2,800 $meters^2$/day/feet) calculated from recovery data for an observation well, Washougal Well 2 and was used for the delineations.

Porosity: A porosity of 0.25 was estimated for the aquifer by matching well record descriptions of aquifer lithology to standard porosity values for rock materials (Heath, 1984). However, other references suggest porosities up to 0.35 could be expected for medium to coarse gravel.

Pumping Rate: Average daily rates were calculated from reported peak year total pumpage. The highest pumpage year for the Camas system was 1987 and the highest pumpage year for Washougal system was 1985. Camas well pumping totals were reported for each well in 1987. Washougal peak year pumpage was allocated to wells proportional to the 1987-1988 pumping rates reported by Collins and Broad (1991). Annual pumpage rates for delineation analysis are:

Camas well 7: 101,650,000 gallons/year
Camas well 6: 32,460,000 gallons/year
Camas well 5: 1,400,000 gallons/year
Washougal well 5: 7,700,000 gallons/year
Washougal well 6: 139,700,000 gallons/year
Washougal well 7: 163,030,000 gallons/year
Washougal well 11: 249,800,000 gallons/year
Washougal well 10: 3,800,000 gallons/year

Delineation Analysis:

Hydrogeologic Mapping: The goal of hydrogeologic mapping was to delineate the extent of the aquifer and area that is likely to contribute to the wells. Two separate wellhead protection areas are defined, one for the western wells and one for well 10 and adjacent low use wells. The delineations include three zones based on individual hydrogeologic characteristics and mapping methods: a one year time of travel radius was drawn around the wells using the average gradient; a total zone of contribution is drawn from boundaries and estimated flow paths; and area where runoff and shallow soil moisture can drain into the aquifer from adjacent hillsides is delineated. These zones are shown on figure CAWA-1.

The one year travel distance was calculated using the GPTRAC model. Uncertainty about flow direction accuracy was incorporated into the delineation by drawing the radius in a wide arc across the area up gradient from the wells.

The total zone of contribution for the western wells was drawn by using horizontal flow paths on Head Map B, aquifer extent, and the Washougal River down gradient (west) of the wells as boundaries.

The same delineation method was used at Washougal well 10 with some modification. At well 10, a 500 foot radius was drawn as a minimum zone of contribution width and down gradient extent. The GPTRAC model gave a zone of contribution about 100 feet wide, this was deemed too small for a conservative protection area. A widening up gradient zone of contribution was drawn due to uncertainty about the accuracy of mapped flow direction. The total zone of contribution is drawn to extend beneath the Washougal River to the aquifer boundary as a conservative approach assuming some ground water flows under the river.

The area of the valley wall from which surface water can drain onto the gravel aquifer was mapped. However, it is likely that much of this water discharges into the Washougal River because the river flows parallel to the valley wall along to the contact between older rocks and the gravel aquifer.

Better data describing ground water flow conditions near the well could produce much more accurate, and probably smaller delineations. As an example, if direct connection was observed between Camas well 7 or Washougal well 10 and the Washougal River, the actual total zones of contribution could be limited to a smaller area, possibly as small as a few hundred square feet.

Analytical Models: Analytical models are difficult to apply to the Camas and Washougal wells due to the high aquifer transmissivity, uncertain and complex boundary conditions, and poor control of water table gradient and flow direction. The EPA WHPA Version 2 GPTRAC model (EPA, March, 1991) was used to make an analytical model for the western wells, Camas wells 5, 6, and 7, and Washougal Wells 5, 6, 7, and 11. This model uses a single uniform aquifer transmissivity, gradient, flow direction, and aquifer thickness. Figure CAWA-2 shows the results.

Values selected were:

Transmissivity: 2,800 meters^2/day
Pumping rate:
    Washougal Wells: 1,450 meters^3/day for well 6; 1,700 meters^3/day for Well 7; 80 meters^3/day for well 5; 2,600 meters^3/day for Well 11.
    Camas Wells: 1,100 meters^3/day for Well 7; 300 meters^3/day for Well 6; 14 meters^3/day for Well 5.
Gradient: 0.003
Flow angle: -150° (240° compass bearing)
Porosity: 0.25
Aquifer thickness: 19 meters
Time of travel: 1 year

A separate RESSQC model was constructed for Washougal well 10. Figure CAWA-2 shows the delineation. The zone of contribution is very long and narrow due to the low pumping rate, high aquifer transmissivity, and relatively steep gradient.

Values selected were:

Transmissivity: 2,800 meters^2/day
Pumping rate: 40 meters^3/day
Gradient: 0.003
Flow angle: -135° (225° compass bearing)
Porosity: 0.25

Aquifer thickness: 19 meters
Time of travel: 1 year

Calculated Fixed Radius: Separate calculated fixed radius delineations were made for the Camas and Washougal wells (Figure CA-1 and Figure WA-1) using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulations volumetric flow equation.

Values selected were:

Camas wells:

Pumping rate: 13,590,000 feet^3/year (101.7 mg/y)
Porosity: 0.3
Length of well screen: 28 feet
Times of travel: 1, 5, 10, 20, and 50 years

Washougal wells:

Pumping rate: 78,950,000 feet^3/year (590.6 mg/y)
Porosity: 0.3
Length of well screen: 31 feet
Times of travel: 1, 5, 10, 20, and 50 years

Fixed Radius: Figures WA-2 (for Washougal Well 10) and CAWA-3 (for Camas and Washougal wells) show the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: Refer to US Geological Survey map report.

References Cited:

Collins, C.A. and T.M. Broad, 1991, Estimated Average Annual Ground-Water Pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90-4018.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: U.S. Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: U.S. Environmental Protection Agency, Office of Ground Water Protection.

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Trimble, D.E., 1963, Geology of Portland, Oregon and Adjacent Areas: U.S. Geological Survey Bulletin 1119, 119p., 1 pl.

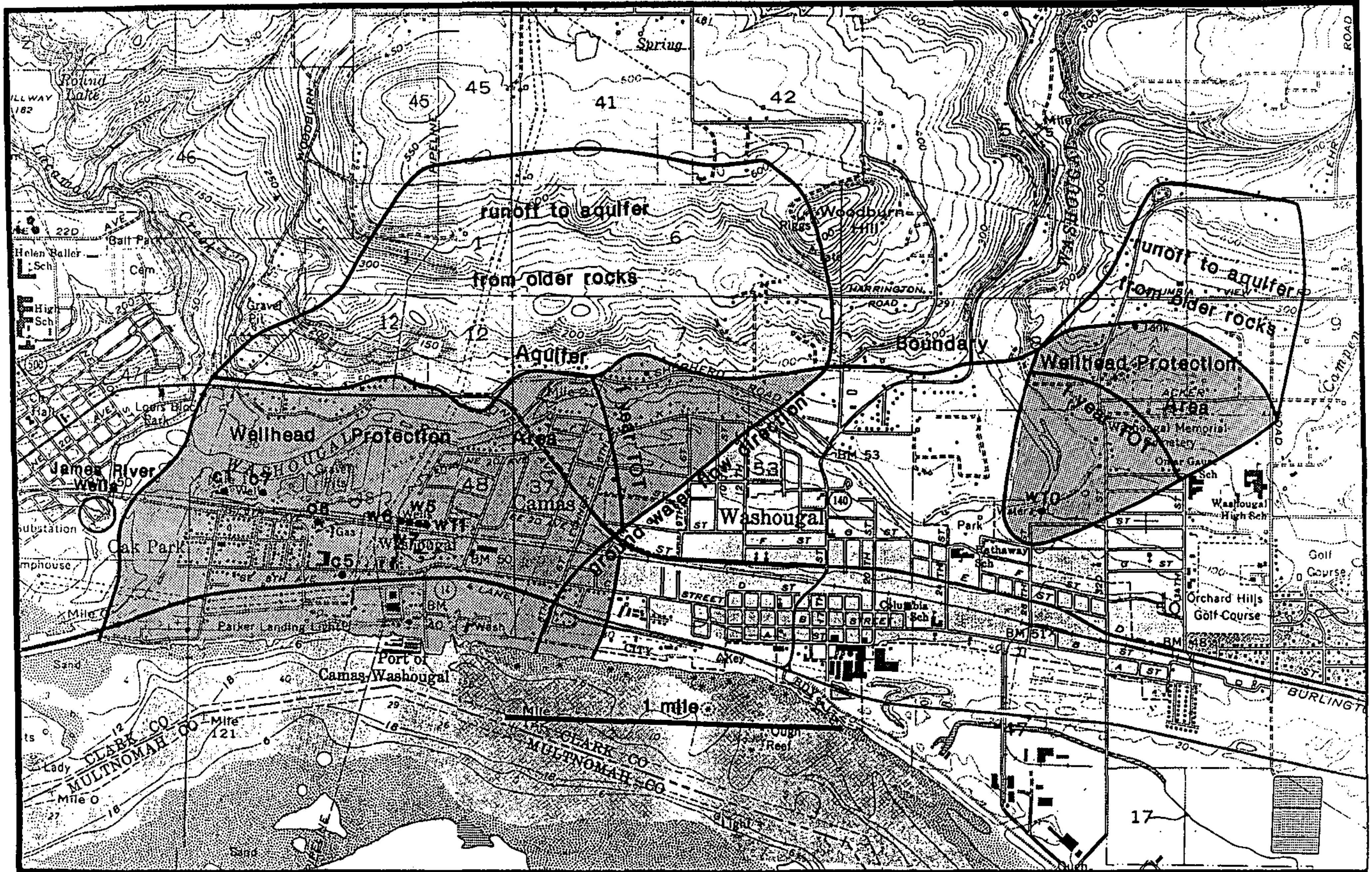

Figure CAWA-1. Wellhead protection zones delineated by hydrogeologic mapping for Camas Wells 5, 6, 7, and 11; Washougal Wells 5, 6, 7, 11, and 10.

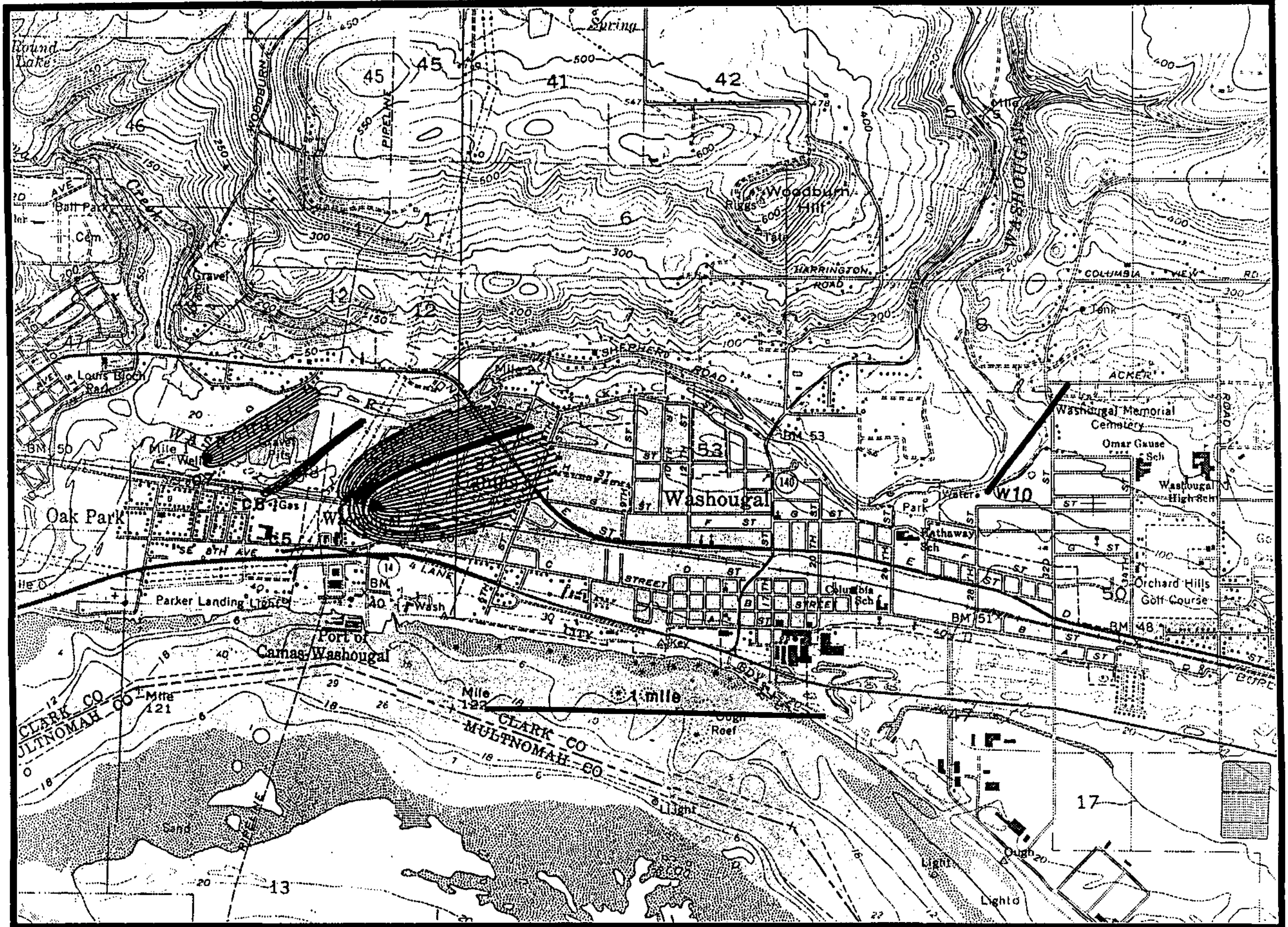

Figure CAWA-2. 1 year time of travel zone of conribution using the EPA WHPA GPTRAC model for Camas wells 5, 6, and 7, and Washougal wells 5, 6, 7, and 11. The RESSQC model was used for Washougal well 10.

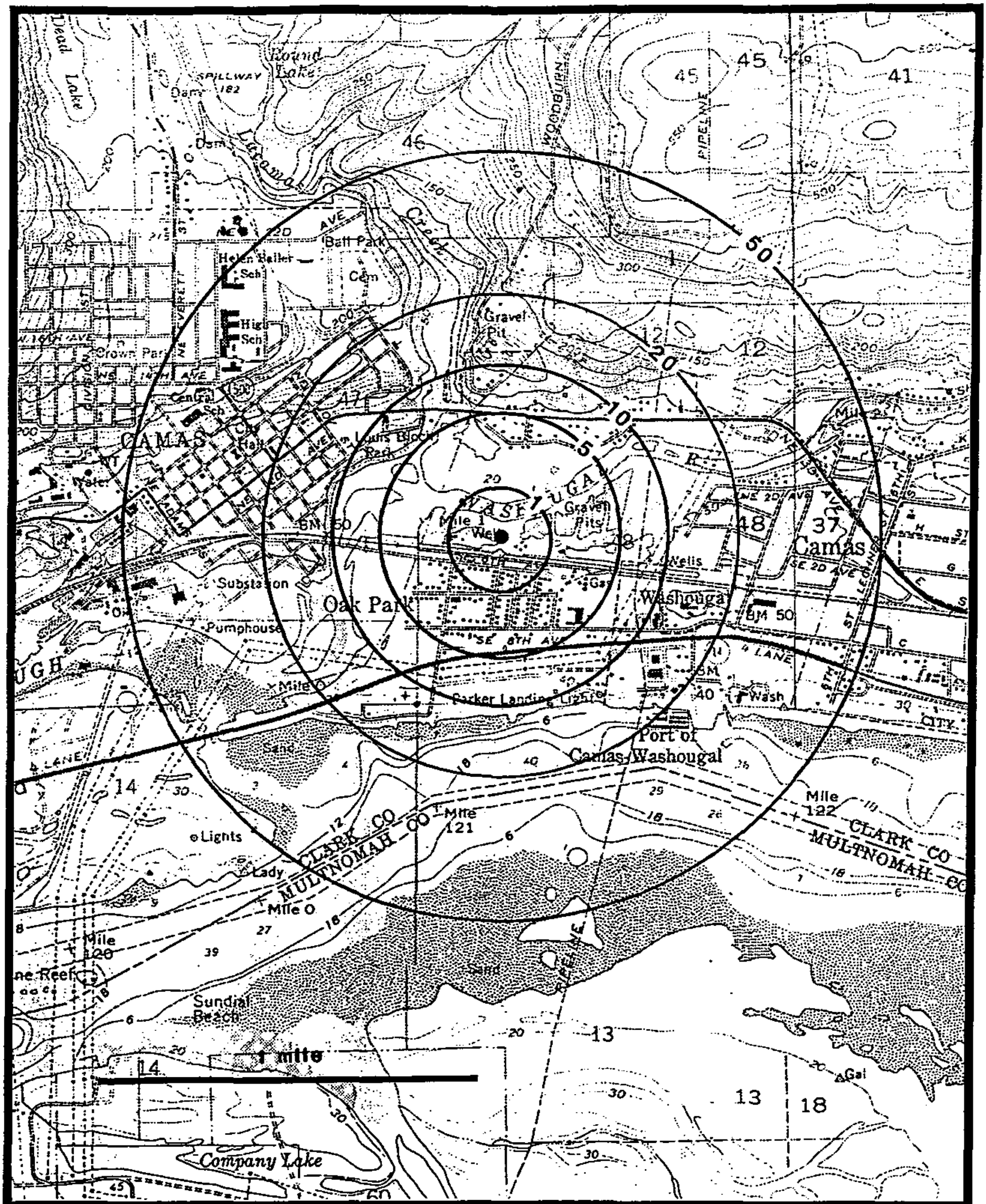

Figure CA-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation for Camas wells.

Figure WA-1. 1, 5, 10, and 20 year time of travel zones of contribution using the volumetric flow equation for Washougal wells.

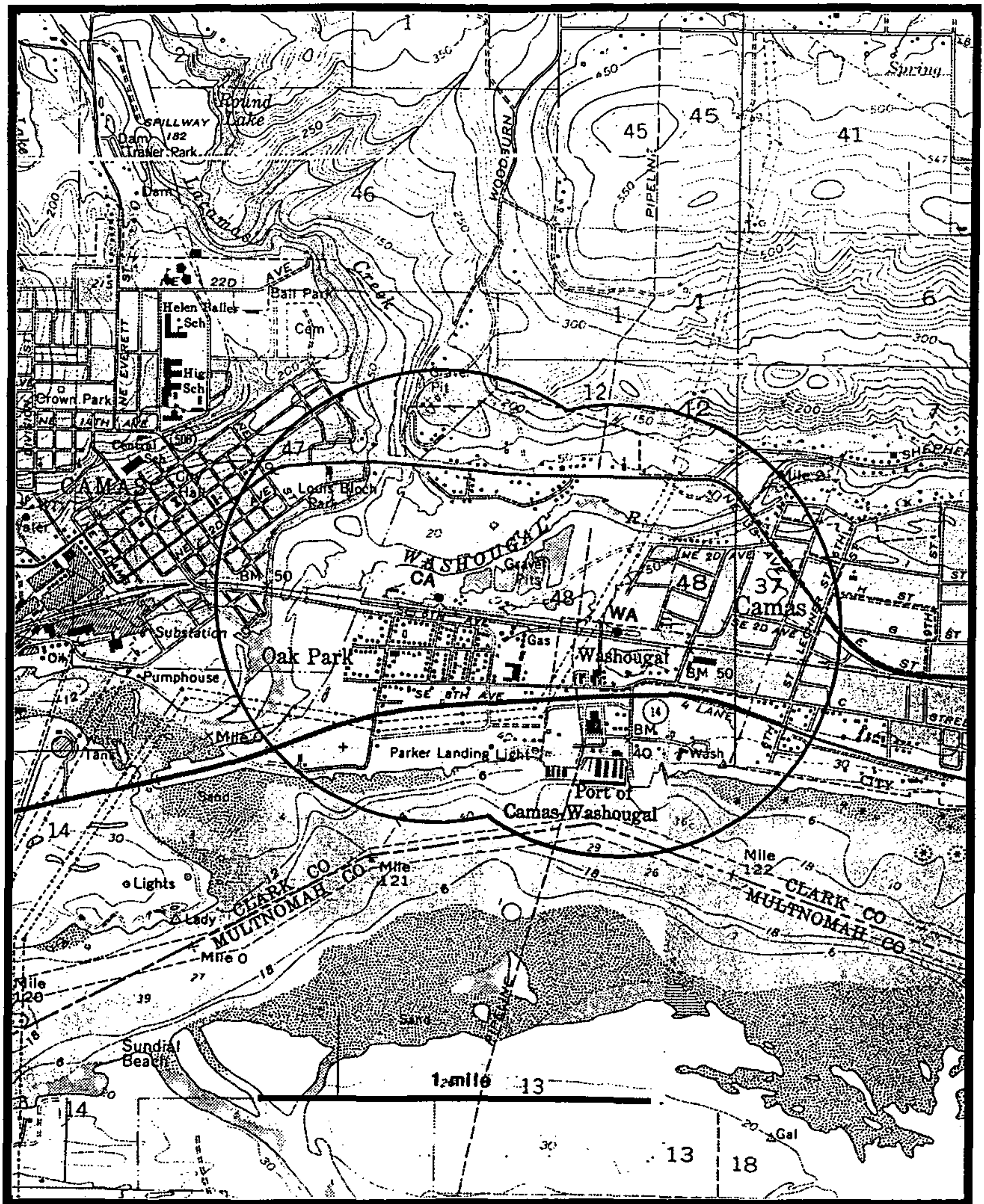

Figure CAWA-3. 3000 foot fixed radius delineation for Camas amd Washougal wells.

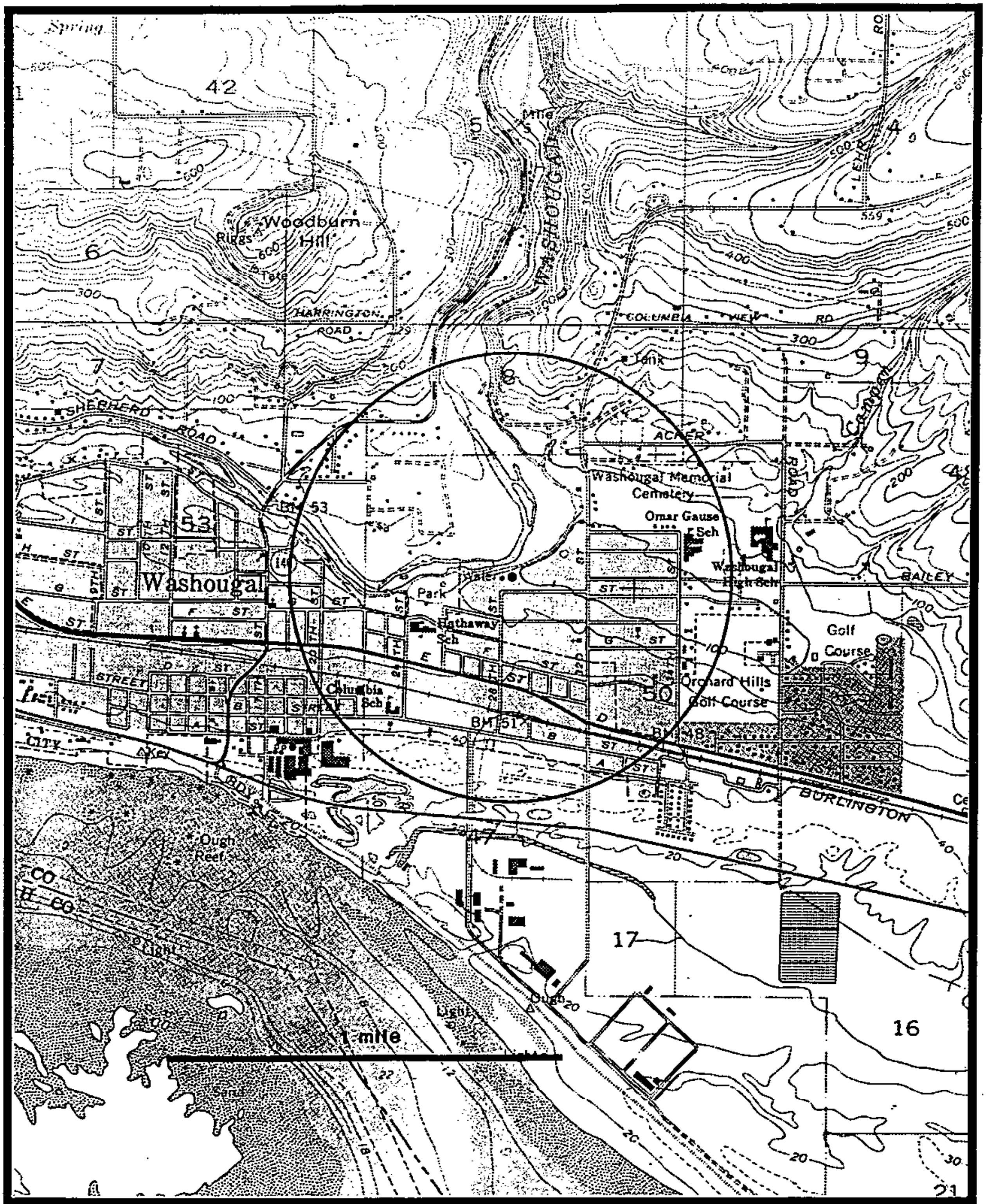

Figure WA-2. 3000 foot fixed radius delineation for Washougal well 10.

Appendix C

WELLHEAD PROTECTION AREA DELINEATION REPORT

CLARK PUBLIC UTILITIES WELL 8.1

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix C
Wellhead Protection Area Delineation Report

Well: CPU-8.1 (Clark Public Utilities Well 8.1)

Setting: CPU-8.1 is on a flat ridge between Salmon Creek and he Columbia River flood plain with a wellhead elevation of about 215 feet. CPU-8.1 is completed in semi-cemented sandy gravel of the upper member of the Troutdale Formation.

The well is 303 feet deep, with screened intervals extending from a depth of 227 to 295 feet. The well is pumped at a lower rate than all of the other Clark Public Utilities Hazel Dell wells.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Mundorff (1964) described the extent of the aquifer and more recent work by the USGS (Swanson and others, 1991) describe the thickness. The aquifer extends from beneath the Columbia River flood plain to the base of the Cascade Mountains foothills.

Aquifer thickness at the well is a bout 330 feet (100 meters). Thickness was determined from mapping done by Swanson and others (1991) with additional review of well report lithology descriptions. Regionally, aquifer thickness varies from over 400 feet to less than 100 feet. Areas with greatest thickness are in southwest Clark County.

A ground water flow divide is mapped about 4,500 feet (1,400 meters) northeast of CPU-8.1, between the well and Salmon Creek based on water level mapping (Mundorff, 1964, and spring 1988 spring water level measurements). The aquifer is underlain by less permeable sandy silt and muddy sediment of the lower member of Troutdale Formation. Interference from other wells does not appear to significantly effect the well based on available well data. The aquifer is semi-confined with recharge to the aquifer is through overlying stratified silty sand and silt deposits.

Gradient and Flow Direction: A map showing the spring 1988 potentiometric surface of the upper Troutdale Formation aquifer was used to measure gradient and flow direction. Generally, ground water flows from east to west and toward the Columbia River. Mapped gradient increases with distance down gradient from the well and is fairly uniform up gradient from the well.

Aquifer Properties:

Transmissivity: A four hour single well pump test was used to calculate a transmissivity of about 8,200 gallons/day/foot (100 meters^2/day) using the Jacob method. A transmissivity of 9,000 gallons/day/foot (112 meters^2/day) was calculated from recovery data.

Porosity: Porosity is estimated as 0.2 by comparing well record lithology and field observations of lithology to standard porosity values for aquifer materials (Heath, 1983).

Pumping Rate: An average pumping rate of 146,000 gallons/day (550 meters^3/day) for CPU-8.1 was calculated from highest total annual pumpage recorded, 53,482,000 gallons (1988).

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping methods were used to define the aquifer geometry, direction and gradient of ground water flow, and identify any aquifer boundaries.

Since boundary conditions were relatively simple to define within the 1 to 50 year zones of contribution, analytical models (WHPA Version 2) were used to determine zones of contribution from compiled hydrogeologic data.

An alternate approach to map zones of contribution was attempted by combining WHPA analytical solutions, flow path mapping, and velocity calculations for 10, 20, and 50 years. Delineations from WHPA RESSQC (EPA, March, 1991) were used to define the lateral extent of zones of contribution, regional horizontal pathlines were used to map up gradient zone of contribution direction, and velocity calculations using hydraulic conductivity, gradient, and porosity were used to calculate the up gradient length of zone of contribution extent. The results are included in Figure CPU-8-1.

Analytical Models: Simple boundary conditions permit the EPA WHPA models to be applied. Using RESSQC (EPA, March, 1991) to model the aquifer as confined, is a conservative approach. The aquifer properties were taken from tests at the well. Analytical model results are shown in Figure CPU-8-2.

Values selected were:

Transmissivity:	100 meters^2/day
Pumping rate:	550 meters^3/day
Gradient:	0.009
Flow angle:	-180° (270° compath bearing)
Porosity:	0.2
Aquifer thickness:	100 meters
Time of travel:	1, 5, 10, 20, and 50 years

Calculated Radius: Figure CPU-8-3 shows calculated fixed radii were calculated using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulations volumetric flow equation.

Values selected were:

Pumping rate:	7,152,000 feet^3/day (53.5 mg/y)
Porosity:	0.2
Length of well screen:	68 feet
Times of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure CPU-8.1-4 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: Method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: See USGS map report.

References Cited:

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C.,

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: United States Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

Mundorff, M.J., 1964, Geology and Ground-Water Conditions of Clark County, Washington, with a Description of a Major Alluvial Aquifer Along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268p., 3 pls.

Swanson, R.D., W.D. McFarland, J.B. Gonthier, and J.W. Wilkinson, 1991, A Description of Hydrogeologic Units in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90-4196.

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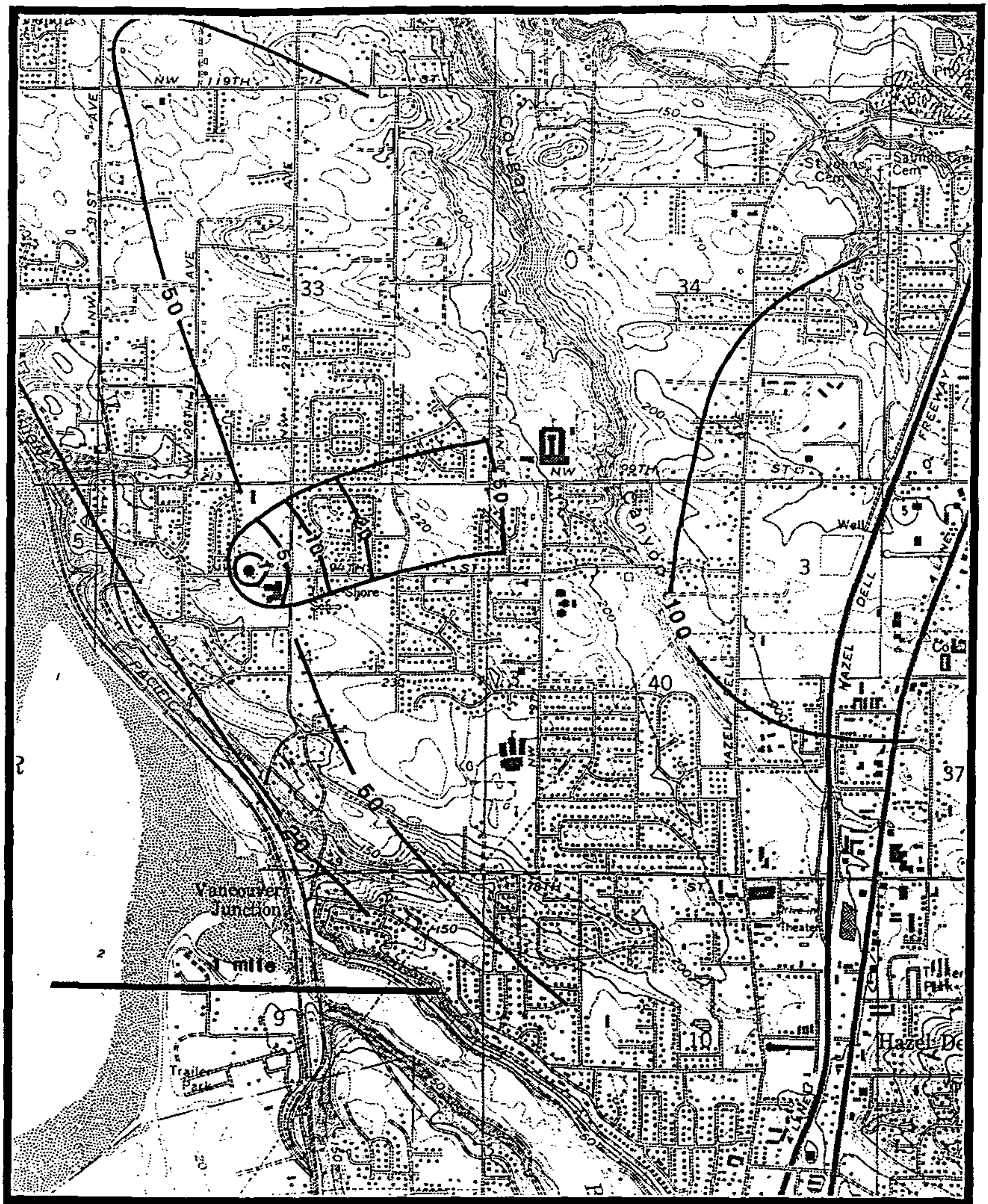

Figure CPU-8.1-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution from hydrogeologic mapping methods.

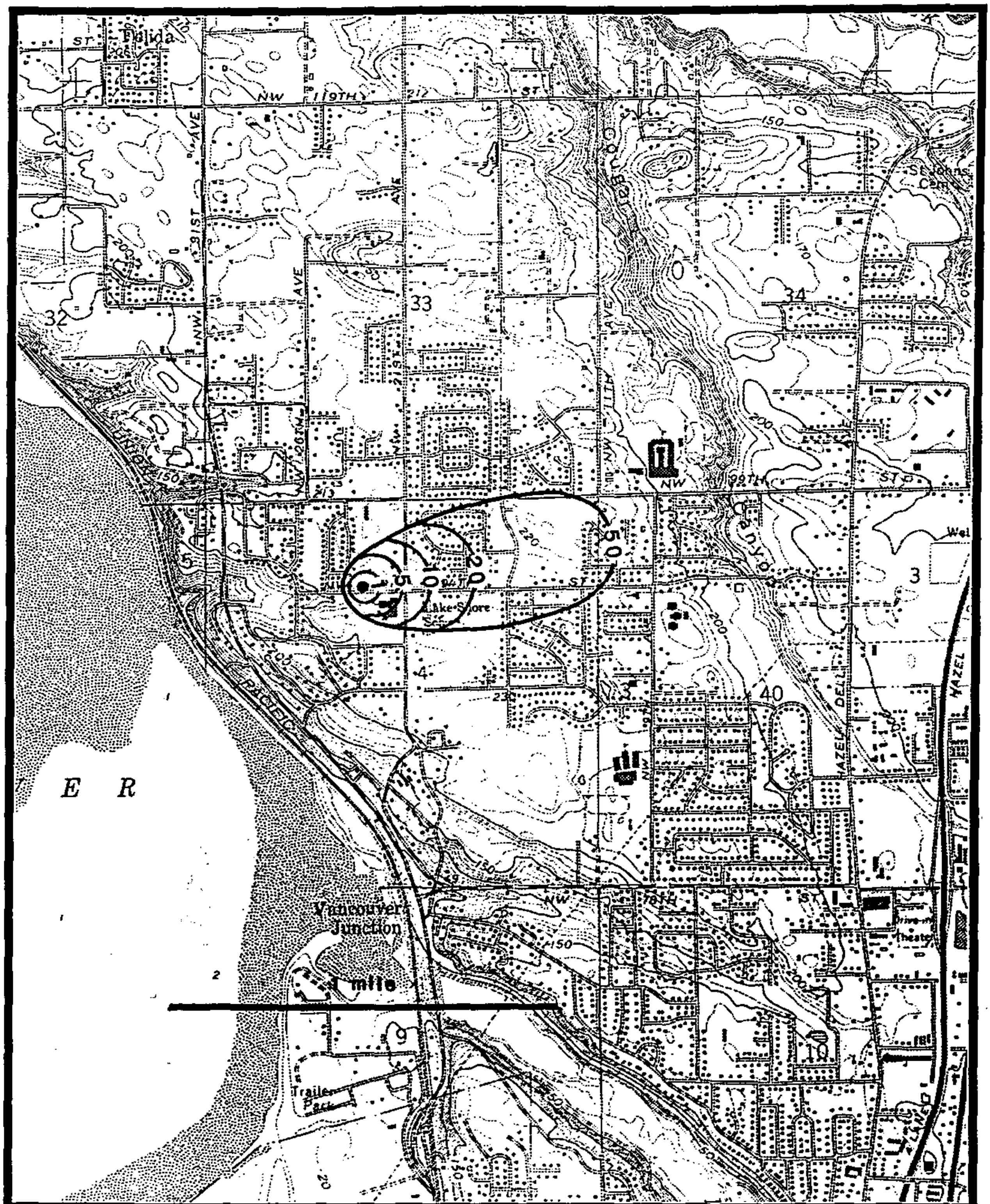

Figure CPU-8.1-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the EPA RESSQC WHPA model.

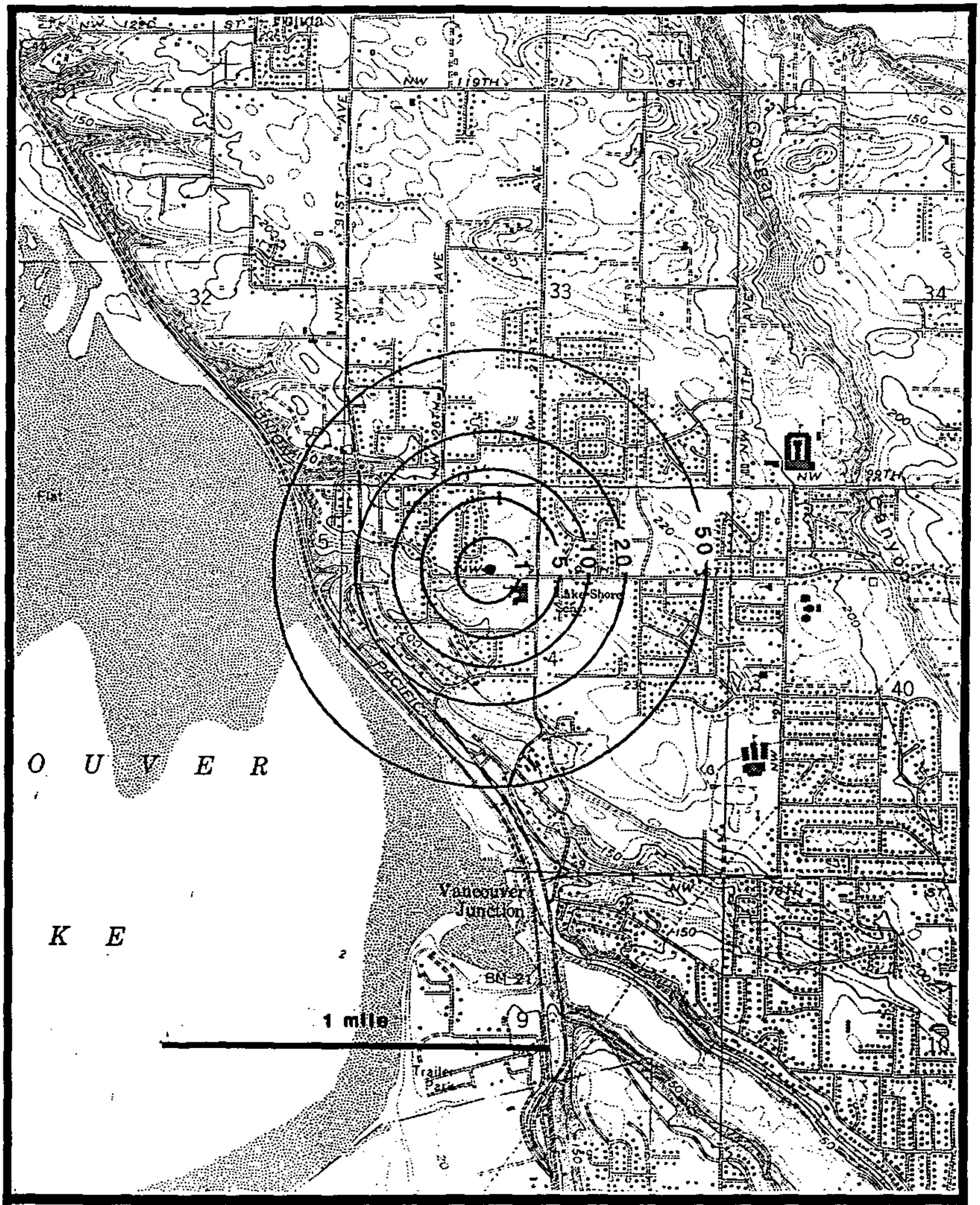

Figure CPU-8.1-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

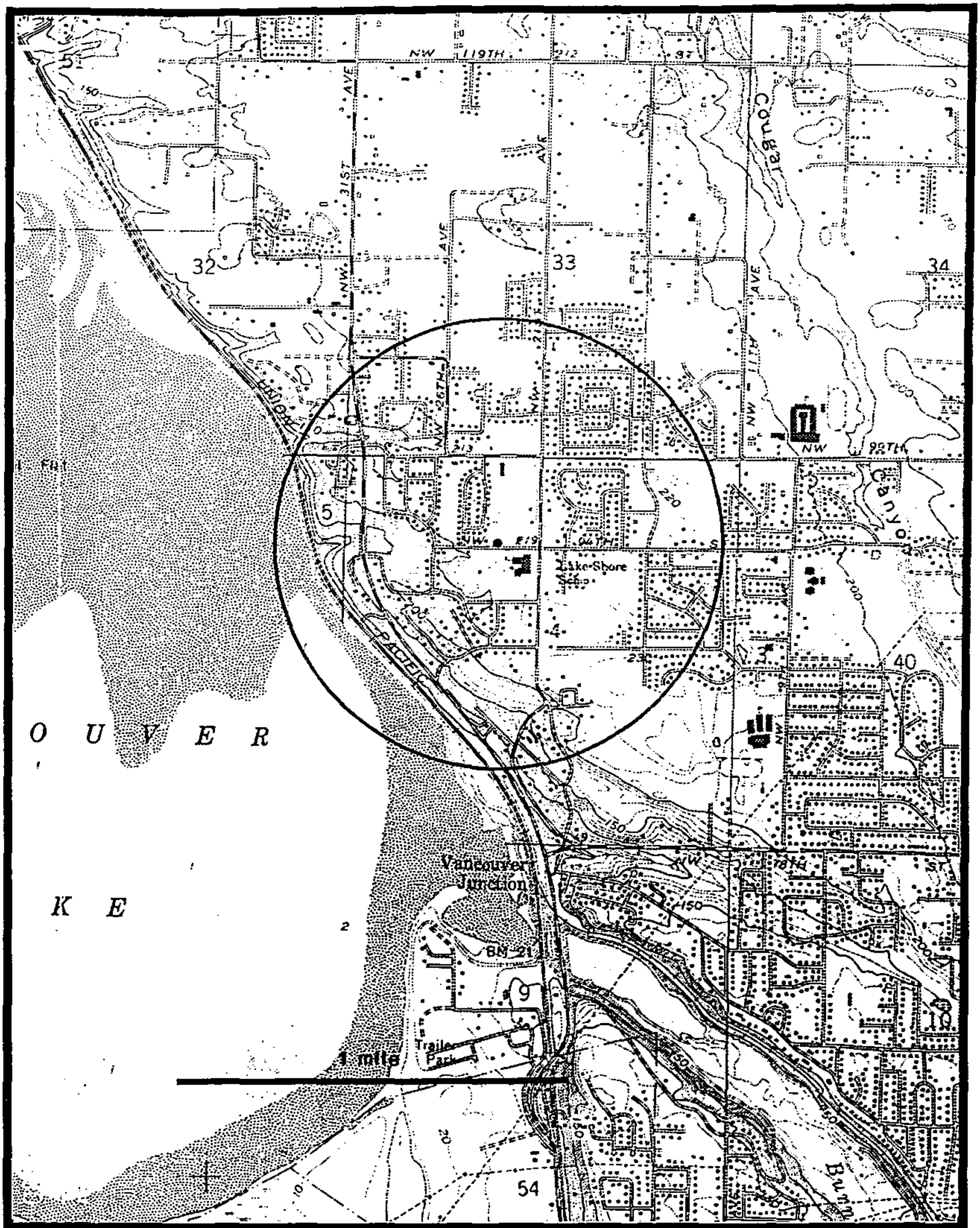

Figure CPU-8.1-4. 3000 foot fixed radius delineation for Clark Public Utilities well.

Appendix D

WELLHEAD PROTECTION AREA DELINEATION REPORT

CLARK PUBLIC UTILITIES WELL 14

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix D
Wellhead Protection Area Delineation Report

Well: CPU-14 (Clark Public Utilities Well 14)

Setting: Well CPU-14 is about a mile southeast of Salmon Creek. The wellhead is at about 250 feet elevation in an area of low rolling hills, draining into Salmon Creek. The well is 426 feet deep and completed in the lower member of the Troutdale Formation.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: CPU-14 is one of a few deeper wells completed in the lower Troutdale Formation. Cross sections made from water well records were used to define extent and thickness of the aquifer. The aquifer a sandy layer near the top of the lower member of the Troutdale Formation bounded above and below by finer grained sediment. The aquifer is described as clayey sand from 310 to 368 feet and sand from 368 to 426 feet.

Little information exists to define any aquifer boundaries within several miles of the well. However, limited available data suggest he aquifer is likely to continue for several miles as interconnected sandy layers on the lower Troutdale Formation. The aquifer is probably semi-confined.

Three other CPU wells either use the aquifer or are planned to be added to production soon. All are at least one mile from CPU-14. No other deep wells are known to exist in the vicinity of CPU-14.

Gradient and Flow Direction: A water level map for the lower Troutdale Formation sand aquifer was made from the few wells that appear to penetrate beneath the upper Troutdale Formation. These wells included four Clark Public Utilities wells. Gradient and flow direction were measured from this map.

Aquifer Properties:

Transmissivity: Recovery data from a single well pump test was used to estimate transmissivity as about 23,000 gallons/day/foot (300 meters^2/day).

Porosity: Porosity is estimated as 0.2 by comparing well record descriptions and field observation of aquifer lithology to standard porosity values for aquifer materials (Heath, 1983).

Pumping Rate: An average pumping rate of 358,000 gallons/day (1,400 meters^3/day) was calculated from a total pumpage of 130,600,000 gallons in the highest year of record, 1989.

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define aquifer extent and thickness, and potentiometric surface. Lack of geologic data and apparent uniformity of hydrogeologic conditions precludes any further hydrogeologic analysis without additional data collection.

Analytical Models: Due to the lack of detailed hydrogeologic information and apparent hydrogeologic uniformity, analytical models are a good method to estimate zones of contribution for this well. Figure CPU-14-1 shows the results of analytical modeling using the EPA RESSQC model (EPA, March, 1991) to delineate 1, 5, 10, 20, and 50 year zones of contribution.

Values selected were:

Transmissivity:	300 meters^2/day
Pumping rate:	1,400 meters^3/day
Gradient:	0.001
Flow angle:	-170° (260° compass bearing)
Porosity:	0.2
Aquifer thickness:	36 meters
Time of travel:	1, 5, 10, 20, and 50 years

A RESSQC model was done to simulate the zones of contribution with well interference between the deep CPU wells. Figure CPU-14-2 this simple subregional RESSQC model.

Values selected were:

Transmissivity:	360 meters^2/day
Pumping rate:	1,400 meters^3/day for CPU-14, 2,460 meters^3/day for CPU-16, 940 meters^3/day for CPU-20, 740 meters^3/day for CPU-90-03
Gradient:	0.001
Flow angle:	-155° (245° compass bearing)
Porosity:	0.2
Aquifer thickness:	23 meters
Time of travel:	1, 5, 10, 20, and 50 years

Calculated Fixed Radius: Figure CPU-14-3 shows calculated fixed radii calculated using the volumetric flow equation referenced by EPA (June,1987) as the Florida Department of Environmental Regulation volumetric flow equation.

Values selected were:

Pumping Rate:	17,460,000 feet^3/year (130.6 mg/y)
Porosity:	0.2

Length of well screen: 43 feet
Times of travel: 1, 5, 10, 20, and 50 years

Fixed Radius: Figure CPU-14-4 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigations.

Variable Fixed Shapes: This was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: See USGS map report.

References Cited:

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: U.S. Environmental Protection Agency, Office of Groundwater Protection, Washington, S.C., EPA 440/6-8-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of wellhead Protection Areas, Version 2.0: U.S. Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

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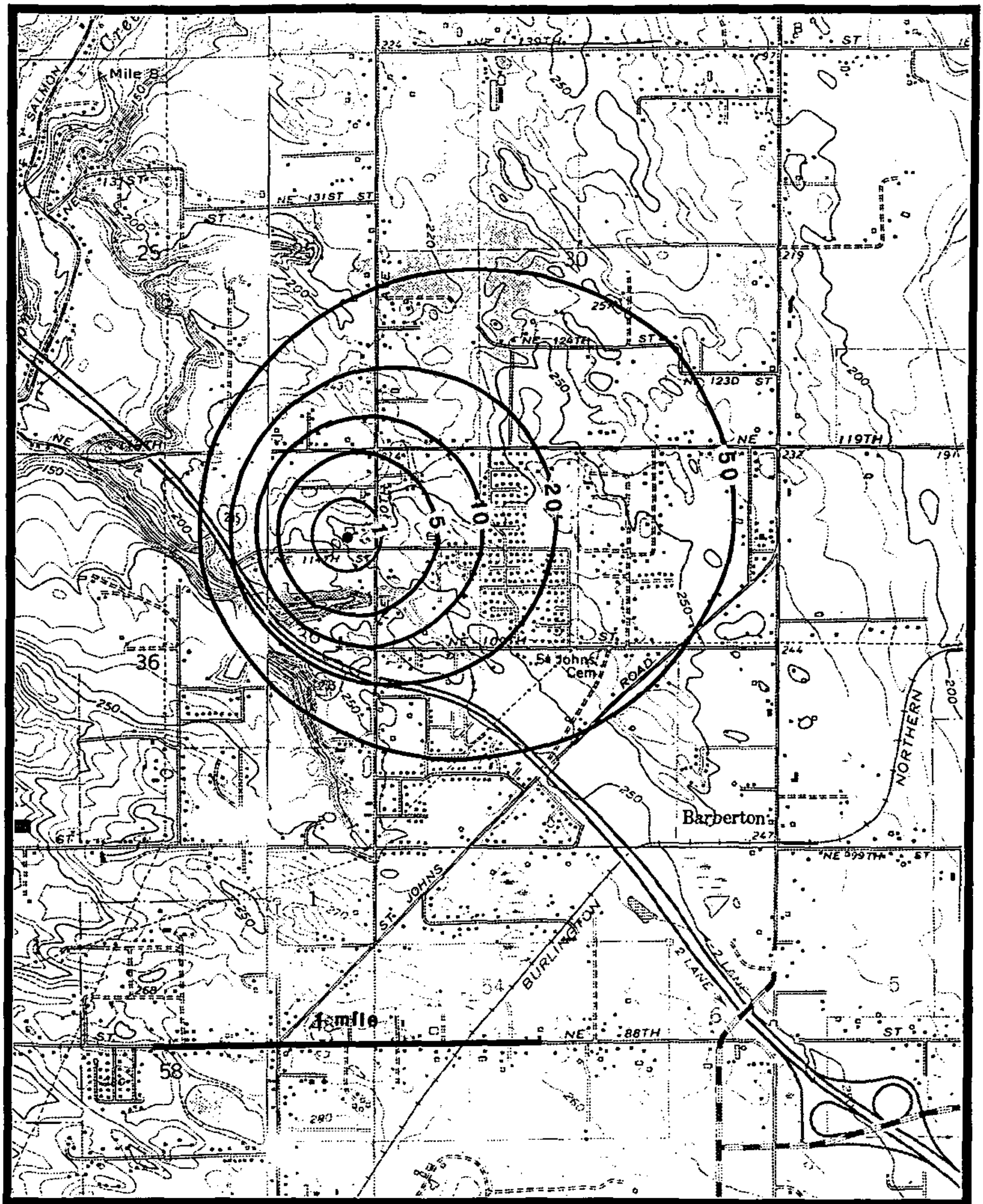

Figure CPU-14-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the EPA RESSQC WHPA model.

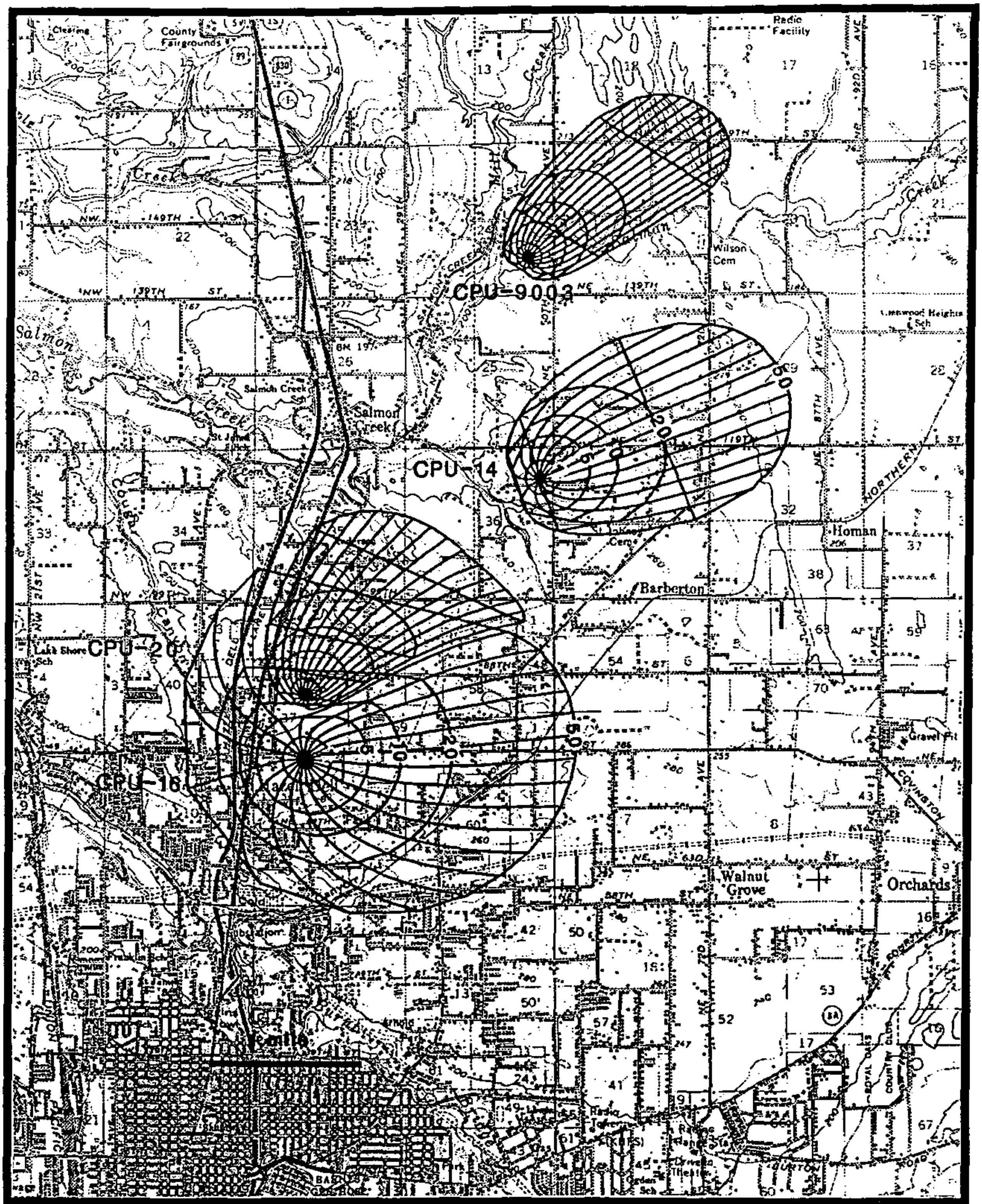

Figure CPU-14-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution for the Clark Public Utilities deep wells using the EPA RESSQC WHPA analytical model.

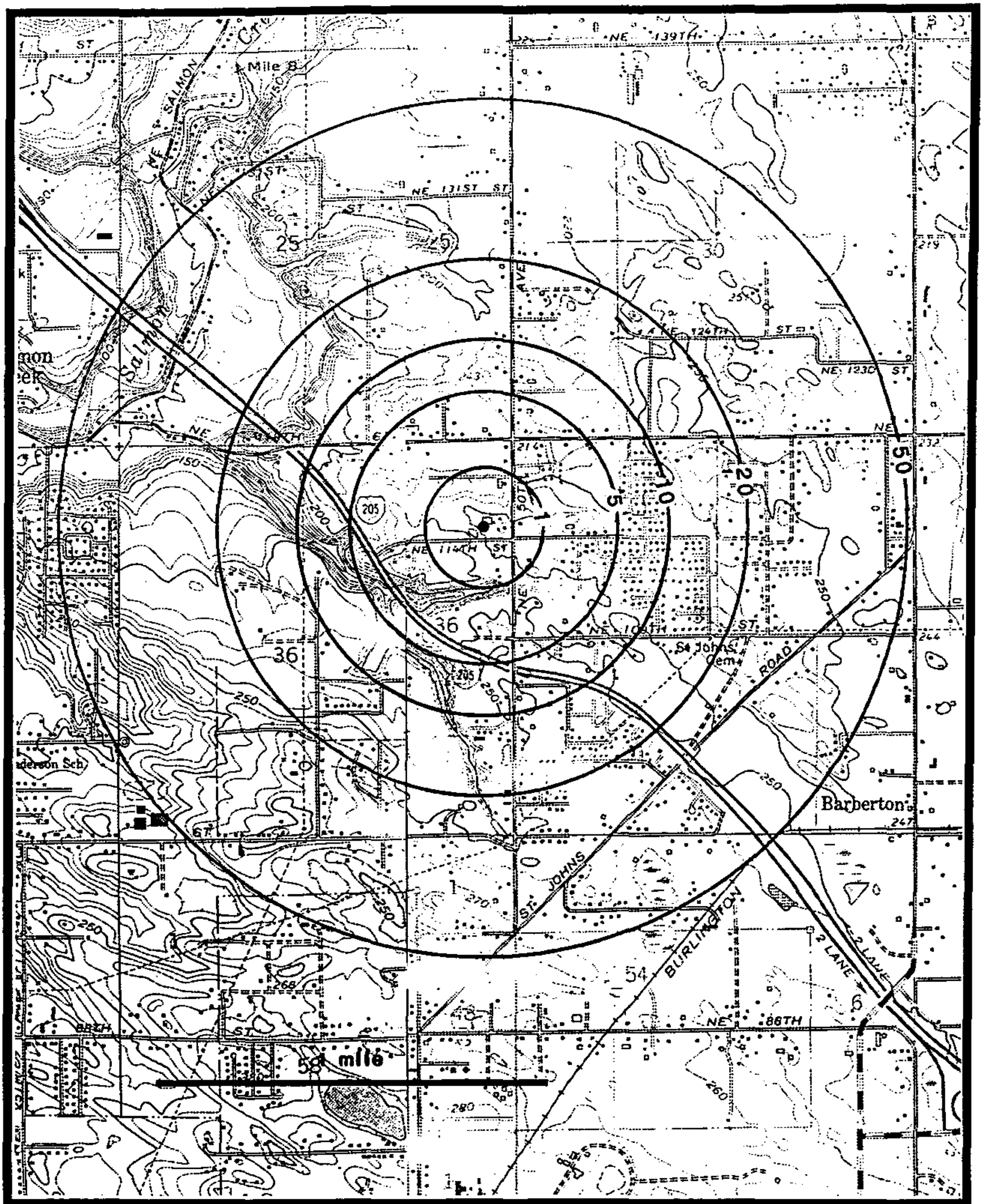

Figure CPU-14-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

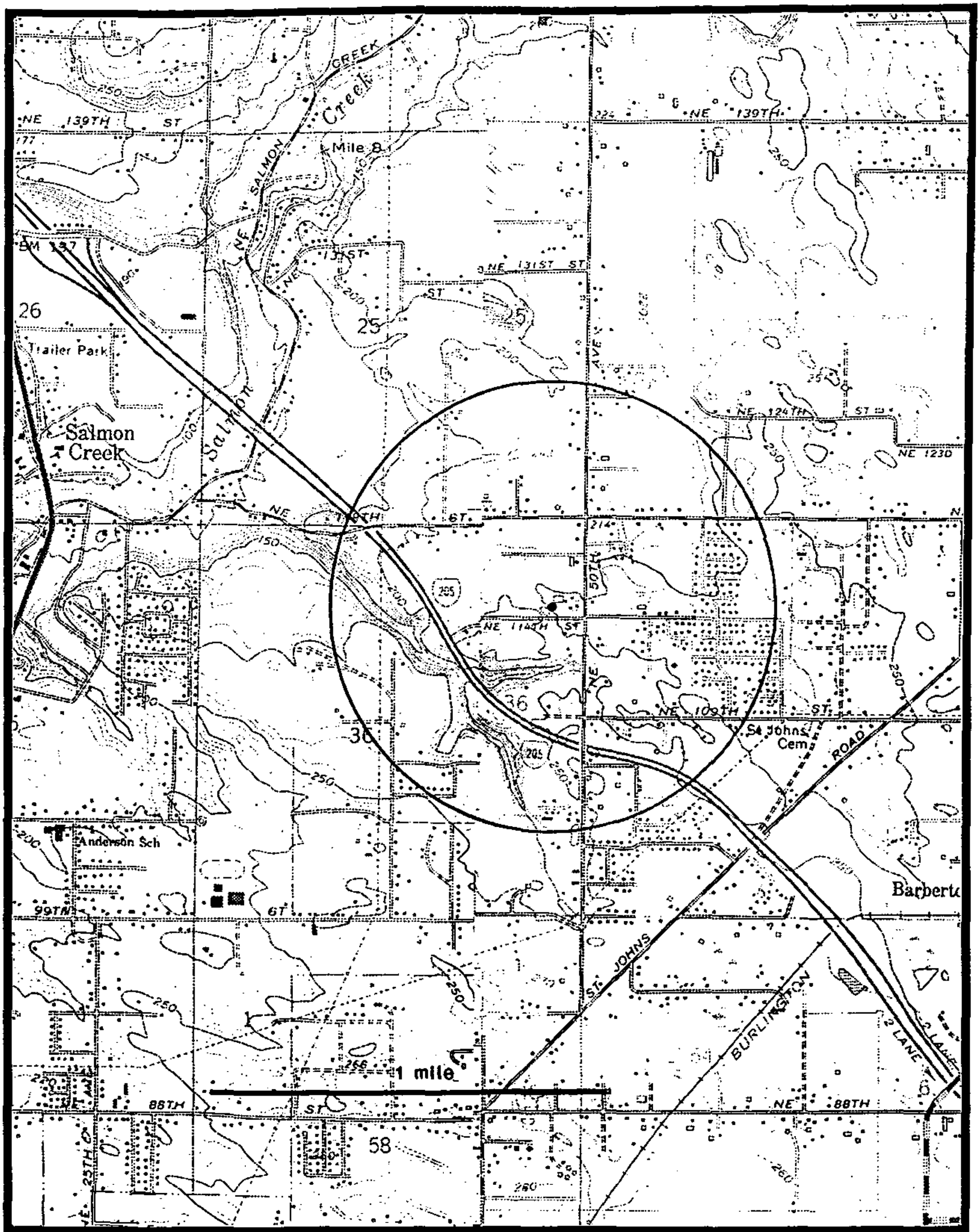

Figure CPU-14-4. 3000 foot fixed radius delineation for Clark Public Utilities well.

Appendix E

WELLHEAD PROTECTION AREA DELINEATION REPORT

CLARK PUBLIC UTILITIES WELL 16.1

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix E
Wellhead Protection Area Delineation Report

Well: CPU-16.1 (Clark Public Utilities Well 16.1)

Setting: CPU-16.1 is between Salmon Creek and Cold Canyon in southwest Clark County, the wellhead elevation is about 230 feet. With a depth of 707 feet, this is one of the areas deeper wells.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Cross sections made from water well records from Clark Public Utilities wells were used to define aquifer geometry. The well is screened in a sandy layer near the top of the lower Troutdale Formation. Data from the Clark Public Utilities wells suggest that this is a separate mappable unit.

The aquifer is probably semi-confined. The unit is bounded above and below by clayey and silty rocks. The water bearing unit appears to extend several miles beyond the well as interconnected sandy layers in the lower Troutdale Formation. The only other known production wells tapping the aquifer are Clark Public Utility wells 14 and 20. One new Clark Public Utilities well is completed in the aquifer but is not yet in production.

Gradient and Flow Direction: A water level surface map for the lower Troutdale Formation was made from available water level data. The flow direction is from east to west, toward the Columbia River. The lower Troutdale Formation water level gradient is about 0.001. There is a downward gradient from the upper to lower Troutdale Formation.

Aquifer Properties:

Transmissivity: A 24 hour single well pump test of the well lower screened interval (460 to 620 feet) was used by Carr/Associates to estimate a transmissivity of 37,000 gallons/day/foot (460 meters^2/day).

Porosity: A porosity of 0.2 was estimated by comparing well record lithology descriptions to standard porosity values for aquifer materials (Heath, 1983).

Pumping Rate: An average pumping rate for CPU-16.1 of 651,000 gallons/day (2,500 meter^3/day) was calculated using the highest total annual pumpage recorded, 237,500,000 gallon/year in 1989.

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping included making cross sections to define aquifer thickness and extent, and mapping water levels to determine flow direction. Since aquifer characteristics appear uniform and little detailed information exists, additional hydrogeologic mapping was deemed impractical without additional data collection.

Hydrogeologic mapping results were used to characterize the aquifer for the EPA RESSQC (EPA, March, 1991) model analysis.

Analytical Models: The approach was to model the well as a simple confined aquifer using the EPA RESSQC model (EPA, March, 1991). Aquifer thickness corresponds directly to the screened interval. Pumping at well CPU 20 was included in one model. Figure CPU-16.1-1 shows delineations for the lower Troutdale Formation aquifer with pumping only at well 16.1.

Values selected were:

Transmissivity:	460 meters^2/day
Pumping rate:	2,500 meters^3/day
Gradient:	0.001
Flow angle:	-155° (245° compass bearing)
Porosity:	0.2
Aquifer thickness:	15 meters
Time of travel:	1, 5, 10, 20, and 50 years

Figure CPU-16.1-2 shows delineations for the lower Troutdale Formation aquifer using average pumping rates at well CPU-20.

Calculated Fixed Radius: Figure CPU-16.1-3 shows calculated fixed radii zones of contribution made using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulation volumetric flow equation.

Values selected were:

Pumping rate:	31,723,000 feet^3/year (237.3 mg/y)
Porosity:	0.2
Length of well screen:	45 feet
Times of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure CPU-16.1-4 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: See US Geological Survey report and maps.

References Cited:

Carr/Associates, Draft Well Report for CPU Well 16.1.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: United States Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

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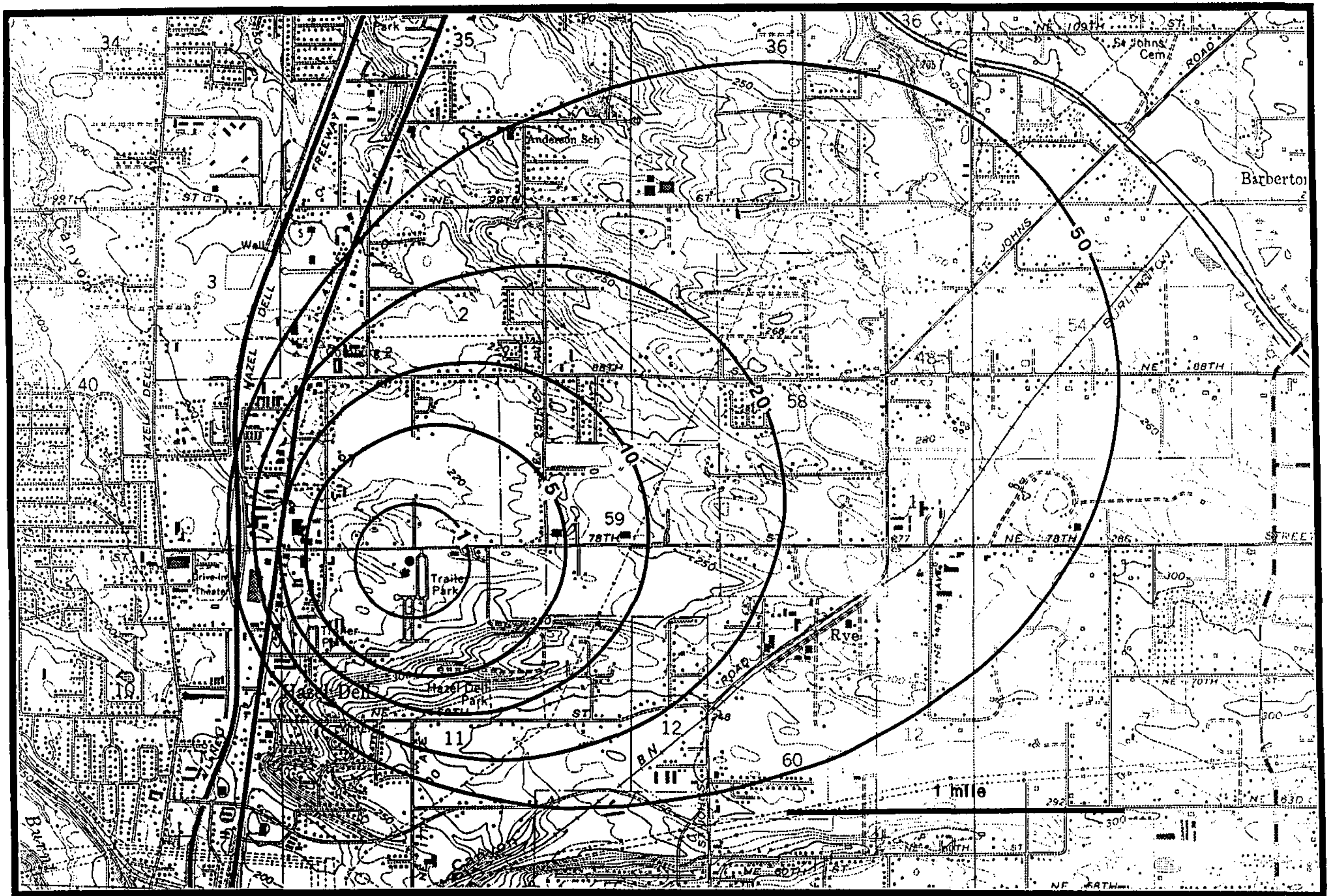

Figure CPU-16.1-1. 1, 5 10, 20, and 50 year time of travel zones of contribution using the EPA RESSQC WHPA model for well CPU-16.1 only.

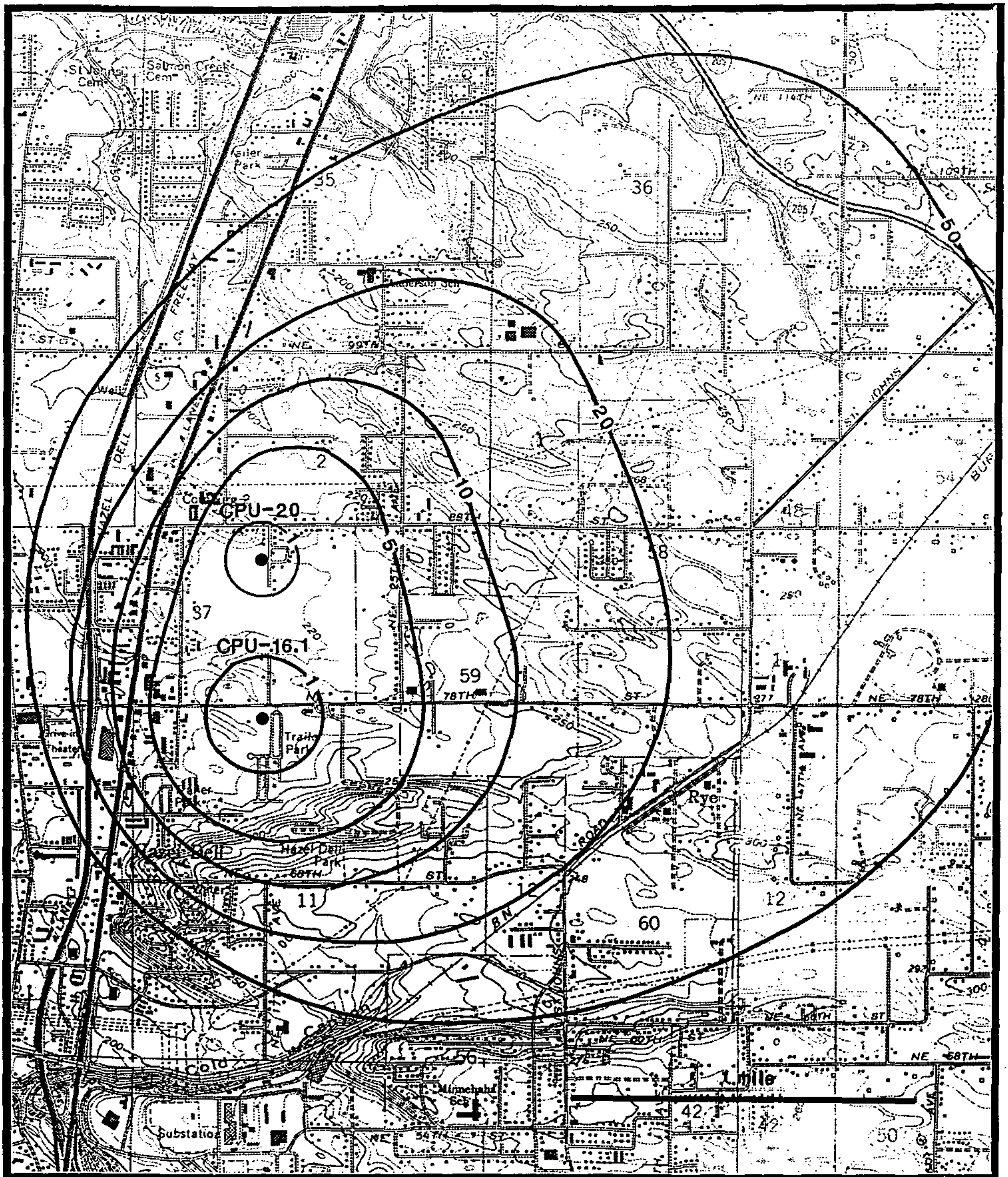

Figure CPU-16-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution for CPU-16.1 and CPU-20 using the EPA RESSQC WHPA model.

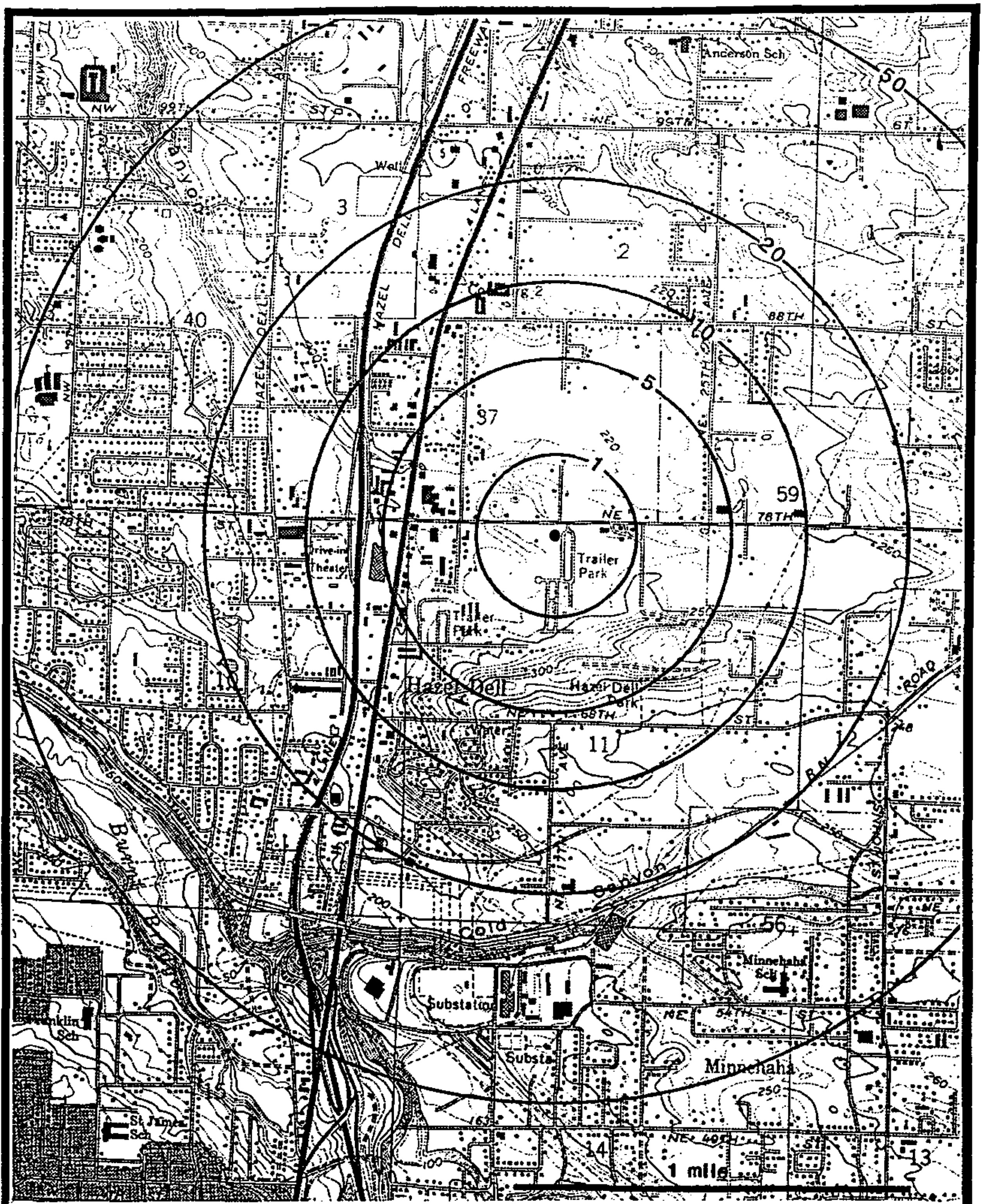

Figure CPU-16.1-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

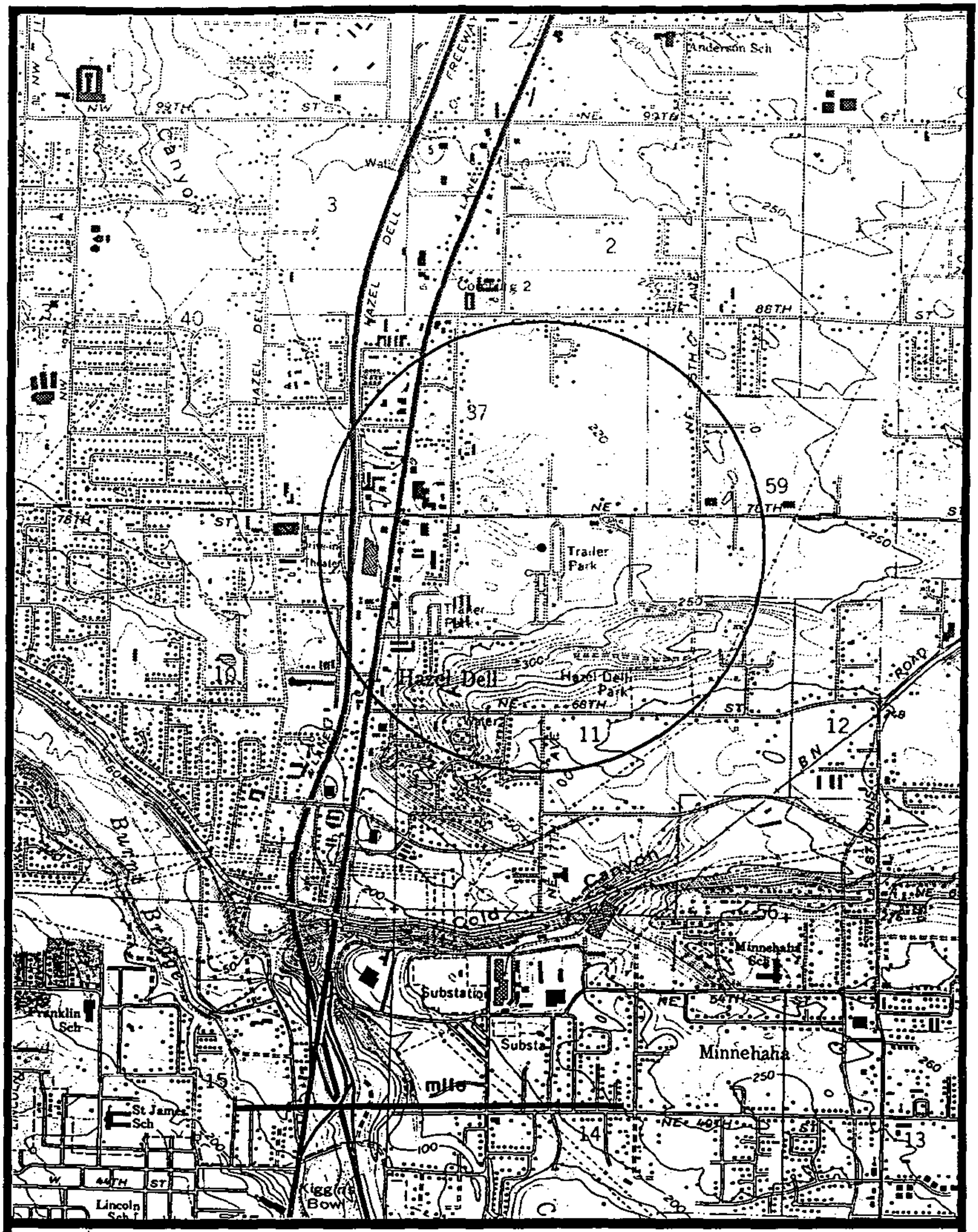

Figure CPU-16.1-4. 3000 foot fixed radius delineation for Clark Public Utilities well.

Appendix F

WELLHEAD PROTECTION AREA DELINEATION REPORT

CLARK PUBLIC UTILITIES WELL 19

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix F
Wellhead Protection Area Delineation Report

Well: CPU-19 (Clark Public Utilities Well 19)

Setting: CPU-19 is located on the Salmon Creek flood plain about 3000 feet downstream from Klineline Pond. The well taps a shallow alluvial gravel aquifer partly filling a valley cut into the Troutdale Formation by Salmon Creek. The well screened interval is from 32 feet to 63 feet.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Aquifer geometry is defined by geologic mapping (Trimble, 1963) and well data from consultant reports (Carr/Associates). The valley fill aquifer is thin and of limited extent, bounded by Troutdale Formation at the valley walls and in stream bed exposures a short distance upstream. Thickness increases from 0 at the valley wall to 40 feet (12 meters) at the well. The aquifer is overlain by 25 feet of muddy gravel and may be semi-confined.

The degree of interconnection between Salmon Creek and the alluvial aquifer is uncertain. However, some well effect on Salmon Creek is likely due to the closeness of the wells and relatively coarse lithology of valley fill alluvium. A time drawdown plot for a pump test of CPU-19 suggests that a recharge boundary is encountered after about 20 to 30 minutes of pumping. No other large scale ground water use occurs near the well (Collins and Broad, 1991).

Gradient and Flow Direction: Water levels from CPU-19 and Salmon Creek stream elevations drawn from topographic maps were used to estimate gradient and flow direction. Water levels at the well appear to be one or two feet higher than the river elevation pulled off the topographic map. Gradient and flow direction in the Troutdale Formation were drawn from a regional water level map made from spring 1988 water level measurements. Although the maps are general, they indicate ground water moves down the Salmon Creek valley filling sediment with a gradient of about 0.004 and upward, out of the Troutdale Formation into the valley fill sediment.

Aquifer Properties:

Transmissivity: A transmissivity of 580,000 gallons/day/foot (7,200 meters^2/day) was calculated using time and drawdown data from a pump test on CPU-19. This transmissivity may be partly controlled by recharge boundaries. An earlier part of the time drawdown curve gave a transmissivity of about 80,000 gallons/day/foot.

Porosity: A porosity of 0.25 was estimated by comparing well record lithology descriptions to standard porosity values for aquifer media from Heath (1983).

Pumping Rate: A pumping rate of 2,100 meters^3/day was calculated from an annual total of 199,400,000 gallons for the high year of record, 1989.

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define wellhead protection area zones and time related zones of contribution based on aquifer geometry and ground water flow directions. Figure CPU-19-1 shows these delineations.

Two principal areas were delineated. A high risk, one year or less travel time zone of contribution was delineated using the extent of the alluvial gravel aquifer, data from pump tests, and analytical models. A more extensive set of time related zones of contribution was drawn to account for ground water discharge from the underlying Troutdale Formation to the alluvial aquifer.

Delineations did not consider including aquifers that discharge to Salmon Creek outside the extent of the area contributing directly to the well because this would create a wellhead protection area at least a mile wide extending up Salmon Creek many miles from the boundary of the alluvial aquifer.

Well lithology data, consultant report geologic descriptions, geologic mapping, and aquifer hydraulic properties were used to define the extent of the alluvial aquifer. The alluvial aquifer is distinguished from the Troutdale Formation gravel by higher transmissivity and lack of cementation. Trimble's (1963) geologic map and topography were used to define the extent of the alluvial aquifer. Aquifer thickness was determined at the well from reported well-cuttings lithology descriptions.

Drawdown data was used to define a down gradient null point about 1000 feet down stream from the well. A drawdown map for observation well measurements after an 8 hour, 1100 gallon/minute pump test on CPU-19 shows a fairly circular cone of depression extending north, at least to Salmon Creek, south to the valley wall, and upstream. However, no observation wells were located downstream of CPU-19. The drawdown data was extrapolated to draw a circular cone of depression, which was superimposed on a down valley gradient drawn from the elevation of Salmon Creek. Capture zone models for the valley fill aquifer using EPA WHPA models always gave shorter distances to the null point than did the extrapolated drawdown data. These analytical solution simulated valley walls and used transmissivities as low as 80,000 gallons/day/foot.

It was determined that the entire aquifer up gradient from the estimated null point is likely to contribute water to the well within short time periods. Delineations for 50, 90 180 and 365 day zones of contribution using the RESSQC model (EPA, March, 1991) showed that much of the up gradient aquifer could contribute to the well in less than a year.

Time of travel zones of contribution for 5, 10, 20, and 50 years were delineated away from the valley wall boundary of the alluvial gravel aquifer (one year or less travel time) in the Troutdale Formation. Travel times between water level contours along selected flow paths were calculated using the Darcy velocity equation, Velocity = Hydraulic Conductivity * Gradient / Porosity. Travel times between head map contours were calculated and specified time of travel lines were drawn by linear interpolation between times at head contours. Spring 1988 water levels for the Troutdale Formation gravel aquifer were used to define water level contours. Hydraulic conductivity was estimated from pump tests and porosity was estimated from lithology descriptions.

Analytical Models: Due to limited aquifer extent and high transmissivity, analytical models are not especially appropriate to apply. The best, but least conservative application in that it limits the zone of contribution to the valley floor, is the GPTRAC model (EPA, March, 1991), strip aquifer option. However, this code did not appear to work accurately for this small valley aquifer. At any rate, several analyses using both stream and barrier boundaries showed the typical elongated zone of contribution delineations associated with high transmissivity aquifers or relatively steep gradient.

Delineations were made using the WHPA version 2 RESSQC model (EPA, March, 1991). Figure CPU-19-2 shows delineations for a high transmissivity alluvial gravel aquifer and Figure CPU-19-3 shows a method where the aquifer was assumed to be the Troutdale Formation.

For the Figure CPU-19-2 high transmissivity aquifer delineation values were:

Transmissivity:	2,250 meters^2/day
Pumping rate:	2,100 meters^3/day
Gradient:	0.004
Flow angle:	valley axis
Porosity:	0.25
Aquifer thickness:	12 meters
Time of travel:	50, 90, 180, and 365 days

Values for the Figure CPU-19-3 Troutdale Formation delineation:

Transmissivity:	400 meters^2/day
Pumping rate:	2,100 meters^3/day
Gradient:	0.004
Flow angle:	-170° (280° compass bearing)
Porosity:	0.2
Time of travel:	1, 5, 10, 20, and 50 years

There is an obvious difference in delineation area between the hydrogeologic mapping approach and the RESSQC model delineations in figure CPU-19-3. Both include flow from the Troutdale Formation, but the hydrogeologic mapping approach considers steep ground water gradients perpendicular to Salmon Creek while the RESSQC model uses a lower gradient parallel Salmon Creek.

Calculated Fixed Radius: Figure CPU-19-4 shows the calculated fixed radius were made using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulations volumetric flow equation.

Values selected were:

Pumping rate: 26,656,000 feet^3/year (199.4 mg/y)
Porosity: 0.3
Length of well screen: 30 feet
Times of travel: 1, 5, 10, 20, and 50 years

Fixed Radius: Figure CPU-19-5 shows the 3000 foot radius delineation. The radius is from analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: See US Geological Survey report and maps.

Cited References:

Carr/Associates, Draft Well report for CPU well 19.

Collins, C.A., and T.M. Broad, 1991, Estimated Average Annual Ground-Water Pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 91-4018.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: U.S. Environmental Protection Agency, Office of Ground Water Protection, Washington, D.C., EPA 440/6-8-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: U.S. Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: US Geological Survey Water Supply Paper 2220, 84p.

Trimble, D.E., 1963, Geology of the Portland, Oregon and Adjacent Areas: US Geological Survey Bulletin 1119, 119p.

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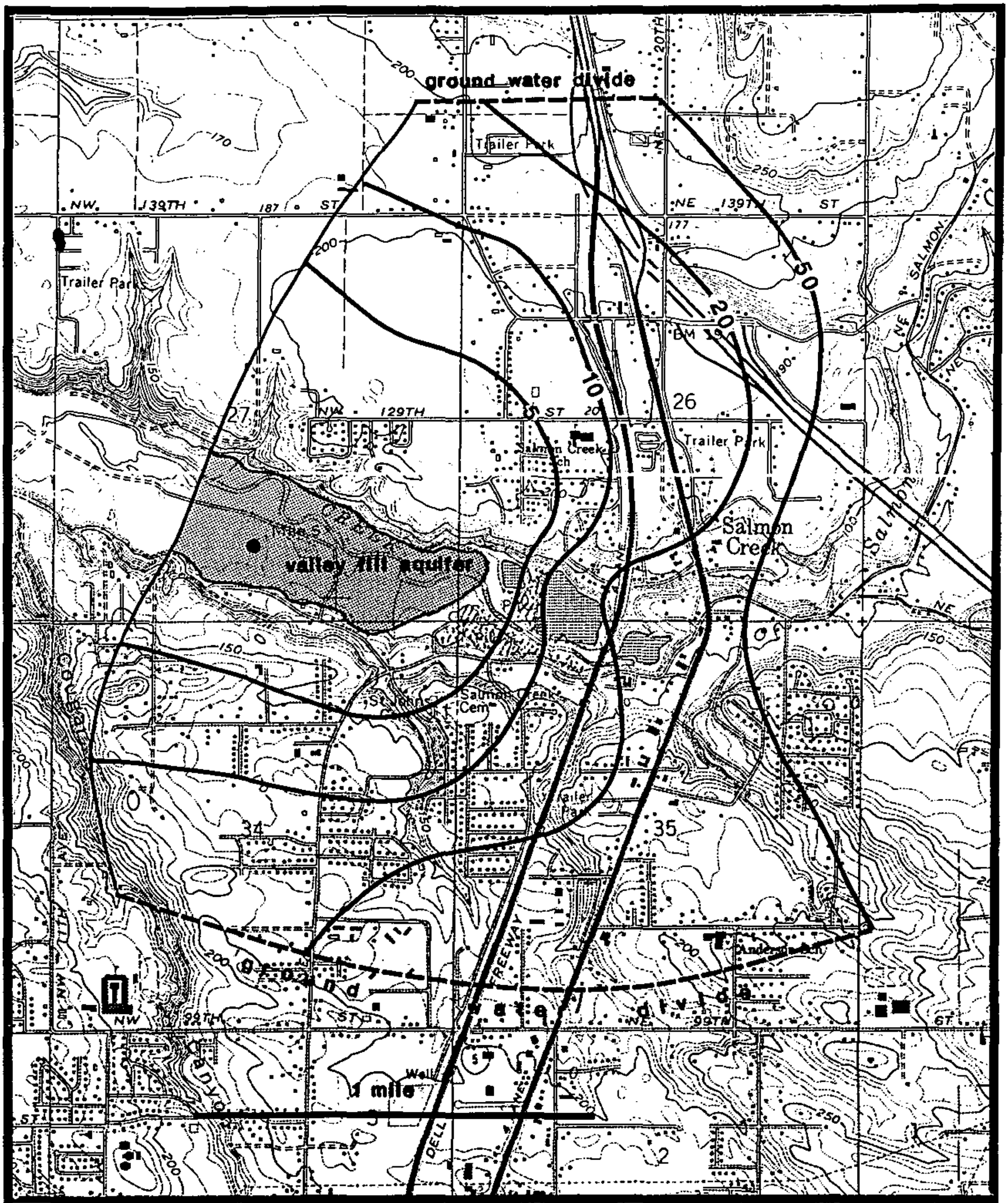

Figure CPU-19-1. Valley fill aquifer (shaded area); and time of travel zones of contribution from hydrogeologic mapping methods.

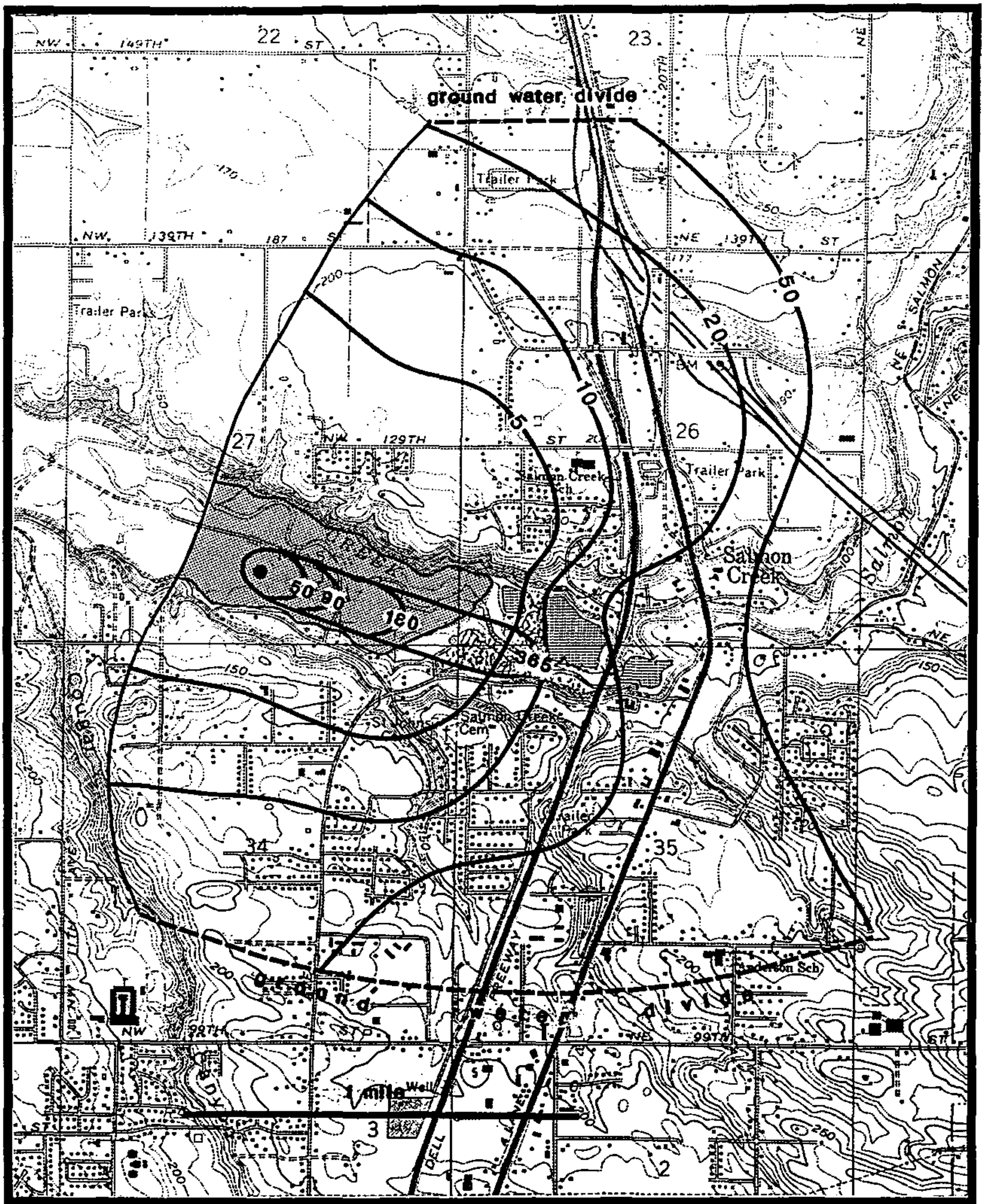

Figure CPU-19-2. 50, 90, 180, and 365 day time of travel zones of contribution for a high transmissivity aquifer using the EPA RESSQC WHPA model.

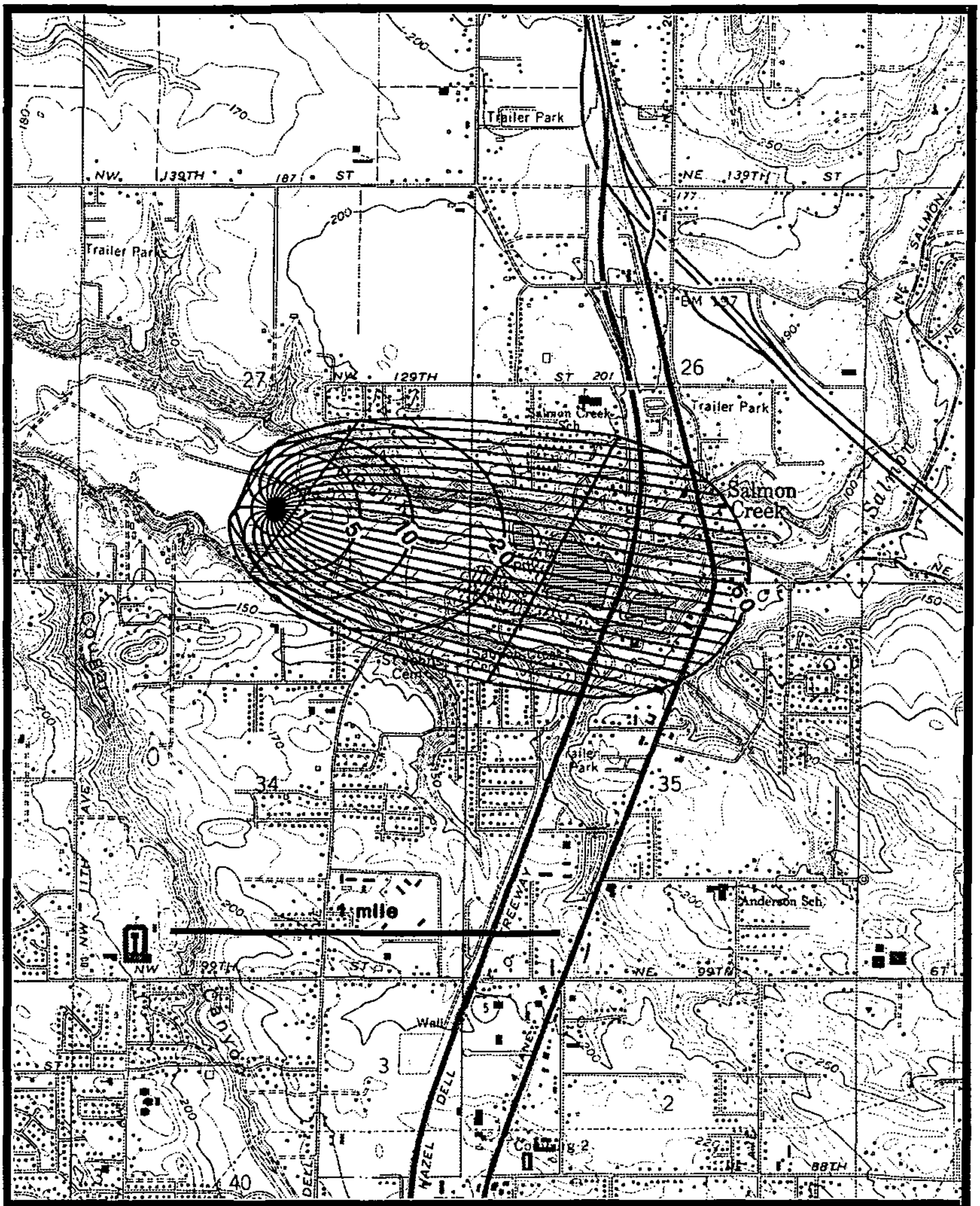

Figure CPU-19-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution for a semi-consolidated gravel aquifer using the EPA RESSQC WHPA model.

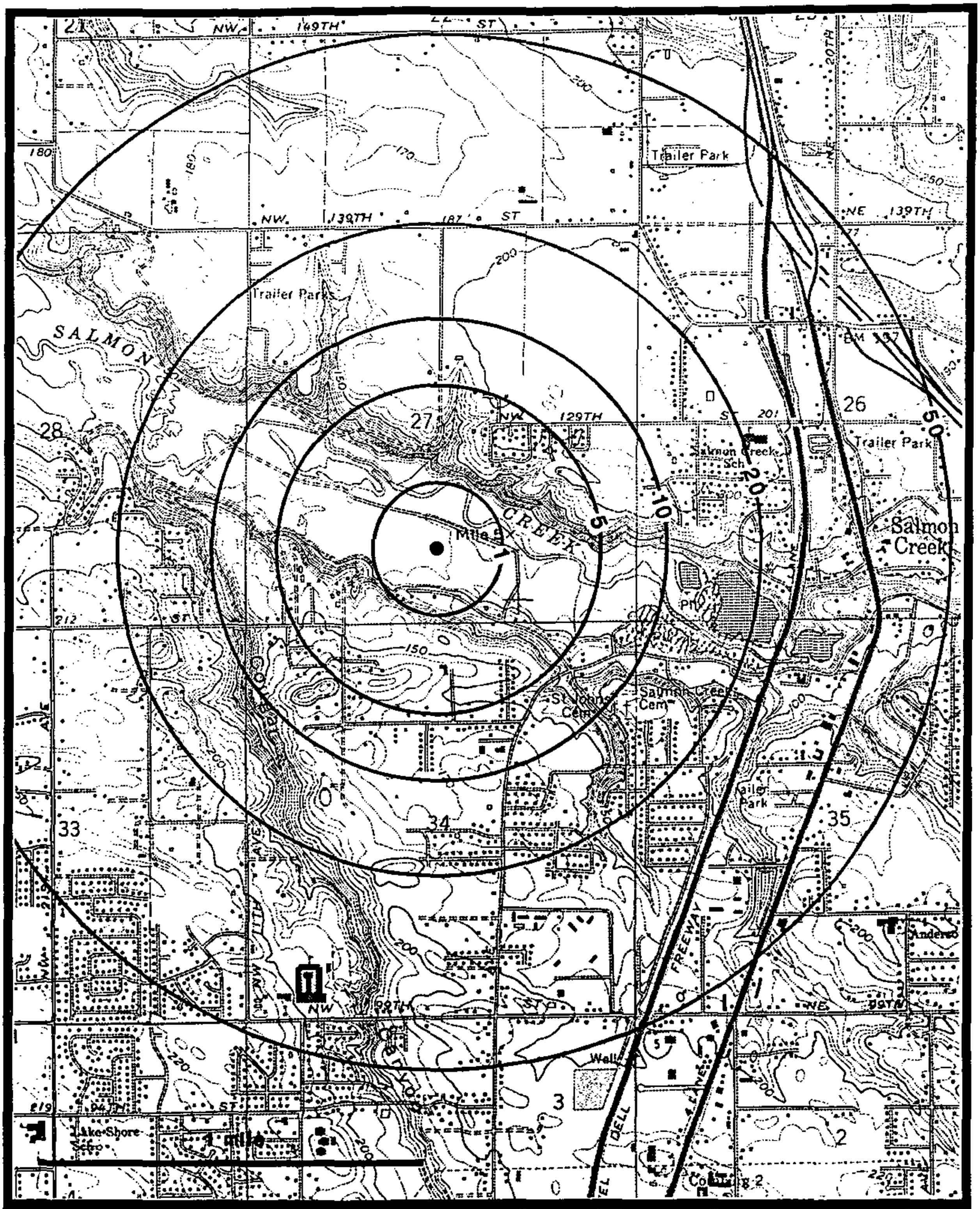

Figure CPU-19-4. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

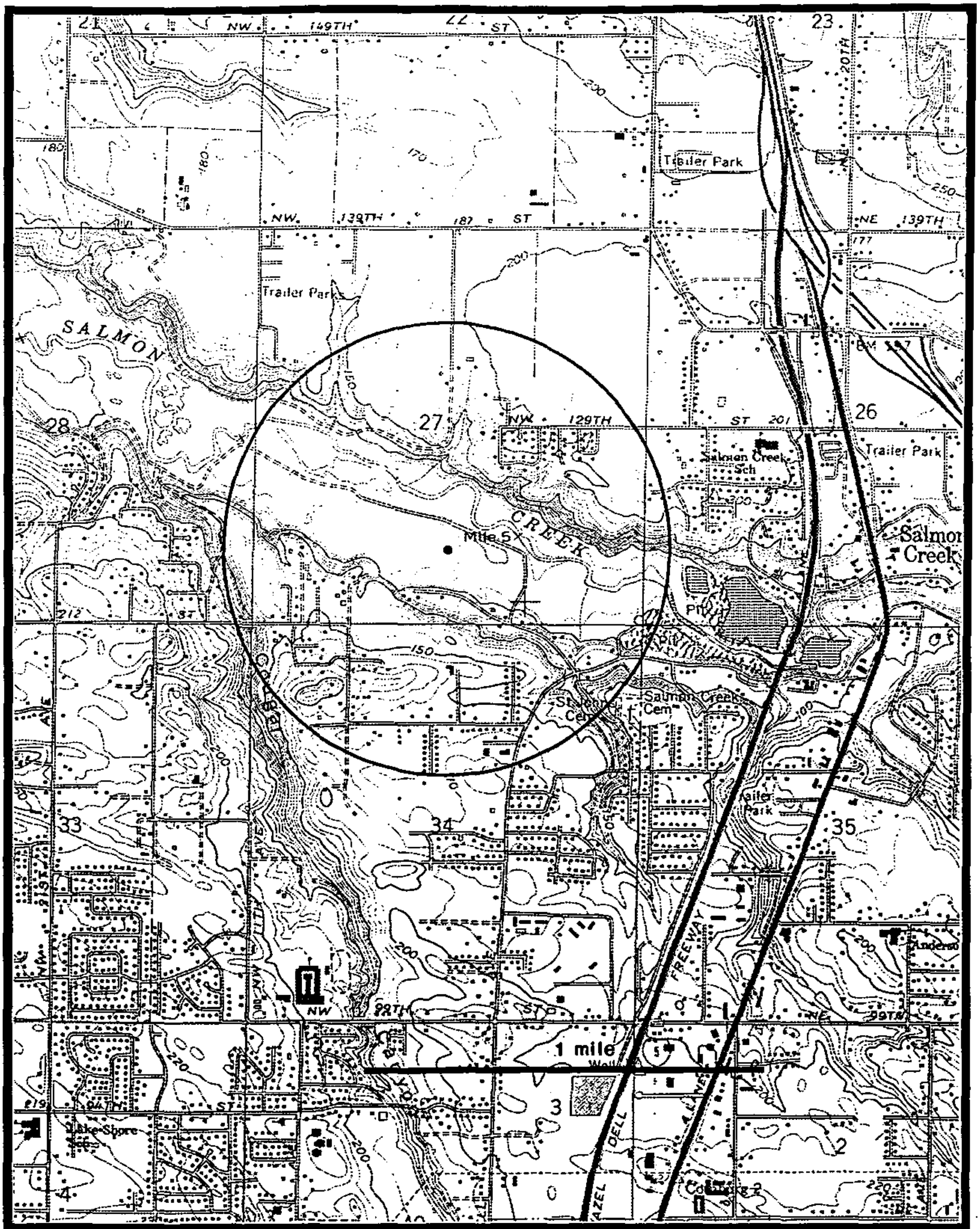

Figure CPU-19-5. 3000 foot fixed radius delineation for Clark Public Utilities well.

Appendix G

WELLHEAD PROTECTION AREA DELINEATION REPORT

LA CENTER WELLS

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix G
Wellhead Protection Area Delineation Report

Well: La Center Wells

Setting: The three La Center wells are in a geologically and topographically complex area in the northwest corner of the Portland Basin. The wells are close together, with wellheads at about 400 feet elevation on a south facing slope that rises from East Fork Lewis River to about 700 feet elevation. This slope parallels faults or a gentle fold that separates an area to the north where the Troutdale Formation is uplifted about 500 feet above its position in the basin.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: The aquifer is semi-consolidated sand in the lower member of the Troutdale Formation. The aquifer has not been mapped as a discrete geologic or hydrogeologic unit. Geologic mapping (Mundorff, 1964) does not differentiate diverse sand, mud, and gravel layers in the Troutdale Formation. More recent hydrogeologic unit mapping by the USGS maps the upper member of the Troutdale Formation and finer grained sand and mud lower Troutdale Formation separately. However, USGS mapping does not distinguish separate aquifer units within the lower Troutdale Formation in the vicinity of the La Center wells.

The aquifer is tectonically deformed and dips parallel to the hill slope in the area of the La Center wells.

Review of area well records showed that the lower Troutdale Formation sand aquifer in which the La Center wells are completed and the overlying upper Troutdale Formation sandy gravel were either connected or in close proximity. This lead to mapping the sand unit and the upper Troutdale sandy gravel as one aquifer unit.

Two methods were used to map the aquifer thickness and distribution. One method was to directly map the saturated thickness of the upper Troutdale Formation gravel and directly underlying sand from the few water wells that penetrated these units. A second method involved drawing a saturated thickness map based on an estimated (from well records, geologic maps, and topography) base of the sand aquifer and a water table elevation map (drawn from water well records and topographic maps). Then subtracting the two. A comparison of the two maps showed that they agreed fairly well even though data was limited.

Saturated thickness varied from less than 50 feet near the ridge crest above the La Center wells to over 100 feet along the relatively flat ridge above the well. An average thickness of 60 to 75 feet was estimated in the well vicinity.

Principal boundary effects are due to topography. The aquifer appeared to be truncated by a northeast-southwest trending Jenny Creek valley wall about 4,000 feet northwest of the wells. The wells are south of a northeast to southwest trending ground water divide separating them from Jenny Creek valley. The aquifer is assumed to be semi-confined. Recharge is through overlying weathered and unweathered gravel and sands, and is estimated to be about 20 inches/year in this area (Snyder and others, 1991).

Gradient and Flow Direction: Ground water divides and two dimensional flow paths were mapped from the water level elevation map. The map was made by comparing well water levels and topography at the points where wells existed then mapping the water level elevation from estimated depth to water below land surface. The water level gradient is about 0.08 from the well to 2,500 feet up gradient and flow direction is almost due south at a compass bearing of 186 degrees. Water levels generally mimic land surface resulting in a very steep gradient. Dipping aquifer units parallel to land surface also may control gradient to some degree. Water levels from wells with varying depths indicate that vertical ground water flow is downward.

Aquifer Properties:

Transmissivity: Two pump tests for the La Center wells give specific capacities of about 2 gallons/foot drawdown and 1 gallon/foot drawdown. A simple graphical solution to solve for transmissivity from specific capacity and storage coefficient (Theis and others, 1963) was used. A storage coefficient of 0.001 was used along with the specific capacities (2 and 1 gallon/foot drawdown) to solve for transmissivities of about 3,500 gallons/day/foot and 1500 gallons/day/foot.

Porosity: A porosity of 0.1 was estimated for this semi-consolidated sandstone by comparing well record lithology description to tables describing aquifer porosity by lithology (Heath, 1983). This porosity is lower than usual for Troutdale Formation sands and this estimate is based on the poor production of the delineated wells.

Pumping Rate: An average pumping rate of 92,000 gallons/day (350 meters^3/day) is calculated for the La Center wells from the highest total annual pumpage recorded 33,700,000 gallons in 1988.

Delineation Analysis:

Hydrogeologic Mapping: The hydrogeologic mapping approach was to map the aquifer extent, aquifer thickness, and aquifer water level surface to determine two dimensional flow paths to the well and provide data for analytical models. The hydrogeologic data is used to modify the analytical EPA WHPA model solution to more accurately reflect hydrogeologic conditions.

Water level gradient and flow direction was determined to be the controlling factor for determining areas with flow to the wells. The very high gradient caused a long, narrow zone of contribution using analytical models. The ground water divide between Jenny Creek and the well acts as an up gradient boundary. Figure LC-1 shows hydrogeologic mapping zones of contribution based on analytical model solution and two dimensional flow direction. A more conservative approach might draw the zone of contribution farther up gradient along the divide to account for flow down the ridge. Another consideration is the possibility that flow from the Jenny Creek basin could flow to the wells due to interlayered low permeability beds that can constrain downward flow within the aquifer.

Analytical Models: The La Center wells are an example of an area where application of simple models is complicated by extreme values for gradient and complex geology and topography. A simple model using MWCAP (EPA, March, 1991) with a barrier boundary simulating the up gradient ground water divide was used to model the well (Figure LC-2). This was compared to a RESSQC (EPA, March, 1991) delineation with no boundary. The only observable at 1:24,000 scale was a eastward shift about 2 degrees (away from the barrier) in the orientation of the MWCAP delineation compared to the MWCAP delineation.

Values selected were:

Transmissivity:	20 meters^2/day
Pumping rate:	350 meters^3/day
Gradient:	0.08
Flow angle:	-96° (186° compass bearing)
Porosity:	0.1
Aquifer thickness:	20 meters
Time of travel:	1, and 5 years

Calculated Fixed Radius: Figure LC-3 shows the delineation using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulation volumetric flow equation.

Values selected were:

Pumping rate:	4,505,000 feet^3/day (33.7 mg/y)
Porosity:	0.2
Length of well screen:	11 feet
Times of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure LC-4 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: See USGS map report.

References Cited:

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: U.S. Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: U.S. Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

Mundorff, M.J., 1964, Geology and Ground-Water Conditions of Clark County, Washington, with a Description of a Major Alluvial Aquifer Along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268p., 3 pls.

Snyder, D.T., Morgan, D.S., and McGRATH, t., U.S. Geological Survey Water Resources Investigation Report 92-XXXX.

Theis, C.V., R.H. Brown, and R.R. Meyer, 1963, Estimating the Transmissivity of Aquifers from the Specific Capacity of Wells: U.S. Geological Survey Water Supply Paper 1536-I, pp. 331-341.

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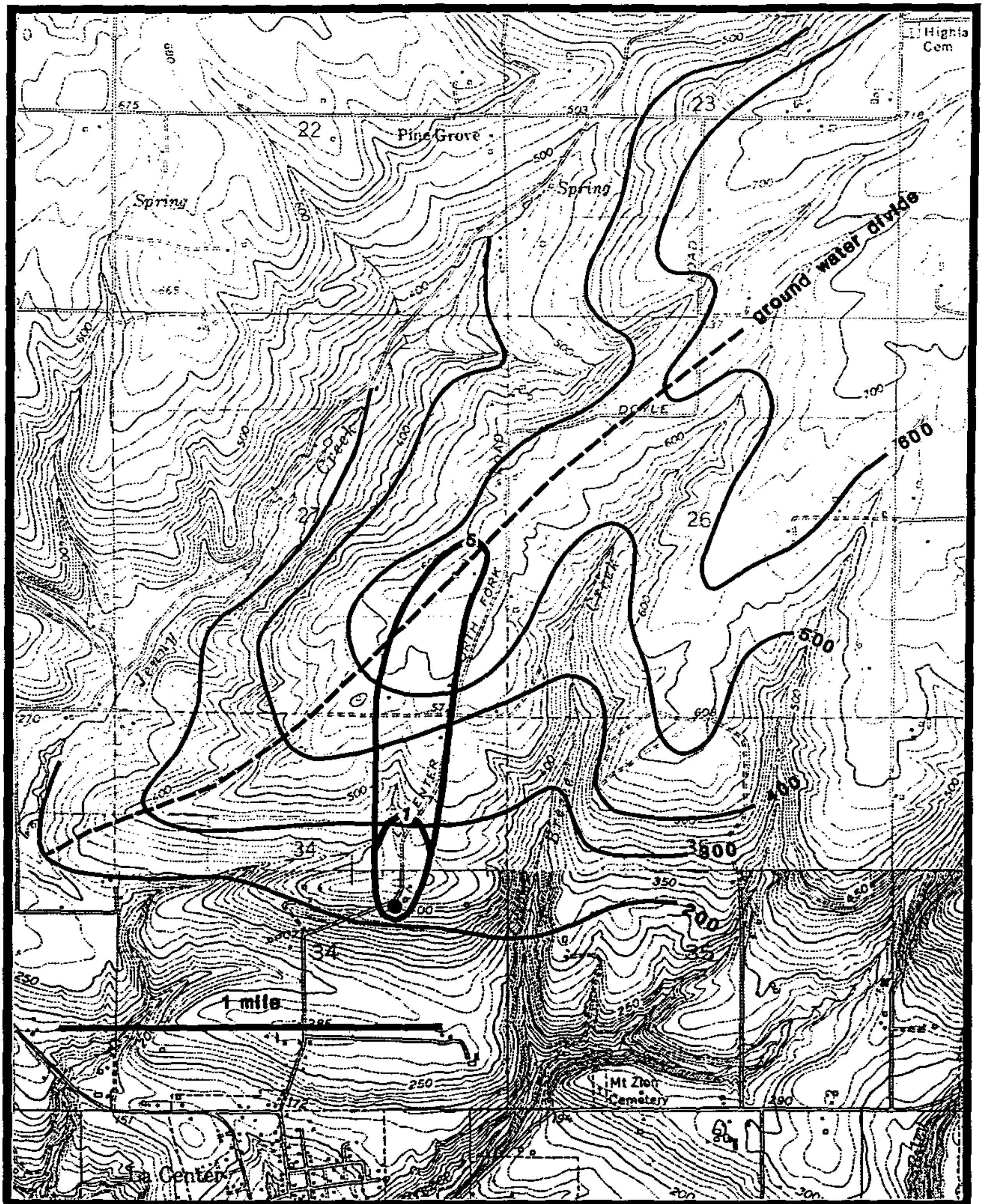

Figure LC-1. 1 and 5 year time of travel zones of contribution based on ground water flow direction and analytical modeling for the LaCenter town wells.

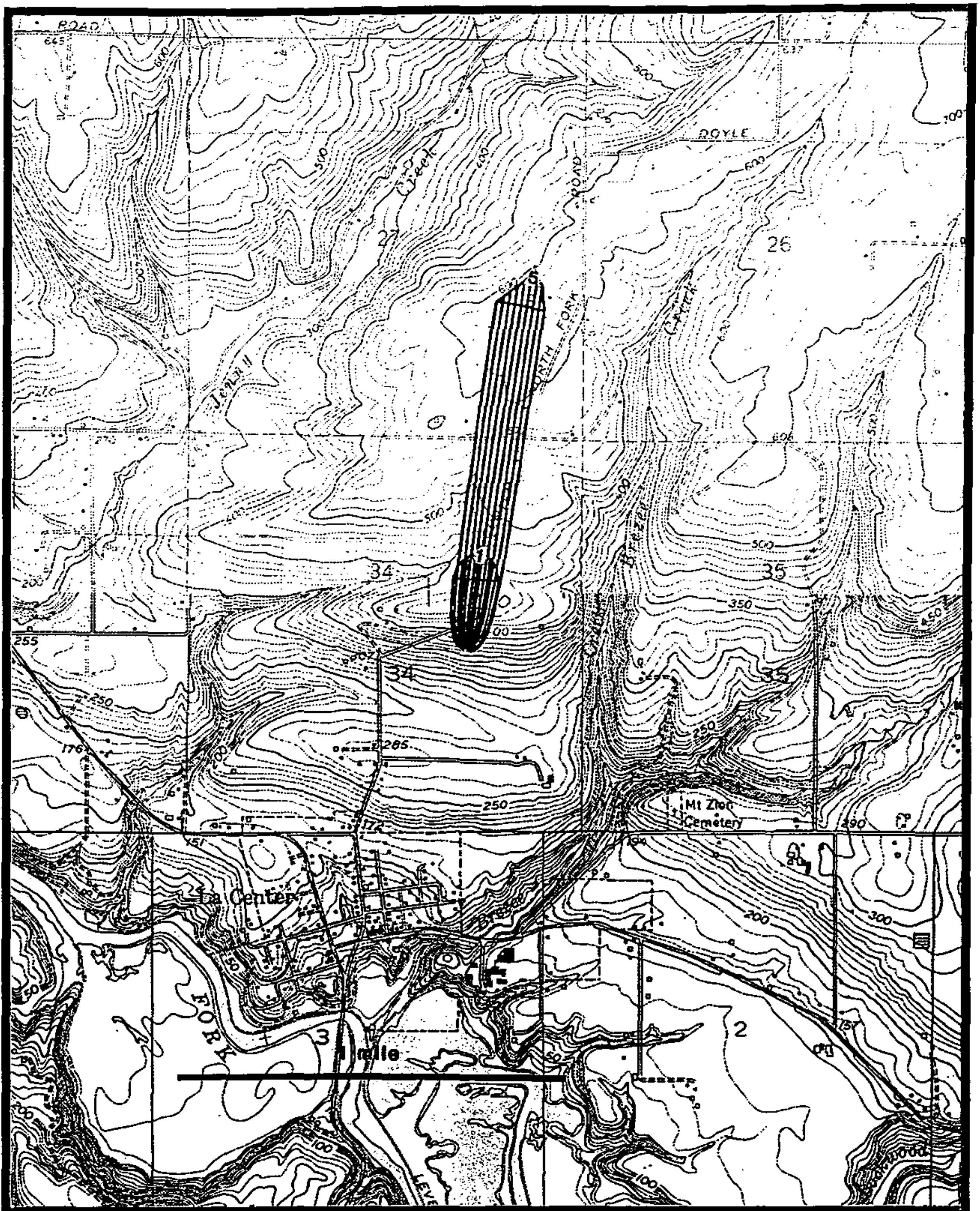

Figure LC-2. 1, and 5 year time of travel zones of contribution for the LaCenter wells using MWCAP with a barrier boundary at the ground water divide.

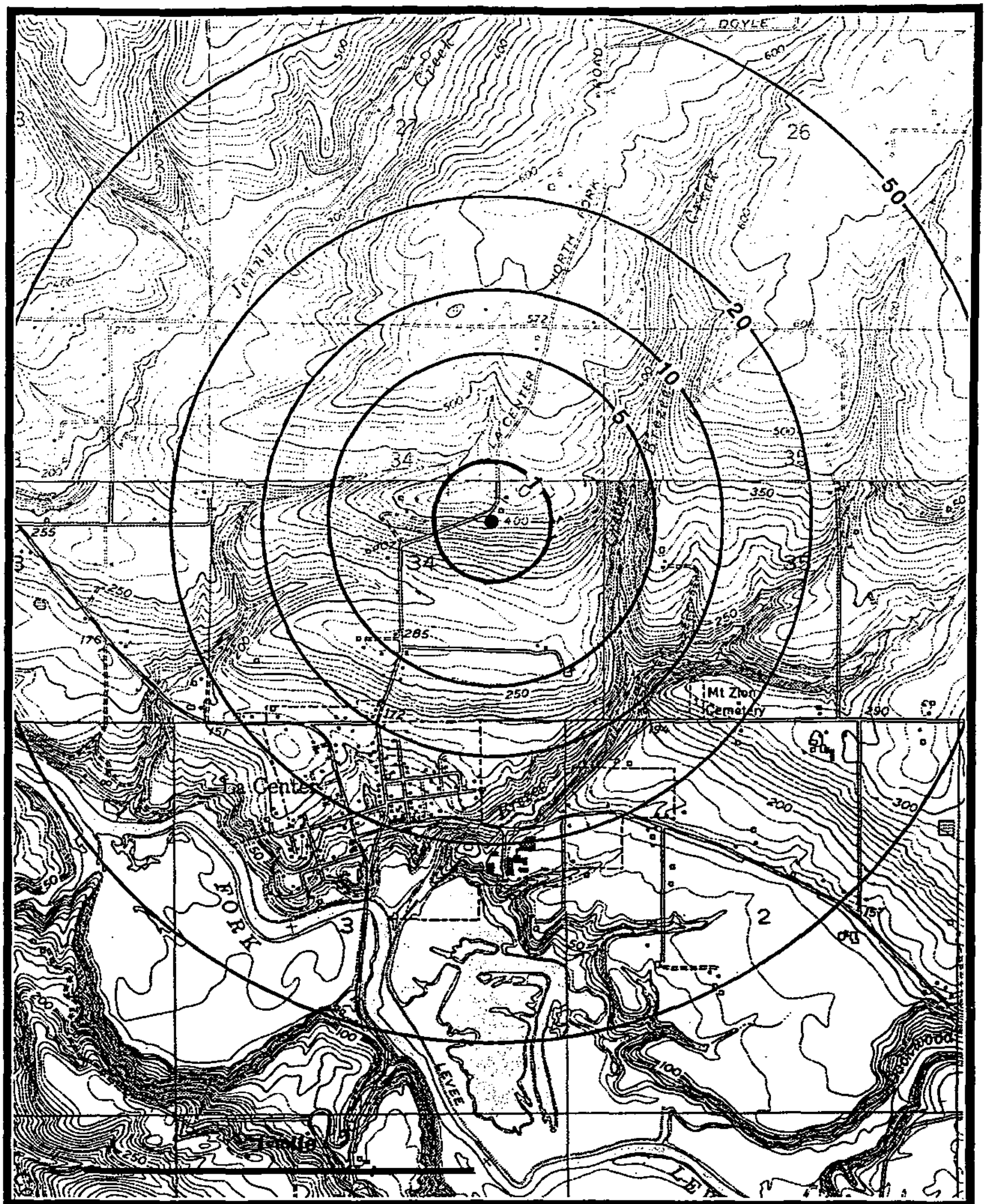

Figure LC-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation for LaCenter well.

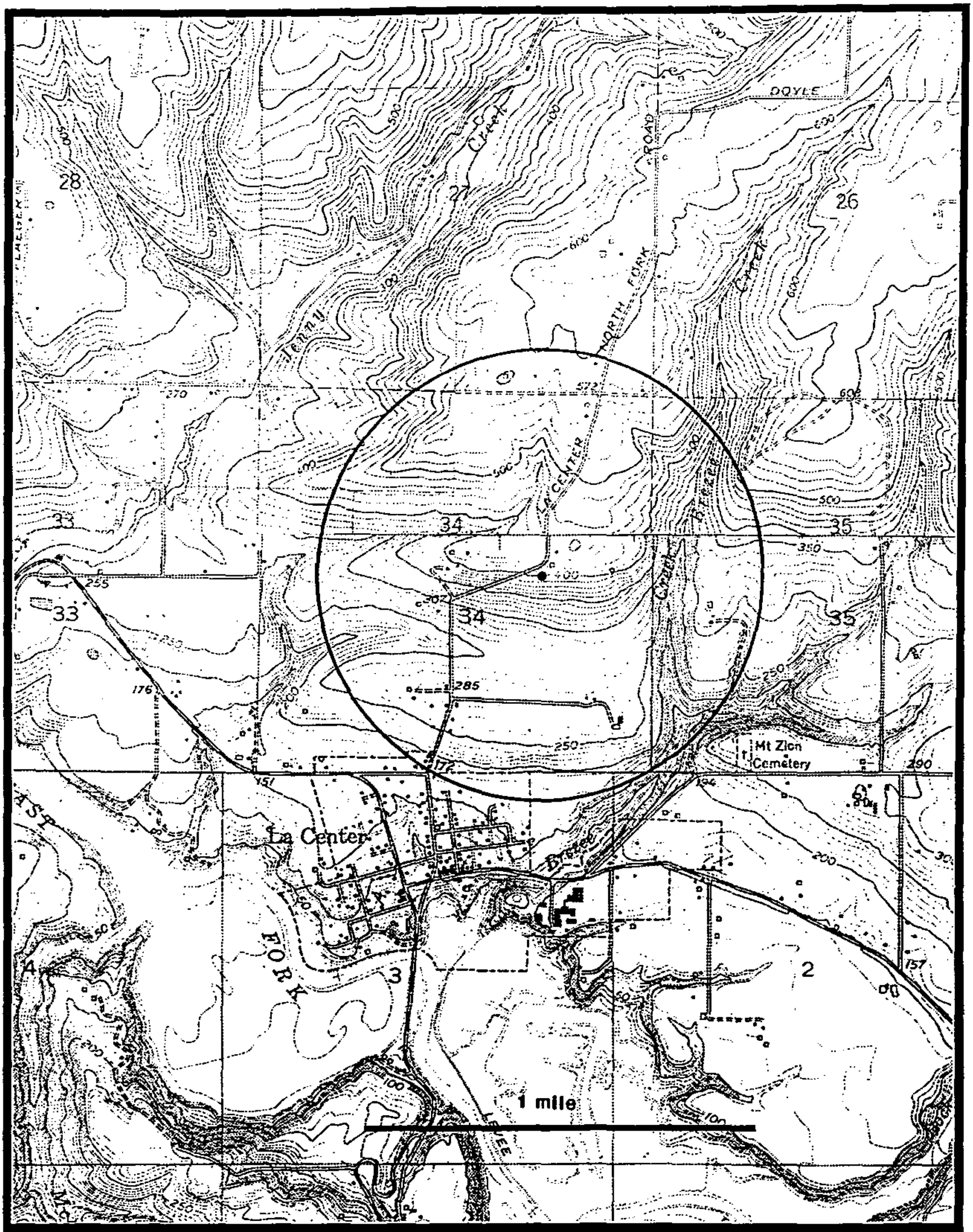

Figure LC-4. 3000 foot fixed radius delineation for LaCenter wells.

Appendix H

WELLHEAD PROTECTION AREA DELINEATION REPORT

MEADOW GLADE DARLING WELL

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix H
Wellhead Protection Area Delineation Report

Well: Meadow Glade Darling Well

Setting: This is the principal supply source for the Meadow Glade water system, serving a developing rural area about three miles east of Battle Ground. The well is on a flat upland area between the East Fork of the Lewis River and Salmon Creek with the wellhead at about 215 feet elevation.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: The well is in a sand aquifer near the top of the lower Troutdale Formation of Mundorff (1964). The lower Troutdale Formation is river laid sand, silt, clay, and sandy gravel with poorly described stratigraphy. Water well lithology descriptions were used to define the thickness and local extent of aquifer. While limited well data makes clear distinction of the aquifer unit difficult, this sandy part of the lower Troutdale Formation appears to extend over two miles beyond the well.

Aquifer thickness was mapped from lithology descriptions from drillers reports for wells within two miles of the Meadow Glade well. Thickness varied from well to well and ranged from about 40 feet at the well to 90 feet. The actual aquifer thickness appeared to be much greater than the screened interval in each well, with the screens at the base of the aquifer. In addition, variations in how drillers describe sandy units, eg. sandy clay versus sand for similar units can lead to varied thickness.

Boundaries are relatively simple for this well. The aquifer is confined to some degree by fine grained deposits. The well is on a broad regional ground water divide between the East Fork of the Lewis River and Salmon Creek. The aquifer layer appears to cross under the East Fork of the Lewis River and not be truncated by the river canyon. A small round hill about 2400 feet (730 meters) east of the well, appears to be the result of about 125 to 150 foot upward structural deformation of the Troutdale Formation. One well on the hill that penetrates the aquifer. This well showed that while the aquifer was uplifted about 100 feet and aquifer water level is about 75 feet higher. Recharge to the aquifer is through the overlying Troutdale Formation and Pleistocene deposits.

Gradient and Flow Direction: No good ground water level map exists for the lower Troutdale Formation because of the lack of deeper wells and difficulty defining discrete aquifer units. Generally flow is to the west with a shallow gradient. Downward flow is indicated by deeper water levels with greater depth, wells in the lower Troutdale Formation have heads up to 150 lower than wells in the upper Troutdale Formation.

Water level data for the few deep wells near the modeled well is not very consistent. Heads from wells competed in the lower Troutdale Formation range from about 50 feet elevation to about 150 feet elevation. However, an attempt was made to construct a potentiometric surface map using the deepest water levels. The results appear to be consistent with other parts of the county where deep wells exist, but the water level does not match the Meadow Glade well water level. Possible reasons for the difference in water level between apparently equivalent aquifer units include borehole connection between upper and lower aquifer and incorrectly mapped aquifer geometry. Additional well data is required to reconcile these accuracy questions.

Using the deep water level potentiometric surface map, the regional gradient is very low, about 0.00015 west toward the Columbia River.

Aquifer Properties:

Transmissivity: A transmissivity of about 10,000 gallons/day/foot (124.2 meters^2/day) was estimated from the well specific capacity of 4 gallons/minute/foot of drawdown, using the method described in Theis and others (1963) with an estimated storage coefficient of 0.001. Recovery data from the driller's pump test gave a straight curve with a calculated transmissivity of 12,000 gallons/day/foot. Using this data to plot water level against the ratio of time since pumping started to time since pumping stopped gave a transmissivity of 9,600 gallons/day/foot.

Porosity: Porosity is estimated to be 0.2 by comparing well record lithology descriptions to standard porosity values for aquifer materials (Heath,1983).

Pumping Rate: An average pumping rate of 227,000 gallons/day (860 meters^3/day) was calculated as two thirds of the water system peak year pumping total.

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to attempt to define aquifer geometry and potentiometric surface in the lower Troutdale Formation. One observation from hydrogeologic mapping is that there is a fairly thick sequence of fine grained sediment over the aquifer. However, the large downward gradient suggests that if routes exist, water could move rapidly into the deeper aquifer.

Analytical Models: Poorly defined and hypothetically simple aquifer geometry and boundary conditions make the EPA analytical models an attractive choice for delineating this well. The EPA WHPA RESSQC model (EPA, March, 1991) was used to delineate time of travel zones of contribution for 1, 5, 10, 20, 50 years (Figure MG-1). Aquifer properties were taken from tests of the well. Gradient were determined by linear interpolation between contours of the deep aquifer potentiometric surface map. The effects of the small hill east of the well are not modeled. This leads to a lower gradient.

Values selected were:

Transmissivity:	125 meters^2/day
Pumping rate:	865 meters^3/day
Gradient:	0.0013
Flow angle:	180°
Porosity:	0.2
Aquifer thickness:	18 meters

Calculated Fixed Radius: Figure MG-2 shows time of travel delineations using the Florida Department of Environmental Regulation volumetric flow equation (EPA, June, 1987).

Values selected were:

Pumping rate:	11,000,000 feet^3/year (83 mg/y)
Porosity:	0.2
Length of well screen:	21 feet
Time of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure MG-3 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: This is being done by the USGS.

References Cited:

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: U.S. Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C., EPA 440/6-8-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: U.S. Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

Mundorff, M.J., 1964, Geology and Ground-Water Conditions of Clark County, Washington, with a Description of a Major Alluvial Aquifer Along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268p., 3 pls.

Theis, C.V., R.H. Brown, and R.R. Meyer, 1963, Estimating the Transmissivity of Aquifers from the Specific Capacity of Wells: U.S. Geological Survey Water Supply Paper 1536-I, pp. 331-341.

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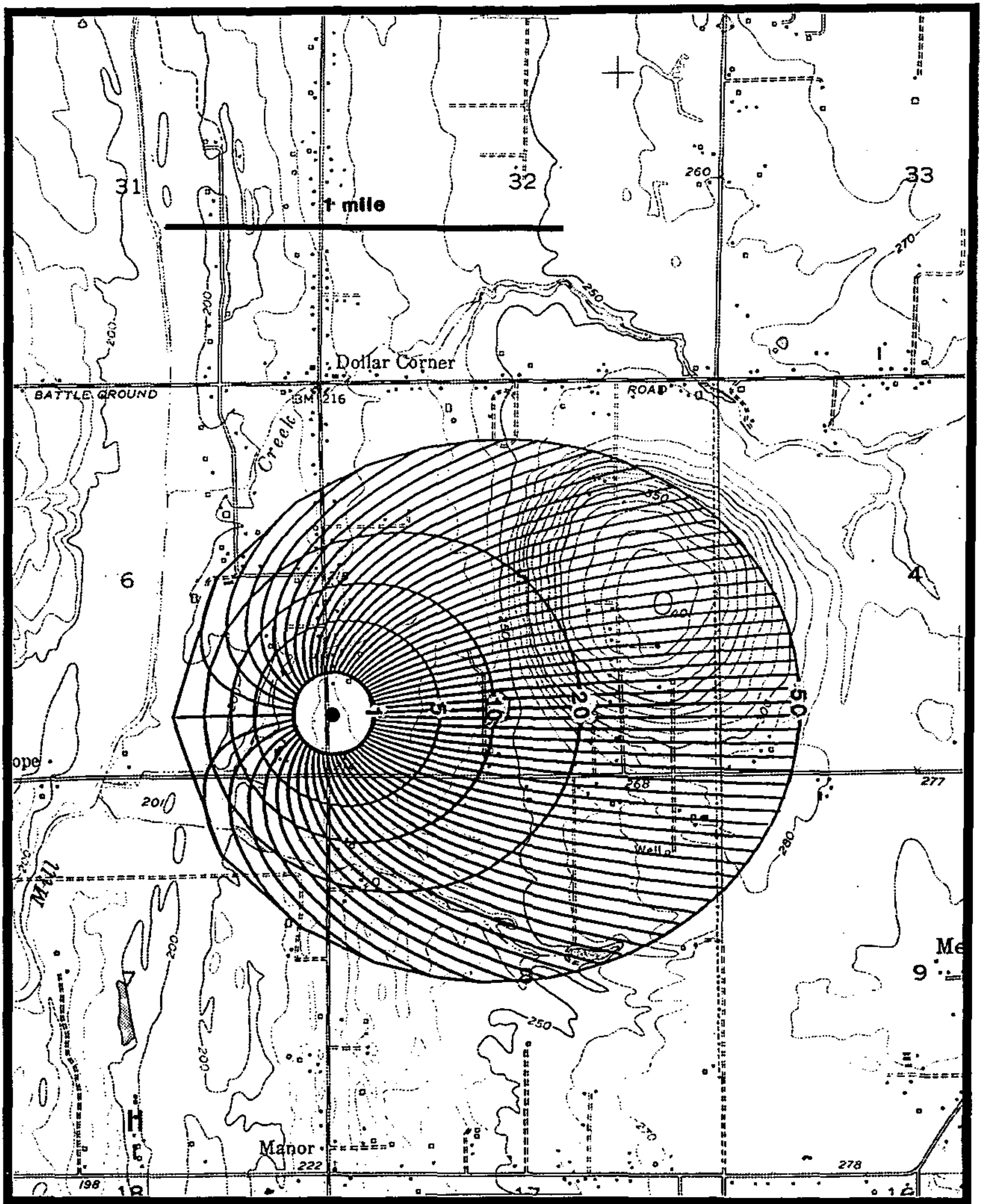

Figure MG-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution for the Meadow Glade Trinity well using the EPA RESSQC WHPA model.

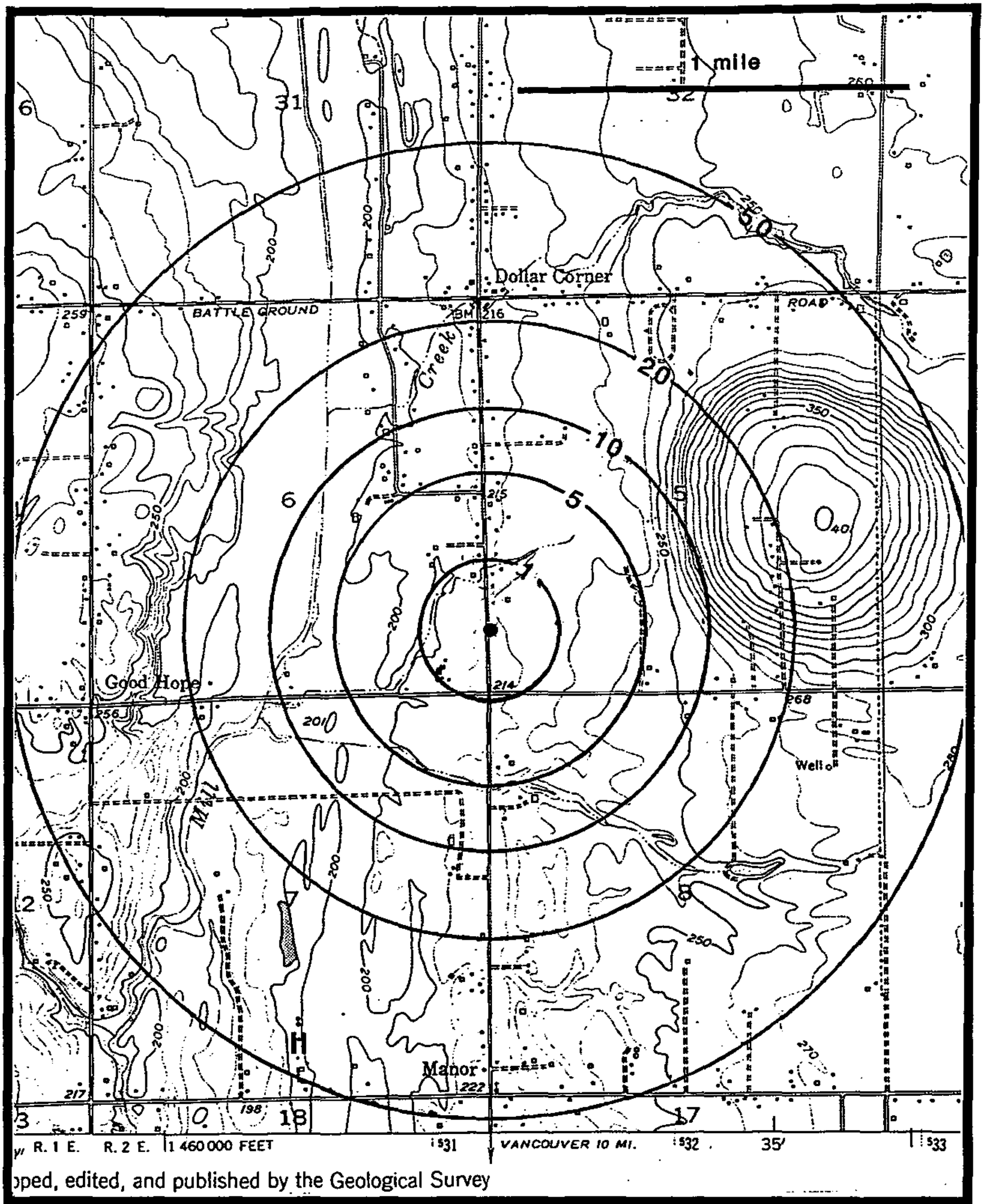

Figure VA-MG-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

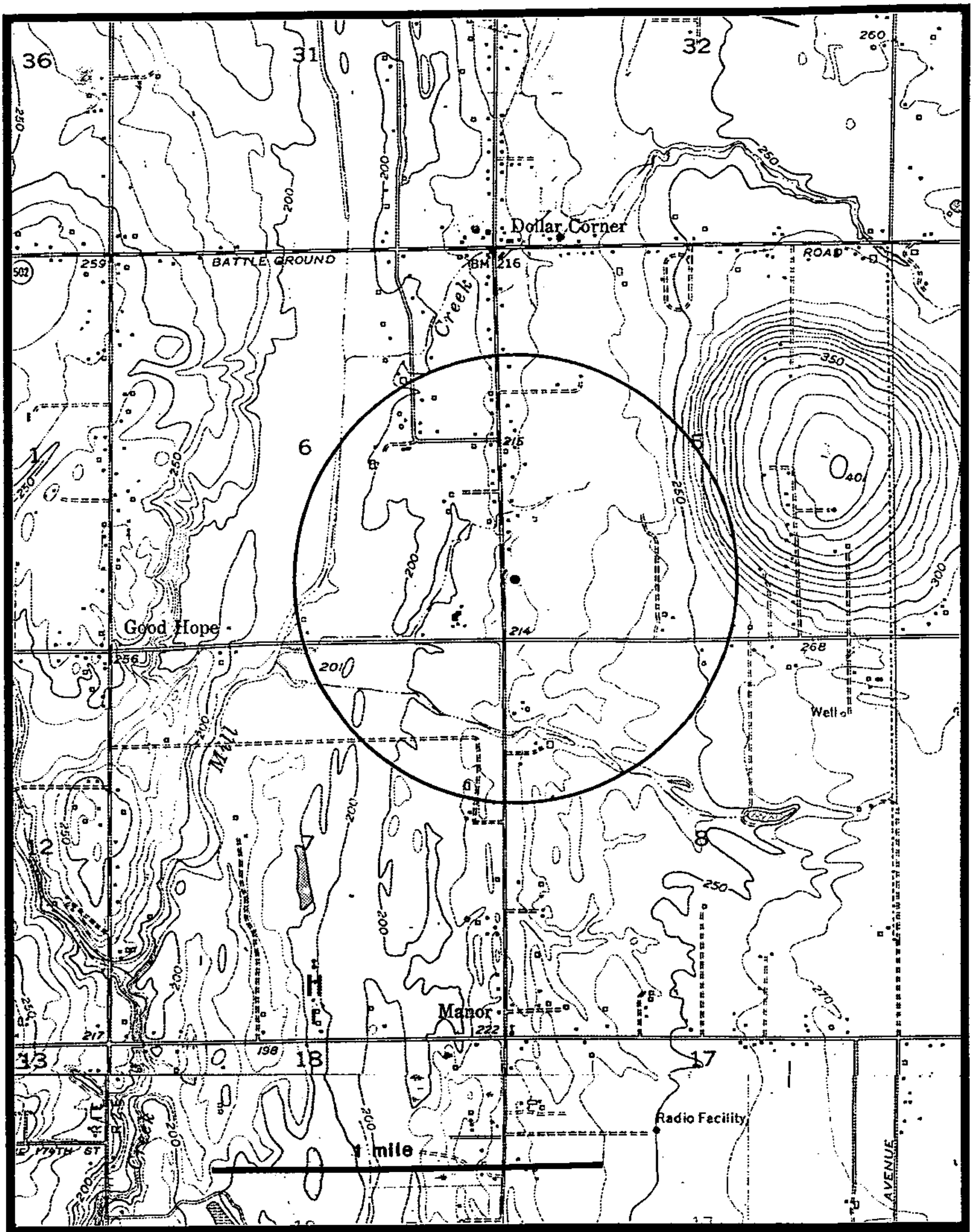

Figure MG-3. 3000 foot fixed radius delineation for Meadow Glade well.

Appendix I

WELLHEAD PROTECTION AREA DELINEATION REPORT

RIDGEFIELD WELLS 7, 8, AND 9

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix I
Wellhead Protection Area Delineation Report

Well: Ridgefield Well Field (wells 7, 8, and 9)

Setting: The three wells that supply the city water system are located on the flood plain of Gee Creek canyon in Ridgefield. Two other nearby wells act as backup supply. The wells modeled, 7, 8, and 9, were constructed to work as a group, pumping equal amounts from the same aquifer. The wells are screened at a depth of about 160 to 200 feet. The wellheads are at about 40 feet elevation.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: The wells are among the stratigraphically deepest wells in the Troutdale Formation because they are in a valley cut into an area slightly tectonically uplifted. Cross sections drawn using lithology descriptions from the few available water wells were used to define the extent and thickness of aquifer. At the well, the aquifer is a 100 foot thick sandy layer in the lower member of the Troutdale Formation. This layer appears to thicken toward the east. The aquifer probably extends, in effect for many miles in all directions as interconnected sandy lenses in the lower Troutdale Formation.

The aquifer is bounded above by silty and clayey sediment interlayered with beds of sand and gravel. The water bearing unit is bounded below by clayey sand, with older volcanic rocks encountered at a depth of 230 feet. No important geologic or hydrologic boundaries are mapped. No large pumping wells are in the vicinity of the Ridgefield wells.

Gradient and Flow Direction: Static water levels from water well reports were used to make a head map for the lower Troutdale Formation sand aquifer. Flow direction was nearly due west and gradient was estimated at 0.0008, or 10 feet in 13,000 feet. There was no data to map gradient west of the well. Generally there is a large, deepening with depth head difference between the upper Troutdale Formation and lower Troutdale Formation aquifers. At the well, limited water level suggest that there is little head difference between the two units. Stream flow data (McFarland and Morgan, 1991) suggest that Gee Creek is a gaining stream at the well site.

Aquifer Properties:

Transmissivity: A transmissivity of about 20,000 gallons/day/foot (250 meters^2/day) was estimated using the graphical method of Theis and others (1964) using a specific capacity of 10 gallons/day/foot drawdown and an estimated storage coefficient of 0.001. A transmissivity of about 21,000 gallons/day/foot (300 meters^2/day) was estimated using recovery data on a single well pump test.

Porosity: A porosity of 0.2 is estimated by comparing well report lithology descriptions to standard porosity values for aquifer materials (Heath, 1983).

Pumping Rate: An average daily combined pumping rate of 880 meters^3/day for wells 7, 8, and 9 was calculated from the peak year pumping total (84,800,000 gallons in 1989). A total daily rate of 12,000 gallons/day (45 meters^3/day) for standby wells 2 and 3 was reported by city staff.

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define aquifer characteristics for use of the EPA WHPA analytical models. Detailed hydrogeologic mapping was not a viable tool to delineate time related zones of contribution because of the lack of detailed hydrogeologic information, and apparently simple, uniform aquifer conditions. Water level maps did show that the total zone of contribution probably narrows to the east because the well is on a low regional ground water divide.

Analytical Models: The RESSQC module of WHPA version 2 (EPA, March, 1991) was used to delineate zones of contribution. One simulation modeled production wells 7, 8, and 9, and standby wells 2 and 3 as separate interfering wells (Figure RF-1), the other simulation uses a composite well for production wells 7, 8, and 9 (Figure RF-2).

Values selected for the model in Figure RF-1 were:

Transmissivity:	250 meters^2/day
Pumping rate:	290 meters^3/day for wells 7, 8, 9 and 23 meters^3/day for wells 2 and 3
Gradient:	0.0008
Flow angle:	-170° (260° compass bearing)
Porosity:	0.2
Aquifer thickness:	30 meters

Values selected for the model in Figure RF-2 were:

Transmissivity:	250 meters^2/day
Pumping rate:	880 meters^3/day
Gradient:	0.0008
Flow angle:	-170° (260° compass bearing)
Porosity:	0.2
Aquifer thickness:	30 meters

Calculated Fixed Radius: Figure RF-3 shows calculated fixed radii for a combined well representing wells 7, 8, and 9. Figure RF-4 shows calculated fixed radii for wells 7, 8, and 9 calculated individually. The volumetric flow equation, referenced by EPA (June, 1987) as the Florida Department of Environmental Regulation volumetric flow equation, was used to calculate the radii.

Values selected were:

Pumping rate:	11,336,000 feet^3/year (84.8 mg/y)
Porosity:	0.2
Length of well screen:	37 feet
Times of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure RF-5 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 tears time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: See USGS map report.

References Cited:

EPA, June, 1987, guidelines for Delineation of Wellhead Protection Areas: U.S. Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: United States Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

McFarland, W.D., and Morgan, D.S., 1992, Description of the Ground-Water Flow System in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water Resources Investigation Report 92-XXXX. (written communication).

Theis, C.V., R.H. Brown, and R.R. Meyer, 1963, Estimating the Transmissivity of Aquifers from the Specific Capacity of Wells: U.S. Geological Survey Water Supply Paper 1536-I, pp. 331-341.

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Figure RF-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution for Ridgefield wells 7, 8, and 9 using the EPA RESSQC WHPA model.

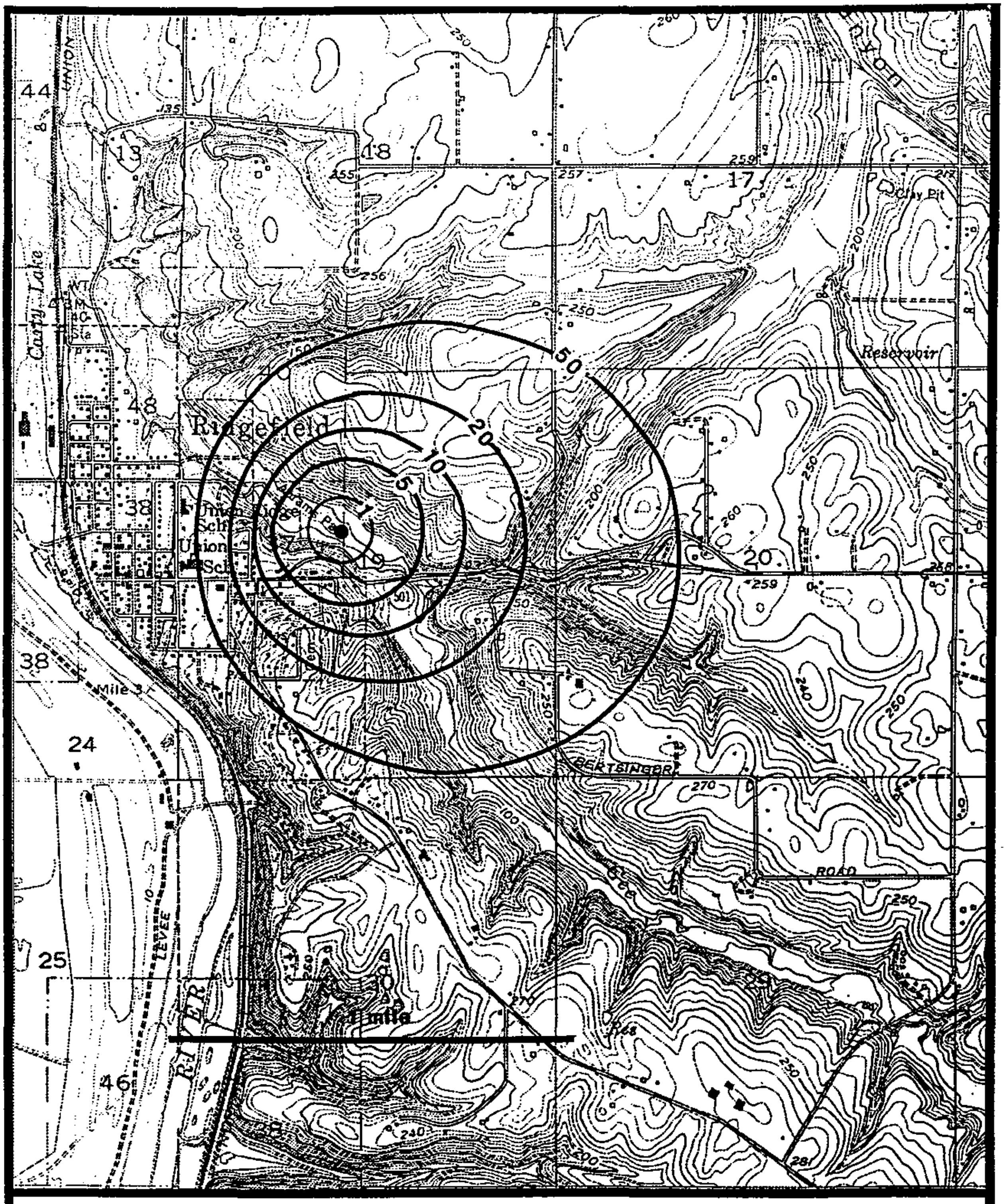

Figure RF-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution for Ridgefield wells 7, 8, and 9 as a single combined well using the EPA RESSQC WHPA model.

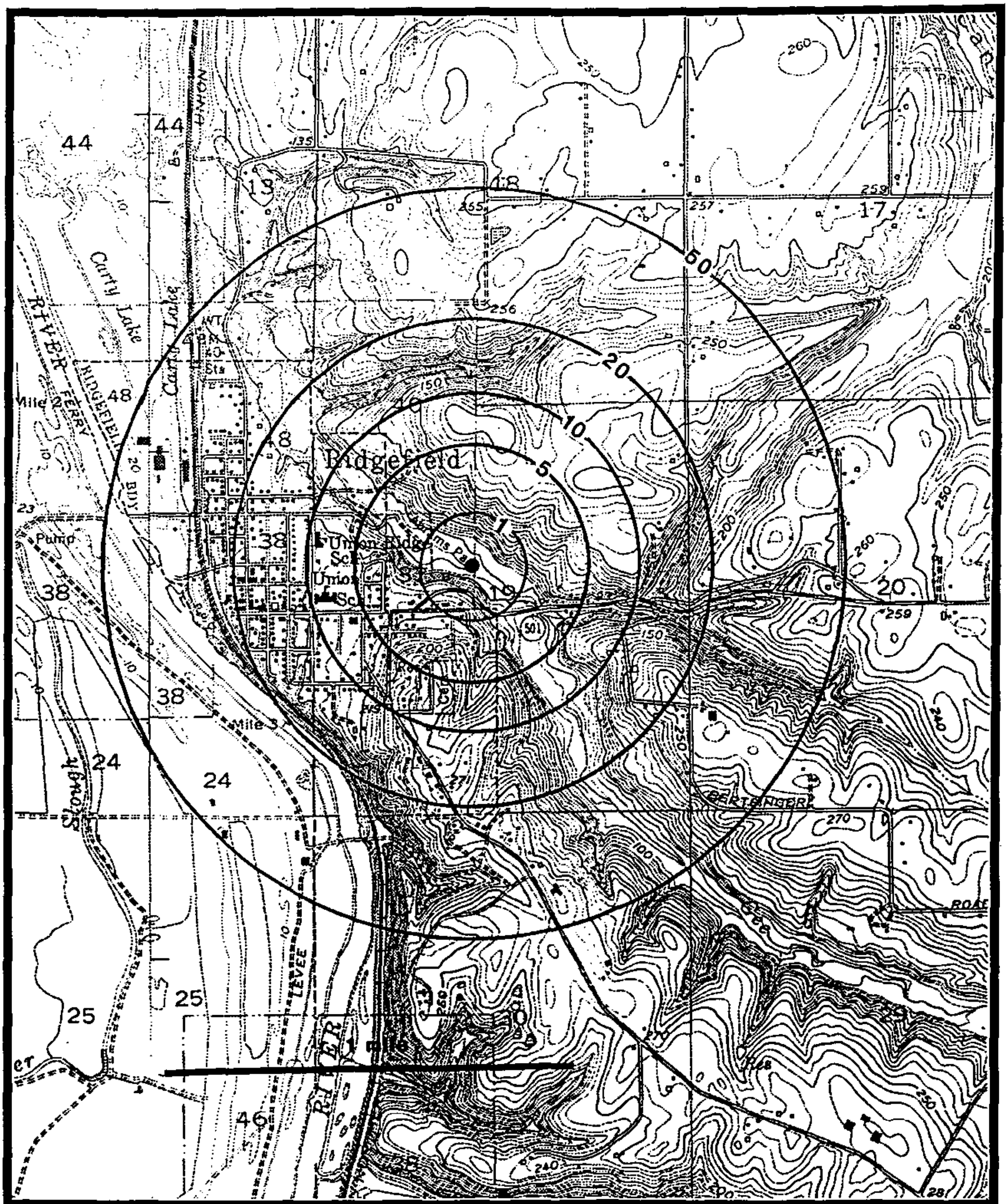

Figure RF-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution calculated for the combined pumping of Ridgefield wells 7, 8, and 9 using the volumetric flow equation.

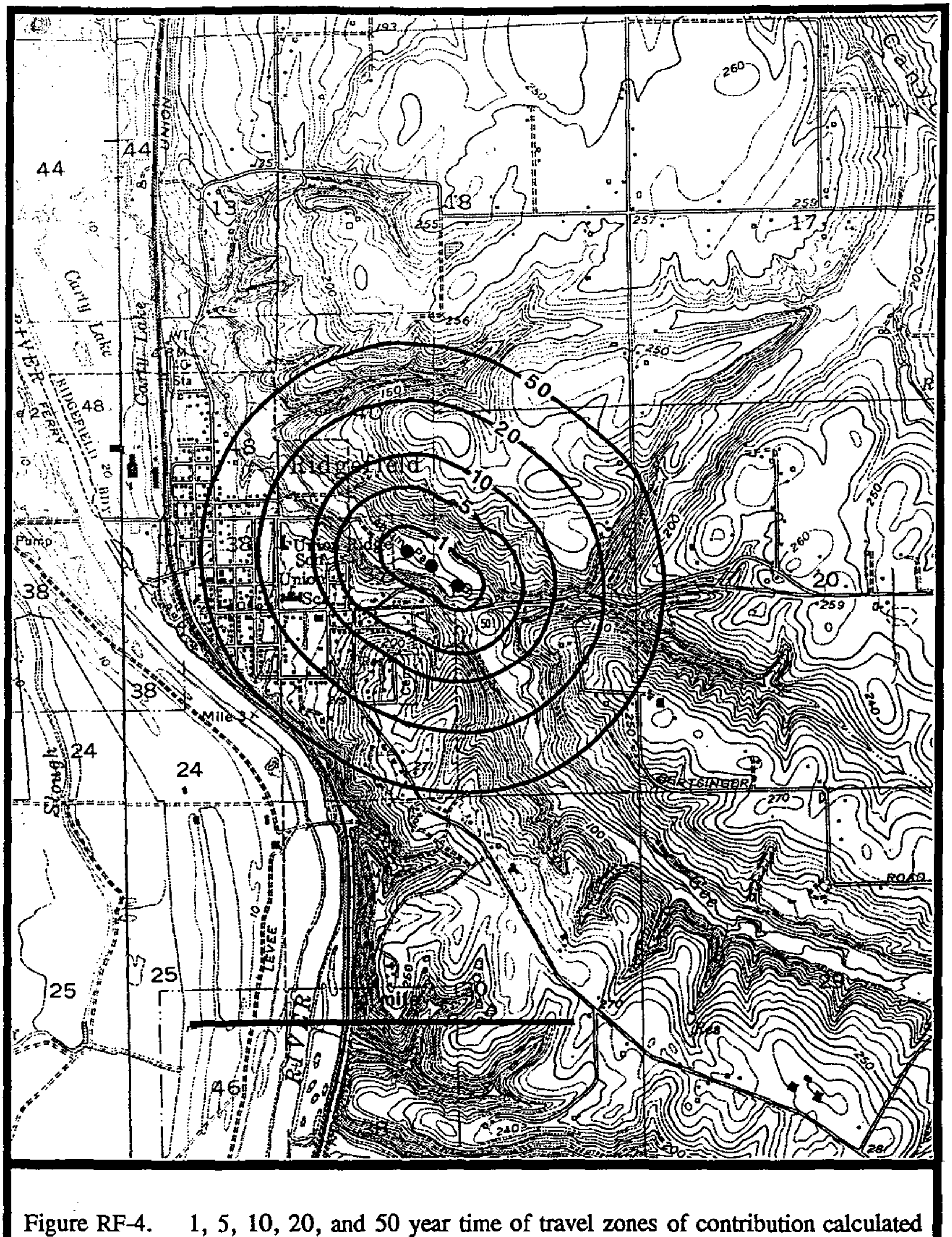

Figure RF-4. 1, 5, 10, 20, and 50 year time of travel zones of contribution calculated individually for Ridgefield wells 7, 8, and 9 using the volumetric flow equation.

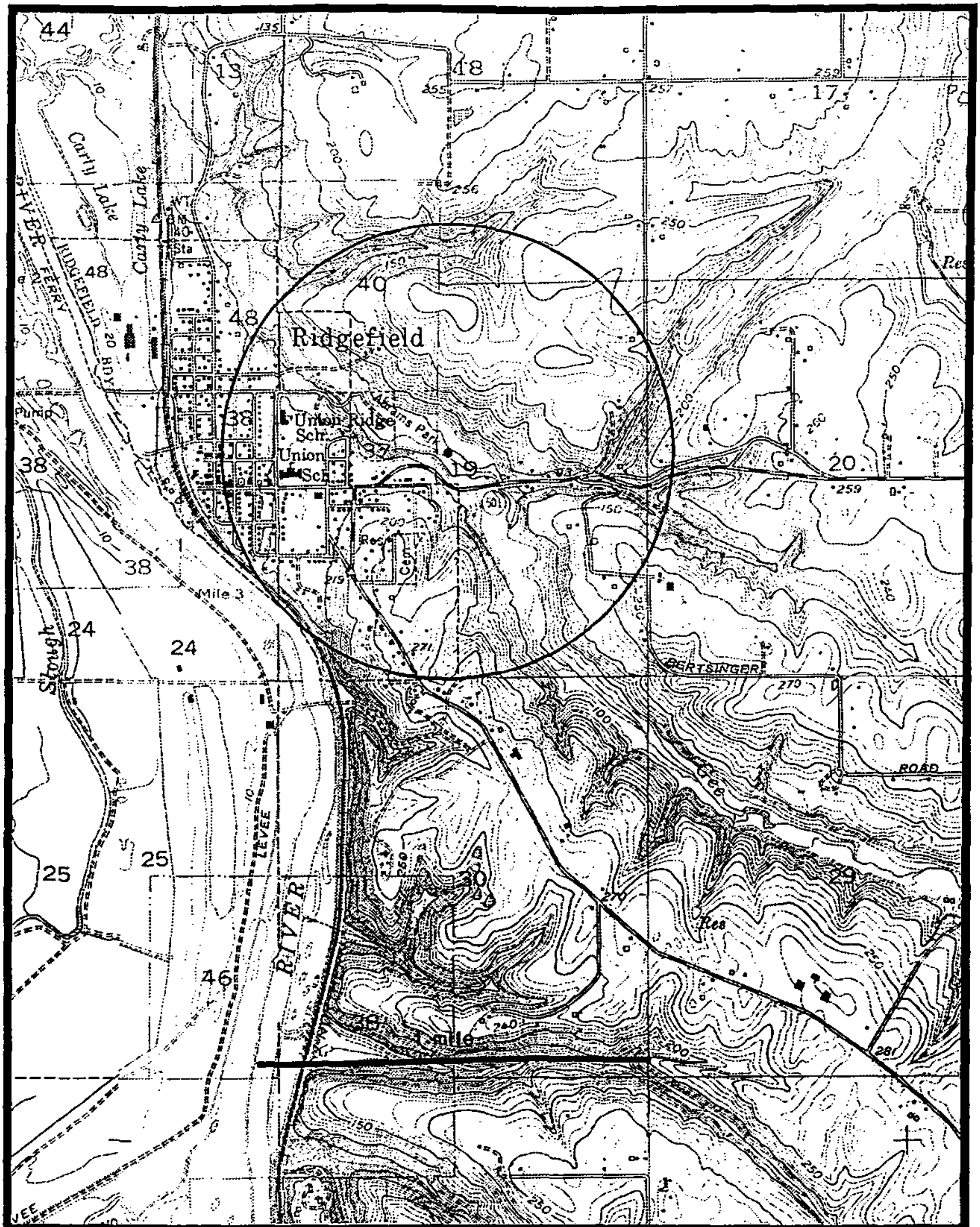

Figure RF-5. 3000 foot fixed radius delineation for Ridgefield wells.

Appendix J

WELLHEAD PROTECTION AREA DELINEATION REPORT

VANCOUVER WELL STATIONS 1, 3, AND 4

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix J
Wellhead Protection Area Delineation Report

Well: Vancouver Well Stations 1, 3, and 4

Setting: Vancouver Well Stations 1, 3, and 4 are principal water sources for the Vancouver water system. The wells are in the older part of Vancouver and are between one half and two miles from the Columbia River. The aquifer water level is near river level and the aquifer is in connection with the Columbia River. Along with the public supply use, there is a concentration of industrial pumpage in this area.

Well Stations 1, 3, and 4 are delineated together because they all use the same coarse sand and gravel deposits along the Columbia River and zones of contribution delineations are expected to interfere with each other.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: These wells are in a complex setting that can be characterized as a valley aquifer with uncertain valley wall boundaries. The aquifer is unconsolidated sand and gravel deposited by Pleistocene catastrophic flooding of the Columbia River.

The saturated extent of the unconsolidated gravel aquifer is controlled by the distribution of the Pleistocene catastrophic flood - gravel facies (the aquifer unit), the elevation of the top of the underlying Troutdale Formation, and the regional water table.

Since the aquifer mantles the Troutdale Formation, the thickness and distribution are to a large extent controlled by the upper surface of the Troutdale Formation. In the area of stations 1, 3, and 4 the Pleistocene deposits fill an older canyon cut over 150 feet below sea level into the Troutdale Formation, and have a total thickness over 250 feet. The saturated thickness is equal to the distance between the top of the Troutdale Formation and the level of the Columbia River, at about 8 feet above sea level. The top of the Troutdale Formation rises away from the Columbia to over 100 feet elevation two miles east of the wells, separating any saturated part of the catastrophic flood deposits from hydraulic connection with the Columbia River.

A comparison of the regional water table with the top of the Troutdale Formation mapped by Madin (1991) shows that the overlying catastrophic flood deposits may be unsaturated immediately up gradient from stations 1, 3, and 4. However, good data is scarce in this area and some uncertainty exists in describing the actual elevation of the top of the Troutdale Formation. This creates an uncertain boundary immediately up gradient of the wells, where there may be some flow through the aquifer, flow discharging from the underlying Troutdale Formation, or both.

Within the catastrophic flood deposits, a change in lithologic facies from predominantly coarse sand and gravel to finer sand and silt causes a decrease in hydraulic conductivity. This facies change has been mapped by Trimble (1963) and Madin (1991), and is evident from review of well record lithology and aquifer tests. This facies change roughly follows Burnt Bridge Creek, with finer material north and east of the creek.

Saturated aquifer thickness was determined by subtracting the elevation of top of Troutdale Formation (Madin, 1991) from the regional gravel aquifer potentiometric surface water level map drawn from USGS spring 1988 water level measurements.

The Columbia River and the Troutdale Formation act as controlling hydrogeologic boundaries. During pumping, water levels at stations 1, 3, and 4 stabilize a few feet below river level, suggesting the river is a recharge boundary south and west of the wells. The Troutdale Formation may act as a leaky valley wall boundary east and north of the wells. The Troutdale Formation, with bulk horizontal hydraulic conductivities ranging from about 10 feet/day to about 50 feet/day (US Geological Survey, written communication, 1990) is a much lower hydraulic conductivity unit than the catastrophic flood deposits, Robinson, Noble, and Carr (1980) show this in a diagrammatic cross section. This boundary is not well defined because good well information describing lithology is lacking.

The aquifer is considered to be semi-confined by overlying stratified silty gravel or sand.

Large amounts of industrial pumping occurs along the Columbia River shore in west Vancouver. The USGS has inventoried this use (Collins and Broad, 1991). Hydraulic effects of industrial pumping appear to be limited to the immediate area of the wells due to close proximity to the Columbia River (Mundorff, 1964).

Gradient and Flow Direction: Ground water gradient and flow direction were taken from a potentiometric surface map for the regional gravel aquifer made from spring 1988 water level measured by USGS. The average water level of the Columbia River was taken from hydrograph data in Mundorff (1964) and average water level elevation of the Columbia River in downtown Vancouver provided by National River Forecasting Center in Portland (Verbal communication, August, 1991).

Gradient is low in the aquifer, about 0.0003 between the 10 water level contour and the Columbia River. Up gradient from the wells, gradient steepens greatly. At the 20 foot water level contour, gradient is at least 0.01. Between the 20 and 50 foot water level contours, gradient is as much as 0.06. The increase in gradient corresponds with increasing elevation of the base of the Troutdale Formation. Flow direction is to the southwest.

Aquifer Properties:

Transmissivity: The Jacobs method was used to calculate a transmissivity of 878,900 gallons/day/foot (10,900 meters^2/day) for Well Station 3 and 586,000 gallons/day/foot (7,300 meters^2/day) for Station 4 (Robinson and Noble, Vancouver City records). Robinson and Noble (1982) report a transmissivity of 2,000,000 gallons/day/foot (24,800 meters^2/day) for Station 1.

Porosity: A porosity of 0.3 was estimated for the catastrophic flood deposits by comparing lithology descriptions to standard porosity values for aquifer materials (Heath 1983).

Pumping Rate: Daily average pumping rates were calculated from the total annual pumpage for the highest year of record. The Station 1 average was 1,200,000 feet^3/day (8,980,000 gallons/day or 34,000 meters^3/day) based on 3,276,000,000 gallons in 1990. Station 3 average was 293,000 feet^3/day (2,200,000 gallons/day or 8000 meters^3/day) based on 802,000,000 million gallons total pumpage in 1990. Station 4 average pumpage is 715,000 feet^3/day (5,350,000 gallons/day or 20,000 meters^3/day) based on a total annual pumpage of 1,953,000,000 gallons in 1988.

Delineation Analysis

Hydrogeologic Mapping: Hydrogeologic mapping based delineations for these wells involved several steps. The hydrogeologic setting was described using available geologic and hydrogeologic maps and well record data from the City wells. This included defining the saturated extent of the aquifer unit, defining the hydrogeologic boundaries, and defining regional ground water flow direction.

Delineations were made using a combination of analytical modeling and hydrogeologic mapping. The EPA WHPA GPTRAC (EPA, March, 1991) model was used to define time related zones of contribution in the low gradient part of the aquifer near the wells and between the wells and the Columbia River. Upgradient from the wells, gradient increases greatly and aquifer media may be either the Troutdale Formation or more permeable Pleistocene deposits. Up gradient travel times were calculated for both the Troutdale Formation and the Pleistocene deposits using the Darcy velocity equation.

The 20 foot water level contour was used as the boundary approximate up gradient extent of the aquifer and as the point where Darcy velocity calculations away from the aquifer began. This line was used because it is the point at which the gradient begins to steepen, approximates the unsaturated edge of the aquifer, and is a feature that is easy to map. The gradient increases from 0.002 at the 20 foot contour to 0.1 500-1000 feet away from 20 foot water level contour.

The delineation map (Figure VA-134-1) includes aquifer contribution zones for different times based on analytical models and velocity calculations up gradient from the well. Travel times were calculated for both the Pleistocene deposits and the Troutdale Formation to give both the fastest velocities (Pleistocene deposits) and slower velocities (Troutdale Formation). Only the travel times in the Pleistocene deposits were mapped in Figure VA-134-1. Upgradient time of travel zones were calculated for 5, 10, 20, and 50 years in the Troutdale Formation and 1, 5, 10, 20, and 50 years in the catastrophic flood deposits.

Travel times were calculated for a set of flow paths up gradient from the 20 foot water level contour. Travel time between water level map contours were calculated and specified travel time contours were drawn by linear interpolation between travel times at water level contours. The two distinct catastrophic flood deposit facies were assigned differing hydraulic conductivities. The gravel facies was assigned a value of 150 feet/day and the sand and silt facies was assigned a hydraulic conductivity of 75 feet/day. A porosity of 0.3 was assigned to the catastrophic flood deposits. A hydraulic conductivity of 15 feet/day and a porosity of 0.2 was used for the Troutdale Formation. Hydraulic conductivities were estimated from pump test data and Portland Basin Ground Water Flow Model hydraulic conductivity values (written communication, USGS, 1991). Porosity was based on general properties of aquifer materials (Heath, 1983). The contact between fine and course Pleistocene deposits was taken from Madin (1991).

Several analytical model simulations of the Pleistocene deposits aquifer were tested using GPTRAC and RESSQC (EPA, March, 1991). The principal goal was to model the up gradient aquifer boundary, the interfering effects of the wells, and the Columbia River recharge boundary. A secondary consideration was the effect of industrial supply wells along the Columbia River.

No single WHPA model simulation was able to do this. However, the GPTRAC strip aquifer model was able to simulate conceptualized conditions at Stations 1 and 3 fairly well. The GPTRAC strip aquifer model did not work well for station 4 because of problems simulating up gradient barriers, and nonparallel stream and barrier boundaries at Station 4. The GPTRAC strip aquifer is an option that simulates an aquifer with parallel boundaries. These boundaries can include any combination of fully penetrating stream or barrier boundaries as might be found in an valley alluvium aquifer. The use of image wells to simulate one of the boundaries might be a good approach to attempt at Station 4.

The first simulations tested the effects of industrial pumping and well interference using a GPTRAC strip aquifer model and pumpage data from USGS (Collins and Broad, 1991). Results showed that the industrial pumping made small zones of contribution between the pumping wells and adjacent Columbia River. Figure VA-134-2 is a 20 year time of travel delineation for all the industrial and public supply wells in the aquifer.

Industrial pumping was not included in subsequent modeling because the effects were limited mainly to area outside the 20 year delineation; also the elimination of industrial sites from the public supply well zones of contribution by industrial supply pumping would end if pumping ceased at the site.

Two models were used to complete the delineation in Figure VA-134-1. A GPTRAC strip aquifer model simulating both a barrier at the up gradient extent of the aquifer and the fully penetrating Columbia River delineated 1, 5, 10, 20, and 50 year time of travel zones of contribution for Stations 1 and 3. Station 4 was modeled using a simpler GPTRAC model simulating the fully penetrating Columbia River and interference from Station 1.

Values used in the models were:

Transmissivity:	8,300 meters^2/day
Barrier Boundary:	20 foot water level contour

Pumping rate:
    Station 1: 34,000 meters^3/day
    Station 3: 8,300 meters^3/day
    Station 4: 20,000 meters^3/day
Gradient: 0.0003
Flow angle: -90° (relative to barrier boundary)
Thickness: 42 meters
Porosity: 0.3
Time of travel: 1, 5, 10, 20, and 50 years

Analytical Models: Analytical models were used in conjunction with hydrogeologic mapping due to limited aquifer extent and complex boundary conditions. The principal problem with using the analytical models is the "leaky" barrier boundary associated with the up gradient transmission from a thick high transmissivity aquifer to a very thin high transmissivity aquifer overlying a less permeable aquifer.

Calculated Fixed Radius: Figure VA-134-3 shows calculated fixed radius delineations for Stations 1, 3, and 4 using the volumetric flow equation (EPA, June, 1987). This delineation does not consider well interference.

Values selected were:

Station 1

Pumping rate: 437,938,000 feet^3/year (3276.0 mg/y)
Porosity: 0.3
Length of well screen: 62 feet
Times of travel: 1, 5, 10, 20, and 50 years

Station 3

Pumping rate: 107,212,000 feet^3/year (802.0 mg/y)
Porosity: 0.3
Length of well screen: 28 feet
Times of travel: 1, 5, 10, 20, and 50 years

Station 4

Pumping rate: 261,078,000 feet^3/year (1953.0 mg/y)
Porosity: 0.3
Length of well screen: 16 feet
Times of travel: 1, 5, 10, 20, and 50 years

Fixed Radius: Figure VA-134-4 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: See Appendix S.

Three Dimensional Regional Model: See US Geological Survey map report.

References Cited:

Collins, C.A. and T.M. Broad, 1991, Estimated Average Annual Ground-Water Pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 91-4018.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington,D.C., EPA 440/6-87-010.

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Mundorff, M.J., 1964, Geology and Ground-Water Conditions of Clark County, Washington, with a Description of a Major Alluvial Aquifer Along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268p., 3 pls.

Robinson, Noble, & Carr Inc., July, 1980, City of Vancouver Ground Water Source and Use Study: Volumes I and II, Tacoma, Washington.

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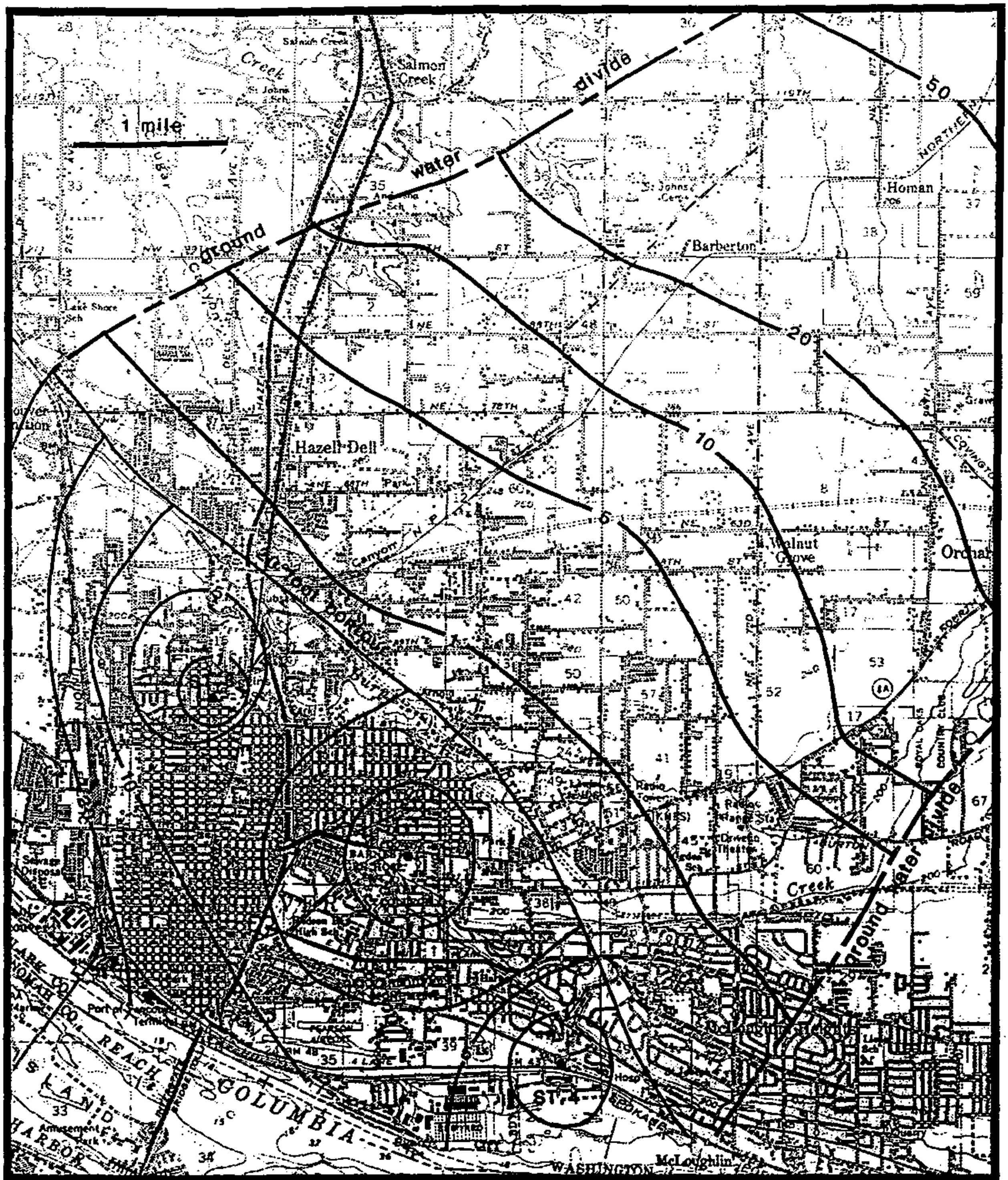

Figure VA-134-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution for Vancouver well stations 1, 3, and 4 using analytical models in the aquifer (below 20 foot contour) and hydrogeologic mapping up gradient from the aquifer (above 20 foot contour).

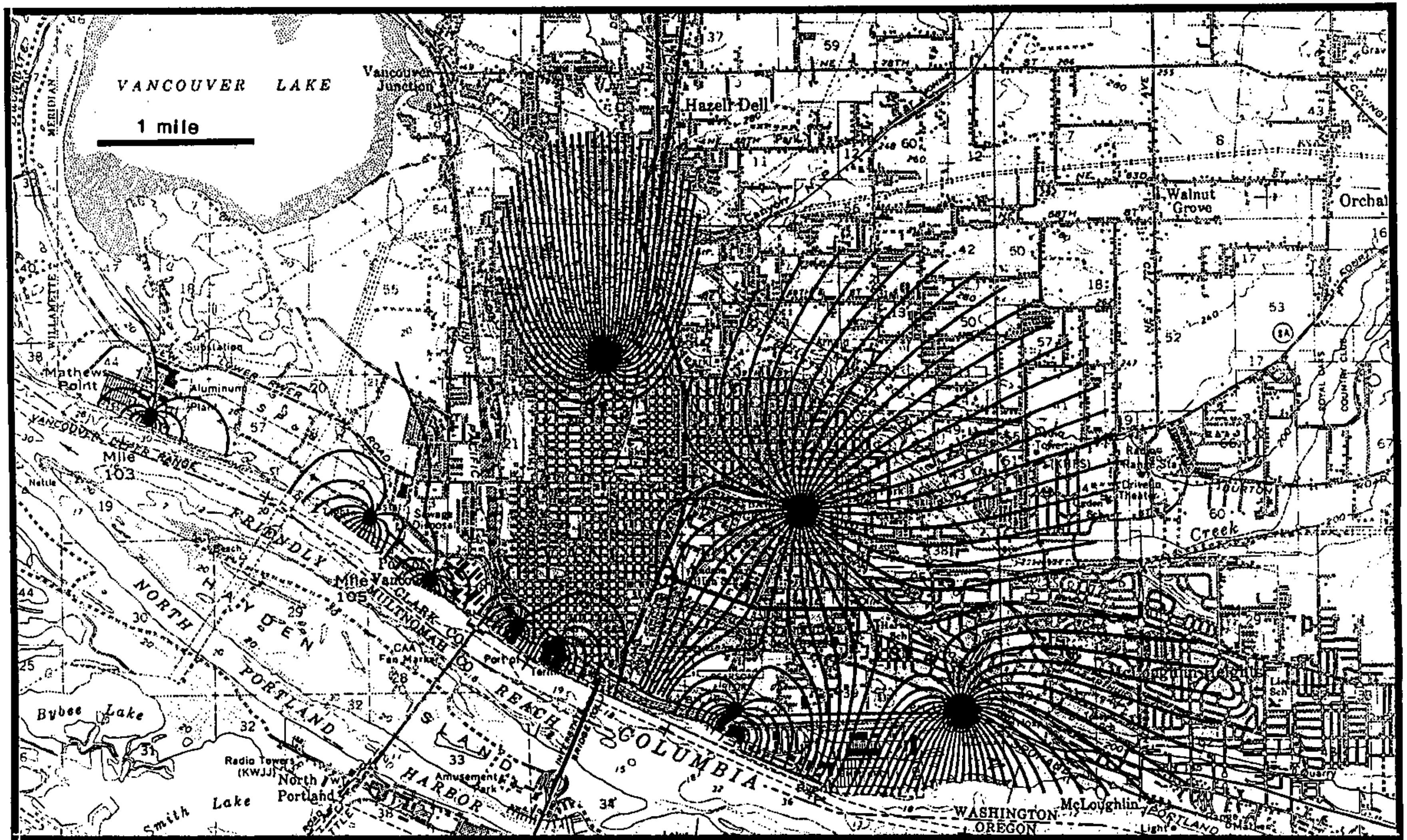

Figure VA-134-2. 20 year time of travel delineation using GPTRAC strip aquifer model for all the industuial and public supply wells in the aquifer

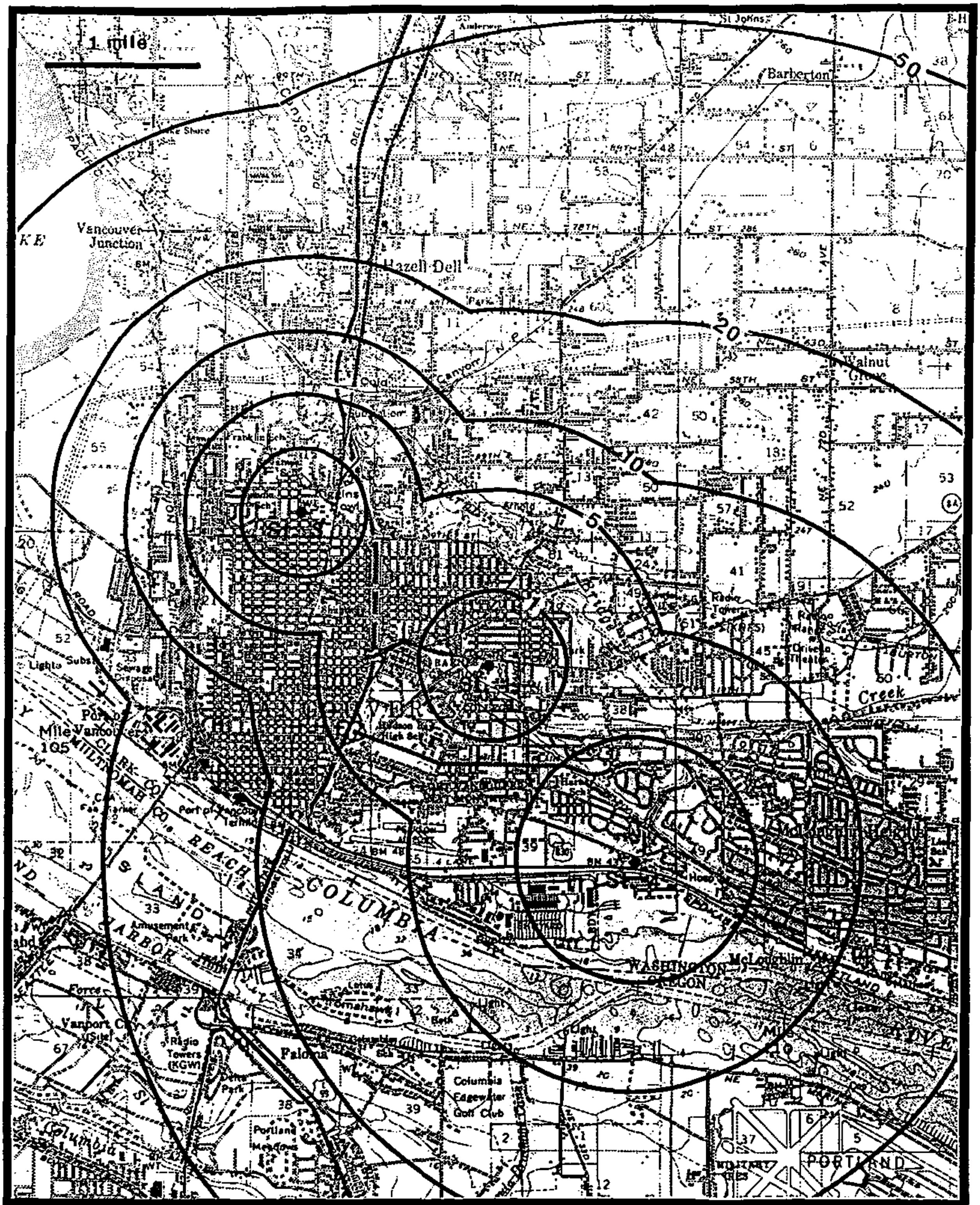

Figure VA-134-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution for Vancouver well stations 1, 3, and 4 using the volumetric flow equation.

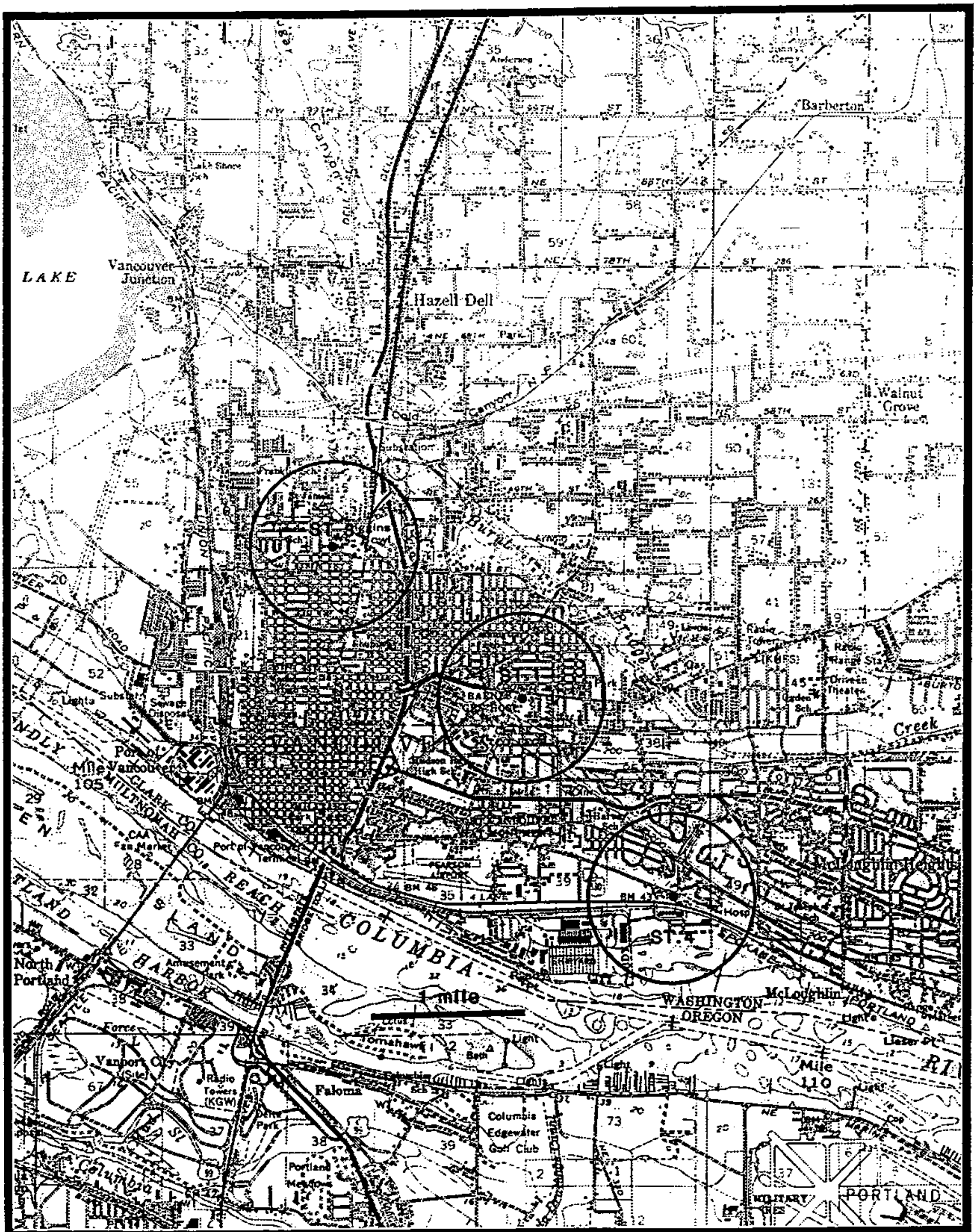

Figure VA-134-4. 3000 foot fixed radius delineation for Vancouver Stations 1, 3, and 4.

Appendix K

WELLHEAD PROTECTION AREA DELINEATION REPORT

VANCOUVER WELL 7.1

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix K
Wellhead Protection Area Delineation Report

Well: Vancouver Well 7.1

Setting: Vancouver Station 7 is on a flat ridge between Burnt Bridge Creek and the Columbia River. The wellhead is at about 311 feet elevation. The well evaluated, 7.1, is the only active supply well at Station 7. The well is completed in the semiconsolidated sandy gravel of the upper Troutdale Formation.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: The aquifer is very extensive and has been mapped by Mundorff (1964), Trimble (1963) and Swanson and others (1991). Swanson and others describe the thickness of this regional consolidated gravel aquifer. The aquifer extends from beneath the Columbia River flood plain to the foot of the Cascade Mountains. Aquifer thickness varies regionally but in the area of the well is about 350 feet (110 meters) thick.

The upper Troutdale Formation is underlain by less permeable silty, clayey sand that are the upper part of the lower member of Troutdale Formation. The aquifer is overlain by the catastrophic flood deposits sandy gravel facies. The upper Troutdale Formation aquifer is semiconfined. Water levels are usually above the unit, but a downward flow gradient is observed by comparing water levels in wells of varying depth. No other large production wells are nearby Station 7. The closest large capacity wells are at Evergreen Memorial Gardens, about one quarter mile to one half mile south of Station 7.

Gradient and Flow Direction: A water level contour map for the regional gravel aquifer drawn from spring 1988 water level measurements was used to estimate gradient and flow direction. The gradient is between 0.002 and 0.0025 with flow to the south.

Aquifer Properties:

Transmissivity: A transmissivity of about 18,000 gallons/day/foot (230 meters^2/day) was estimated from a specific capacity of 7.5 gallons/minute/foot drawdown and an estimated storage coefficient of 0.001 using the graphic method described by Theis and others (1964).

Porosity: Porosity is estimated as 0.2 by comparing well record and field descriptions of aquifer lithology to standard porosity values for aquifer materials Heath, 1983).

Pumping Rate: A daily average pumping rate of 3,800 meters^3/day was calculated for well 7.1 from 364,000,000 gallons total annual pumpage for the highest year of record (1988).

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define aquifer extent, direction, gradient, and any boundaries. The EPA WHPA models (EPA, March, 1991) were deemed to be a more appropriate means to define time related zones of contribution for the uniform, low gradient conditions at this well.

Analytical Models: The WHPA version 2 RESSQC model (EPA, March, 1991) was used to delineate zones of contribution for 1, 5, 10, 20, 50 years (Figure VA-7.1-1). The delineations are conservative because the RESSQC model does not consider recharge or vertical leakage effects. RESSQC is quicker to use than GPTRAC because multiple times of travel can be calculated by a single model. Aquifer properties were taken from well tests at Station 7.

Values used in the model were:

Transmissivity:	230 meters^2/day
Pumping rate:	3,800 meters^3/day
Gradient:	0.002
Flow angle:	-80° (170° compass bearing)
Porosity:	0.2
Aquifer thickness:	110 meters
Time of travel:	1, 5, 10, 20, and 50 years

Calculated Fixed Radius: Figure VA-7.1-2 shows calculated fixed radii for 1, 5, 10, 20, and 50 years using the volumetric flow equation (EPA, June,1987).

Values selected were:

Pumping rate:	49,000,000 feet^3/year (364.0 mg/y)
Porosity:	0.2
Length of well screen:	35 feet
Times of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure VA-7.1-3 shows the 3000 fixed radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: See the US Geological Survey map report.

Cited References:

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington, D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: United States Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

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Swanson, R.D., W.D. McFarland, J.B. Gonthier, and J.W. Wilkinson, 1991, A Description of Hydrogeologic Units in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90-4196.

Theis, C.V., R.H. Brown, and R.R. Meyer, 1963, Estimating the Transmissivity of Aquifers from the Specific Capacity of Wells: U.S. Geological Survey Water Supply Paper 1536-I, pp.

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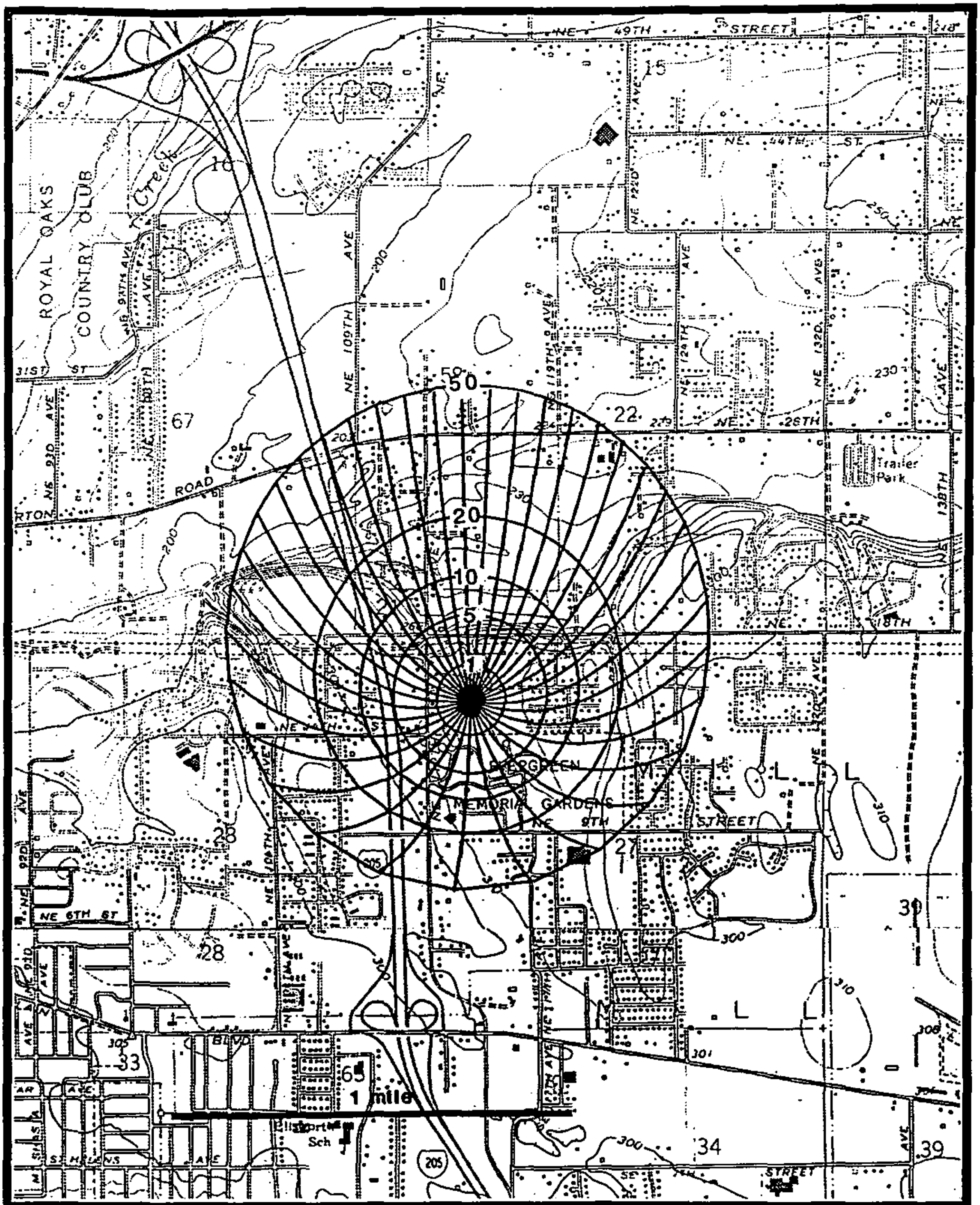

Figure VA-7.1-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution for Vancouver well 7.1 using EPA RESSQC WHPA model.

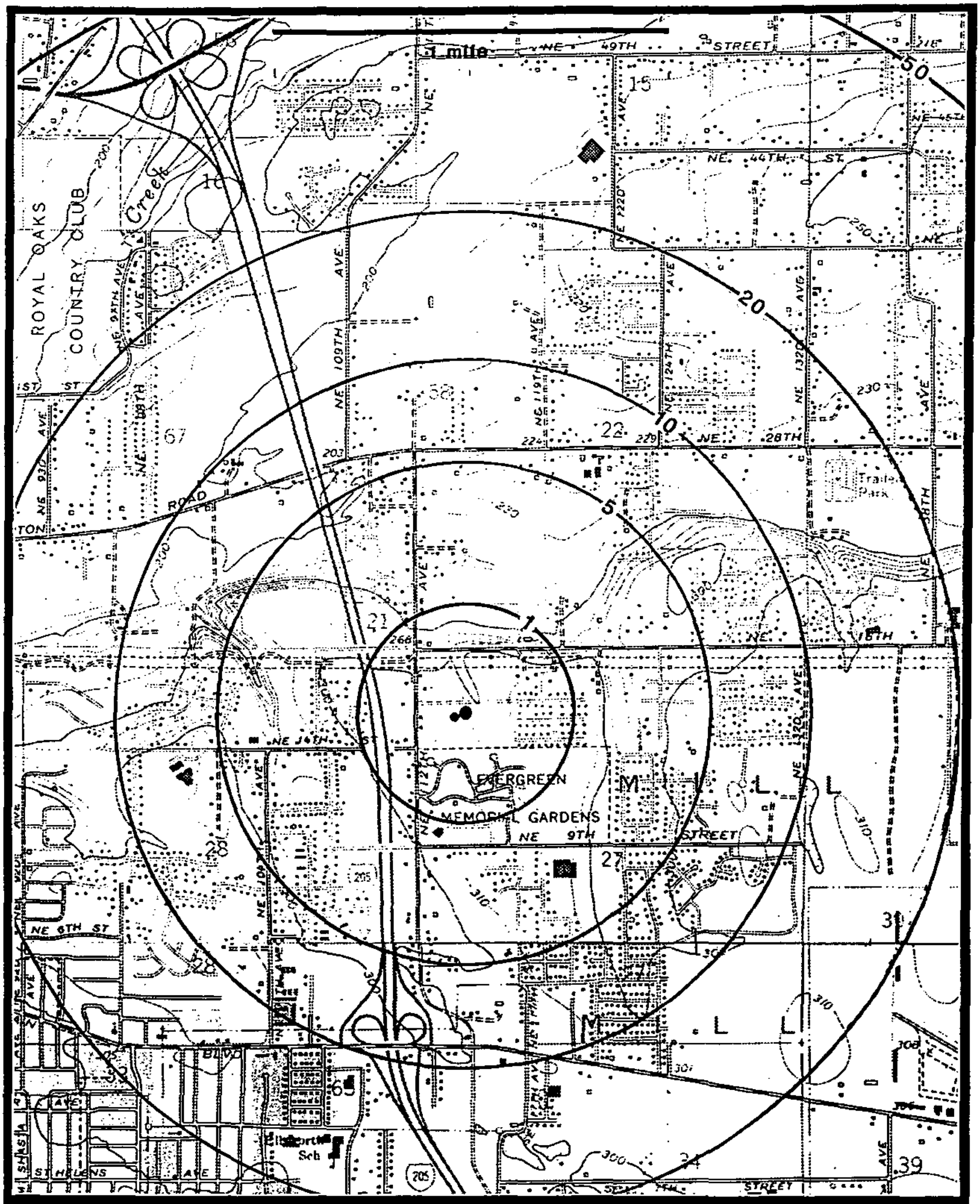

Figure VA-7.1-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

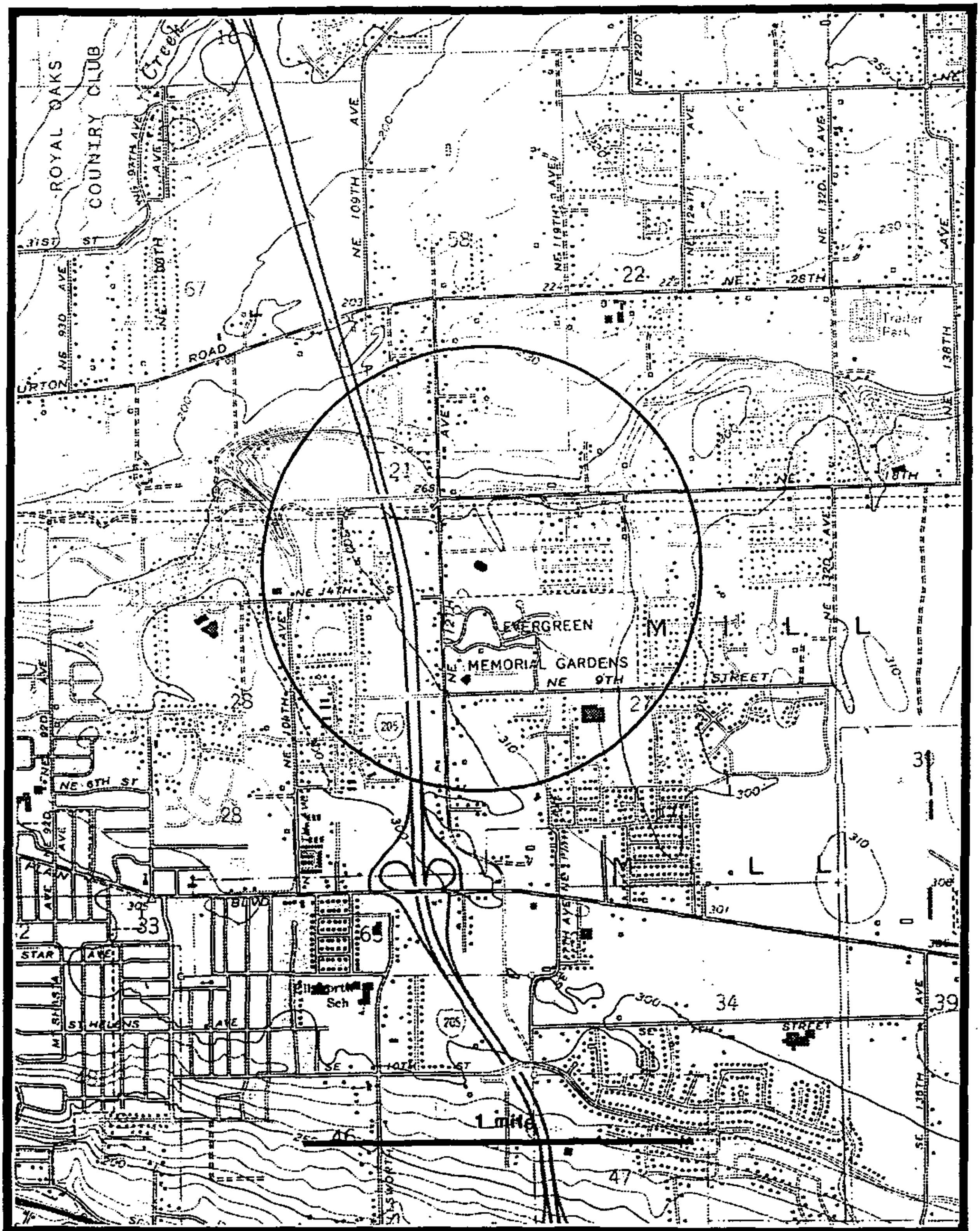

Figure VA-7.1-3. 3000 foot fixed radius delineation for Vancouver Station 7.1.

Appendix L

WELLHEAD PROTECTION AREA DELINEATION REPORT

VANCOUVER WELL 7.2, THE ELLSWORTH SPRINGS WELL AND STATE HATCHERY WELLS

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix L
Wellhead Protection Area Delineation Report

Well: Vancouver Well 7.2, Vancouver Ellsworth Springs Well, and State Hatchery Wells

Setting: Vancouver well 7.2, the Vancouver Ellsworth Springs well, and the two deep State Fish Hatchery wells are in south central Clark County. The wells are grouped together for delineation because they are in the same aquifer and are relatively close to each other. The State Hatchery Wells are included in the delineation analysis because the high projected pumpage at these wells will affect the ground water gradient around the Vancouver wells.

None of these wells are currently in use. The city plans to develop the deep aquifer at Station 7 and at the Ellsworth Springs site. The Fish Hatchery plans to use their two deep wells at near full capacity when water rights are obtained.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Vancouver well 7.2, the Vancouver Ellsworth Springs well, and State Hatchery well are the deepest water wells in Clark County, penetrating deep into the lower Troutdale Formation. Robinson and Noble (1990) identified a deep sand aquifer from 860 feet to 1095 feet depth in Vancouver well 7.2 and from 835 feet to 1065 feet depth in the Ellsworth Springs well. This deep sand aquifer appears to extend southward beneath the Columbia River into the Portland area based on deep well information from the Portland well field. Aquifer extent in Clark County is not known. However, the large thickness of the aquifer where it is penetrated suggests that the unit could extend well beyond the area where it is currently mapped. Aquifer thickness is uniform, at about 230 feet.

The aquifer is overlain by about 500 feet of lower Troutdale Formation stratified silt, clay and sand. This greatly slows vertical flow from the surface to the aquifer.

One other well in Clark County, at SEH America, is completed in the aquifer. Across the Columbia River, the intermittently used City of Portland municipal well field may affect the aquifer because some Portland wells may be completed in the aquifer. Also, large rates of pumpage in other shallower confined Portland well field aquifers may also affect water levels in the deep aquifer.

Gradient and Flow Direction: The water level data reported for deep wells by Robinson and Noble (1990) were combined with other deep well data to estimate the potentiometric surface gradient as 0.001 and flow direction as 210 degrees compass bearing.

Aquifer Properties:

Transmissivity: Robinson and Noble (1990) calculated a transmissivity of 114,000 gallons/day/foot (1,400 meters^2/day) for Vancouver Station 7 Well 2 using single well recovery data for the well. A transmissivity about 45,000 gallons/day/foot (560 meters^2/day) was calculated from single well recovery data from the Ellsworth Springs well (Golder Associates, May, 1985).

Porosity: A porosity of 0.2 was estimated by comparing well record lithology descriptions to tabulated standard porosity values for aquifer materials (Heath, 1983).

Pumping Rate: Projected pumping rates are used for all wells because they are not yet in service. Estimated average pumping rates for the year 2000 (City of Vancouver, written communication) were used for the Vancouver supply wells. These rates are 184,000,000 gallons/year (1,900 meter^3/day) for well 7.2, and of 1,097,000,000 gallons/year (11,400 meter^3/day) for the Ellsworth Springs well. Fish hatchery staff reported an estimated average total pumping rate of 1,750 gallons/minute or 2,520,000 gallons/day (9,500 meter^3/day) when these wells come on line.

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping methods were used principally to define the aquifer extent, direction and gradient of ground water flow, and identify any boundaries. One conclusion from mapping is that the aquifer is overlain by a thick sequence of fine grained sediment, giving it low hydrogeologic susceptibility to contamination.

Analytical Models: Simple near confined boundary conditions and general aquifer uniformity make analytical models appropriate. Delineations were done using the EPA WHPA Version 2 RESSQC and MWCAP models (EPA, March, 1991).

The RESSQC model was used to simulate well interference effects. Figure VA-DP-1 shows the results of the RESSQC simulation. The model uses a single set of aquifer properties for thickness, porosity, transmissivity, gradient, and flow direction. The most variable parameter between wells is transmissivity. Transmissivity for Vancouver Well 7.2 is 114,000 gallons/day/foot, while the Ellsworth Springs Well is 45,000 gallons/day/foot. The difference in transmissivity may be due to differences in the amount of aquifer screened in each well and variation in hydraulic properties within the aquifer. The higher transmissivity well, Vancouver Well 7.2 is screened in less of the aquifer, 137 feet. While the Ellsworth Spring Well is open to almost the entire aquifer thickness, 225 feet. Presumably, the longer screened interval in the Ellsworth Springs well would include more fine grained material. The transmissivity from the Ellsworth Springs was deemed to be most representative of the entire aquifer and used for delineation.

MWCAP was used as an alternate approach to model the wells without interference effects. Figure VA-DP-2 shows the results from MWCAP modeling of Well 7.2 and the Ellsworth Springs Well.

Values selected for the RESSQC model were:

Transmissivity:	560 meters^2/day
Pumping rate:	11,400 meters^3/day for Ellsworth Springs Well, 1,900 meters^3/day for Station 7 Well 2, and 9,500 meters^3/day for Hatchery Well
Gradient:	0.001
Flow angle:	-120° (210° compass bearing)

Porosity: 0.2
Aquifer thickness: 70 meters
Time of travel: 1, 5, 10, 20, and 50 years

Values selected for the MWCAP model were:

Transmissivity: 560 meters^2/day
Pumping rate: 11,400 meters^3/day for Ellsworth Springs Well, 1,900 meters^3/day for station 7 Well 2
Gradient: 0.001
Flow angle: -120° (210° compass bearing)
Porosity: 0.2
Aquifer thickness: 70 meters for Ellsworth Springs Well, 72 meters for Station 7 Well 2
Time of travel: 1, 5, 10, 20, and 50 years

Calculated Fixed Radius: Figure ES-1 and Figure VA-7.2-1 show calculated fixed radii delineations made using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulation volumetric flow equation.

Values selected were:

Pumping rate: 48,700,000 feet^3/year (184.0 mg/y) for Well 7.2
146,648,000 feet^3/year (1,097.0 mg/y) for Ellsworth Springs well
Porosity: 0.2
Length of well screen: 137 feet at 7.2
165 feet at Ellsworth Springs
Times of travel: 1, 5, 10, 20, and 50 years

Fixed Radius: Figure VA-DP-3 shows the 3000 fixed radius delineation for Vancouver Station 7.2 and the Ellsworth Spring Well. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Not done for this well.

Three Dimensional Regional Model: Refer to US Geological Survey map report.

Cited References:

Golder Associates, May, 1985, Geotechnical report for the Ellsworth Springs test well.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington,D.C., EPA 440/6-87-010.

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Robinson, Noble, & Carr Inc., July, 1980, City of Vancouver Ground Water Source and Use Study: Volumes I and II, Tacoma, Washington.

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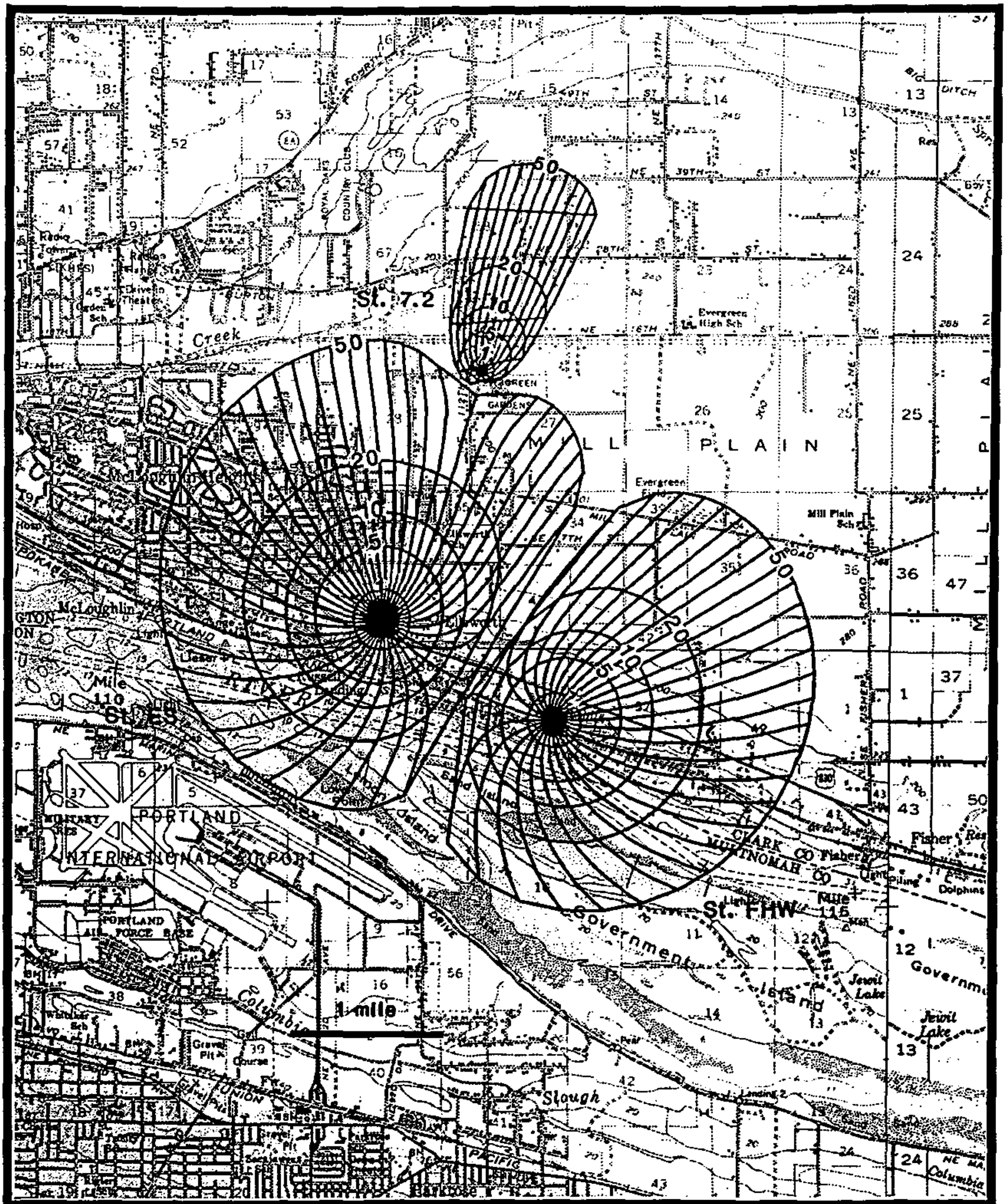

Figure VA-DP-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution for Vancouver well 7.2, the Vancouver Ellsworth Spring well, and the State Hatchery wells using the EPA RESSQC WHPA model.

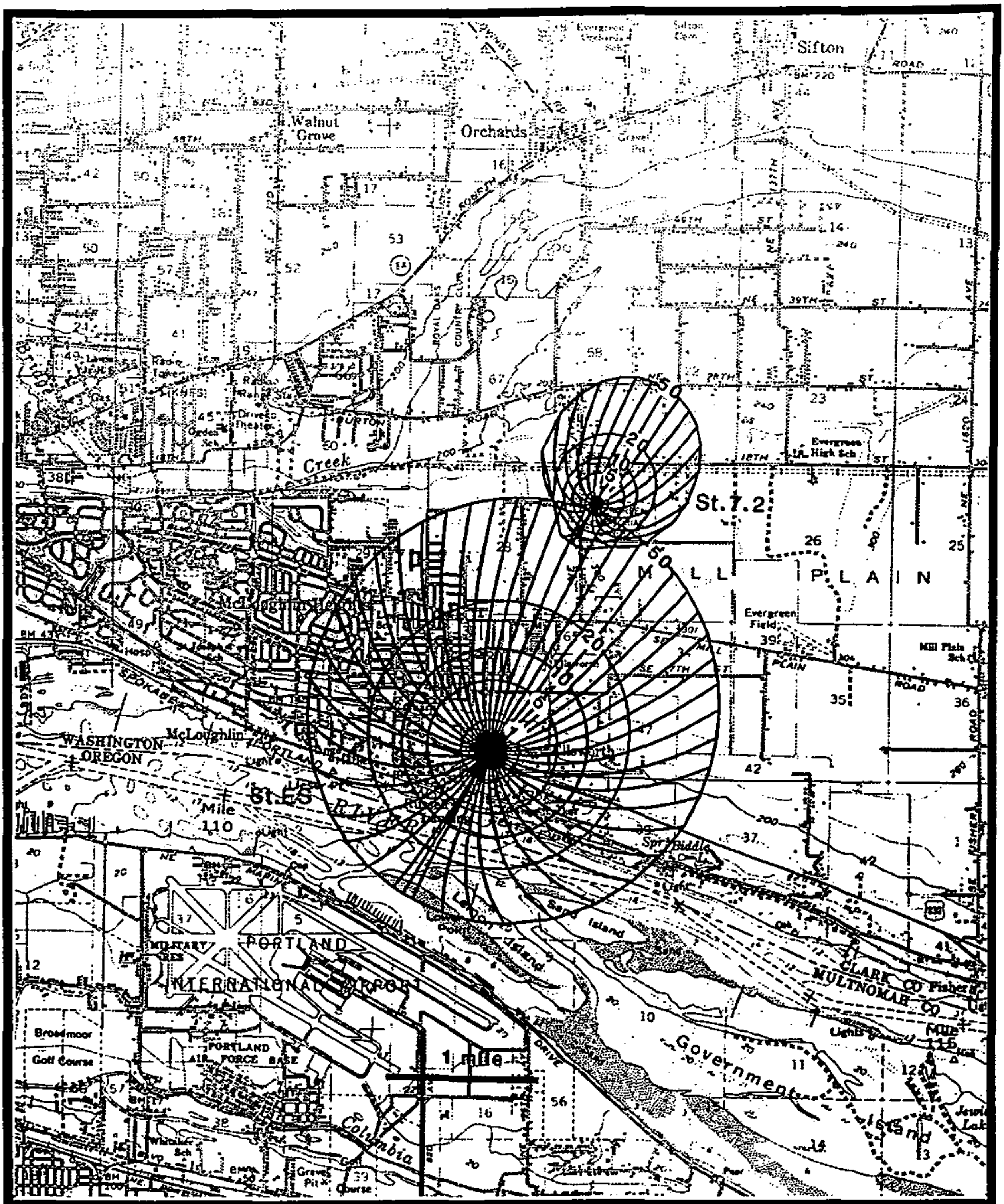

Figure VA-DP-2. 1, 5, 10, 20, and 50 year time of travel zones of contribution for Vancouver well 7.2, the Vancouver Ellsworth Spring well using the EPA MWCAP WHPA model.

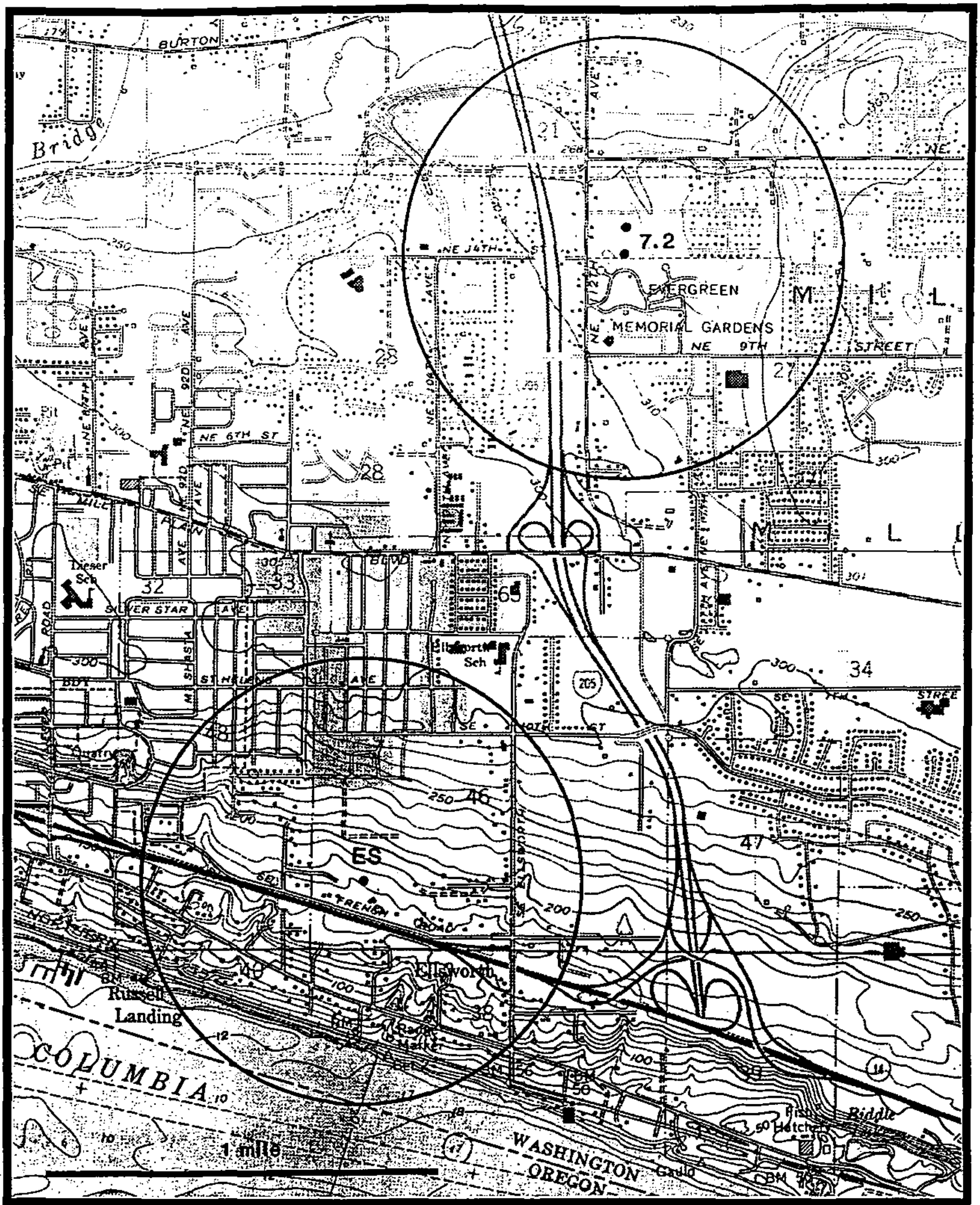

Figure VA-DP-3. 3000 foot fixed radius delineation for Vancouver Station 7.2 and the Ellsworth Springs well.

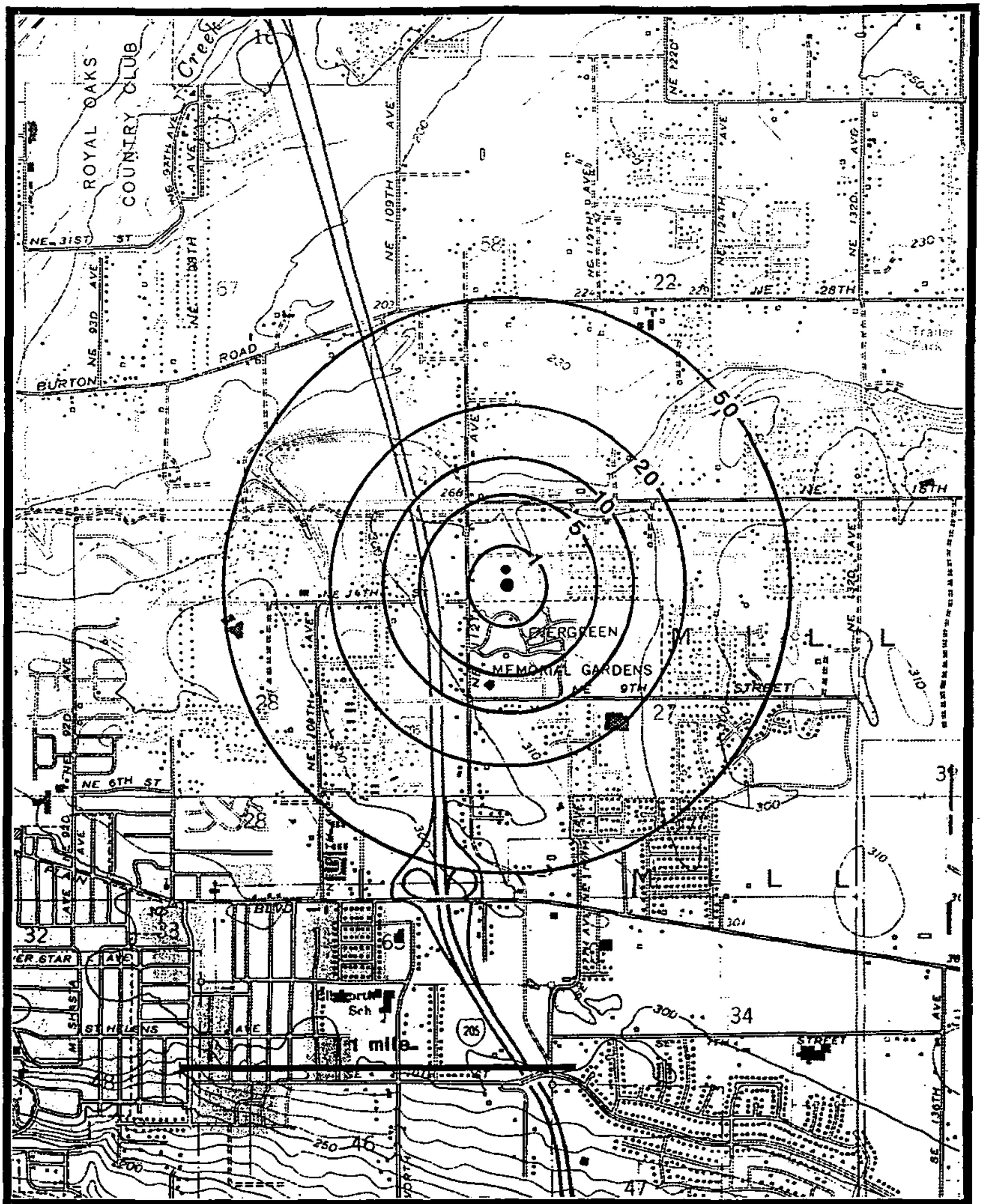

Figure VA-7.2-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation.

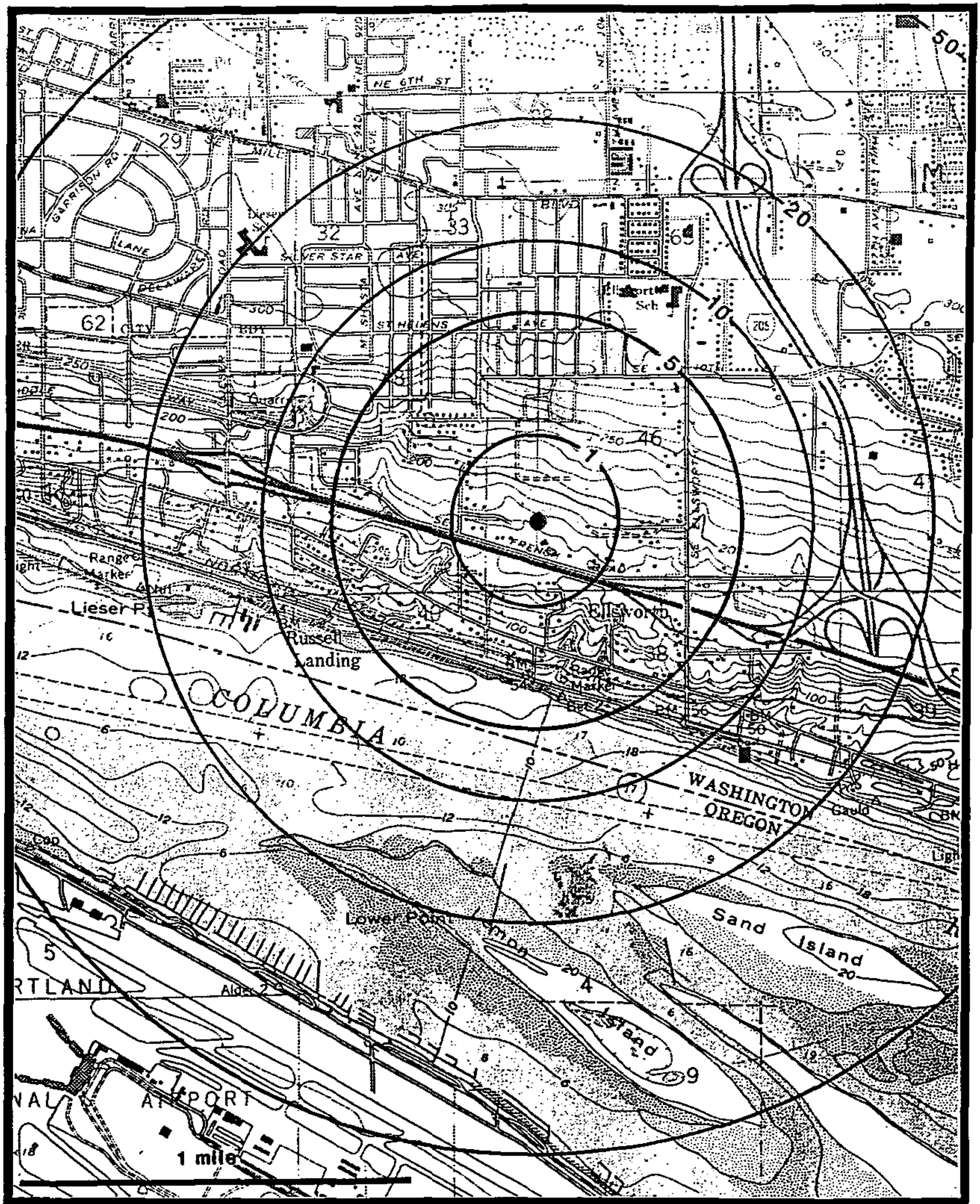

Figure ES-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation for Ellsworth well.

Appendix M

WELLHEAD PROTECTION AREA DELINEATION REPORT

VANCOUVER WELL STATION 8

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix M
Wellhead Protection Area Delineation Report

Well: Vancouver Well Station 8

Setting: Well Station 8 is on the east edge the town of Orchards near Interstate Highway 205. The wells are at about 220 feet elevation on a gentle slope toward Burnt Bridge Creek. The wells tap a high transmissivity gravel aquifer that extends several miles up gradient from Station 8.

There are three wells at Station 8. Wells 1 and 2 are 106 and 109 feet deep, well 3 is 200 feet deep. The deeper well, number 3 is the principal source at Station 8. Wells 1 and 2 are used only during wet winter months when rainfall infiltration limits the interference to nearby domestic wells.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: The wells tap two separate water bearing zones in the high yield Pleistocene gravel aquifer that lies above the Troutdale Formation cemented gravel. The distribution of this aquifer coincides with the distribution of Pleistocene catastrophic flood deposits - gravel and sandy gravel facies. The catastrophic flood deposit gravel distribution was mapped by Trimble (1963) and Madin (1991). Well record data from high capacity wells were also used to define aquifer extent.

A total unit thickness is determined based on the bottom of the lower high yield zone and the top of the gravel or regional water table. At Station 8 the total thickness is 125 feet. Individual high yield zones can be identified at Station 8. The upper zone is the water table aquifer and thickness varies with changes in the season and pumping rates. Spring water levels indicate that the upper aquifer is about 32 feet thick. The lower high yield zone tapped by well 3 is 93 feet thick. Static water levels in well 3 are generally deeper than water levels in wells 1 and 2 indicating a downward gradient. The City does not know of any tests of the vertical connection between shallow and deep wells at Station 8 or any other well field (verbal communication, T. McClure, August, 1991).

Boundaries are not clearly defined for separate water bearing zones at Station 8 because they are characterized by hydraulic properties, instead of an identifiable well cutting lithology. The high yield gravel units appear to thin out or become indistinguishable from the Troutdale Formation near the margin of the Pleistocene catastrophic flood deposits gravel facies. Burnt Bridge Creek does not appear to have much influence on the regional gravel aquifer because the stream bed is on several feet of fine grained sediment separating the stream system from the gravel aquifer. The upper water bearing zone is recharged directly by infiltration through soil. The deeper water bearing zone is recharged by infiltration through the overlying silty and sandy gravel. Other than Vancouver Well Stations 14 and 9, no other large scale ground water users are in the vicinity of Station 8 (Collins and Broad, 1991).

Gradient and Flow Direction: Gradient and flow direction were taken from a water level surface map for the regional gravel aquifer drawn from spring 1988 water levels collected by the US Geological Survey. The water level surface gradient is 0.0016 at Station 8. It steepens up gradient to 0.004 at 8,000 feet from the station. Flow direction from the regional gravel aquifer potentiometric surface is 225 to 230 degrees (toward the southwest).

Aquifer Properties:

Transmissivity: At Station 8, transmissivity values calculated for the three wells by consultants range from 110,000 gallons/day/foot to greater than 200,000 gallons/day/foot according to City records. Aquifer properties probably vary greatly in both horizontal and vertical directions depending on the amount of silt, fine sand, and clay matrix. Estimates of hydraulic conductivity for the principal water bearing zone are 500 to 800 feet/day at Station 8. This decreases to 100 to 200 feet/day near the up gradient margin of the aquifer based on specific capacity data for other high yield wells.

An average aquifer transmissivity was calculated using values from Stations 8, 9, 14, and 15.

Porosity: A porosity of 0.3 is estimated by comparing well record and field description of aquifer lithology to standard porosity values for aquifer media (Heath, 1983)

Pumping Rate: An average daily pumping rate for Station 8 of 250,000 feet^3/day (7,200 meters ^{3}/day) was calculated from an annual total of 691,000,000 gallons for the high year of record, 1988. Records of pumpage for individual wells are not available. However, the total was allocated to each well in proportion to estimate of well pumping rates provided by the City (T. McClure, written communication , August, 1991).

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define the extent of the aquifer, water level surface, and aquifer hydraulic properties. Both existing geologic mapping (Trimble, 1963; Madin, 1990, 1991; and Swanson and others 1991) and water well data were used to define the hydrogeologic setting.

A combination of hydrogeologic maps and analytical models was used to delineate 1, 5, 10, and 20 year time of travel zones of contribution for Station 8 (Figure VA-8-1). The contact between the Pleistocene catastrophic flood deposits and the Troutdale Formation is mapped as a boundary for the delineation. An analytical model using the EPA WHPA RESSQC model (EPA, March, 1991) was used to define the width of the zone of contribution and the time related travel distances. The regional water level map was used to determine the orientation of the zone of contribution.

A buffer was drawn around this delineation due to the degree of uncertainty of the hydrologic parameter values, and the long, thin shape of the zone of contribution. The buffer criteria were selected somewhat arbitrarily because there was no good basis for determining the exact margin of error. First, the distance to the down gradient null point, calculated by the RESSQC delineation, was doubled. Then an expanding lateral buffer was drawn up gradient from the well using a 1 to 5 ratio. In other words, for every 500 feet of distance up gradient, the delineation was widened 100 feet. The expanding lateral buffer uses the doubled null point buffer as a starting point.

The delineation extends up gradient into the area where the underlying Troutdale Formation is exposed at land surface. Within this area surface water, and ground water could move to the buffered 20 year or less zone of contribution area. The boundaries for this area are drawn by extending the buffered delineation along drainage boundaries to the uppermost extent of the Troutdale Formation. Drainage boundaries were identified topography on the USGS 1:24,000 scale Lacamas Creek quadrangle map.

The EPA WHPA RESSQC model (EPA, March, 1991) was applied to Station 8 to define the width and length to the high transmissivity aquifer delineation. The analytical models section describes the model.

Analytical Models: The principal use of analytical models in this high transmissivity aquifer with a relatively steep ground water gradient setting is to simulate pumping conditions near the well. Regional conditions vary to the extent that extending a simple analytical model beyond conditions near the well will result in unacceptably inaccurate zone of contribution delineations.

The analytical model used average values for transmissivity and gradient. Transmissivity was averaged for Stations 8, 9, 14, and 15. Gradient represents the average gradient between the well and about 5,000 feet up gradient. To be conservative, the thickness of the principal water bearing zone was used instead of the total aquifer thickness. The model is also conservative in that recharge to the aquifer is not considered in the RESSQC model. Figure VA-8-2 shows the RESSQC delineation.

Values selected were:

Transmissivity:	4,590 meters^2/day
Pumping rate:	7,200 meters^3/day
Gradient:	0.002
Flow angle:	-140° (230° compass bearing)
Porosity:	0.3
Aquifer thickness:	18 meters
Time of travel:	1, 5, 10, and 20 years

Calculated Fixed Radius: Calculated fixed radii delineations were made using the volumetric flow equation reference by EPA (June, 1987) as the Florida Department of Environmental Regulation (FDER) volumetric flow equation. All pumping was combined to simulate the station as a singe pumping well. The delineation is shown in Figure VA-CFR-1.

Values selected were:

Pumping rate:	92,400,000 feet^3/year
Porosity:	0.3

Length of well screen:	29 feet
Times of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure VA-AFR-1 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Well Station 8 is included in a two dimensional model using the FLOWPATH model. Wells Stations 9, 14, and 15 were also included in the model. Description of the model and model results is in Appendix S.

Three Dimensional Regional Model: Refer to the US Geological Survey map report.

References Cited:

Collins, C.A. and T.M. Broad, 1991, Estimated Average Annual Ground-Water Pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 91-4018.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington,D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: United States Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

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Madin, I.P., 1991, Earthquake-Hazard geology maps for the Vancouver and Orchards Area,Washington, 7-1/2 minute U.S. Geological Survey Quadrangles: IRC map reports.

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Trimble, D.E., 1963, Geology of Portland, Oregon and Adjacent Areas: U.S. Geological Survey Bulletin 1119, 119p., 1 pl.

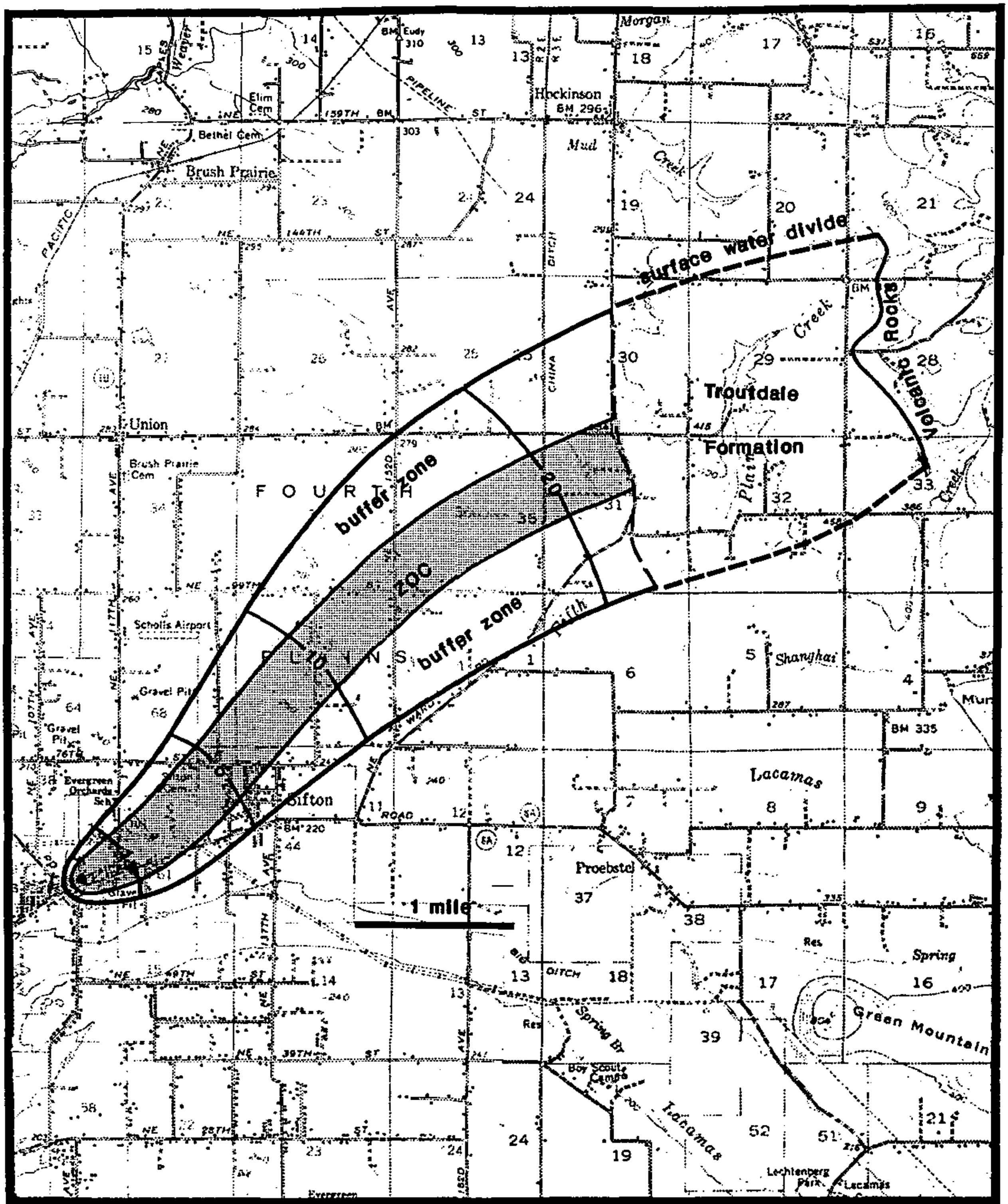

Figure VA-8-1. 1, 5 and 10 year time of travel zones of contribution and buffer zone from hydrogeologic mapping and analytical methods for Vancouver Station 8.

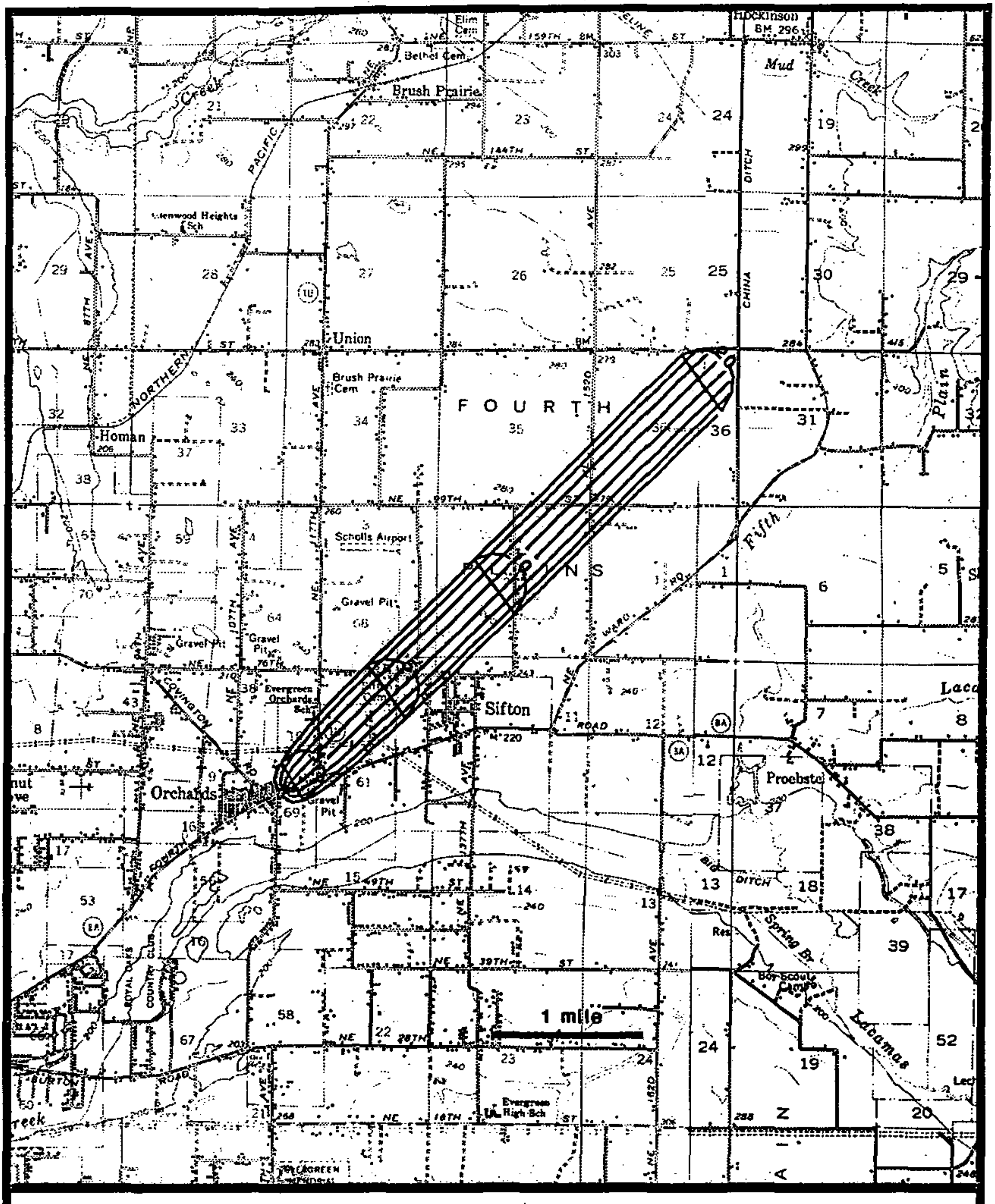

Figure VA-8-2. 1, 5, 10, and 20 year time of travel zones of contribution for Vancouver Station 8 using the EPA RESSQC WHPA model.

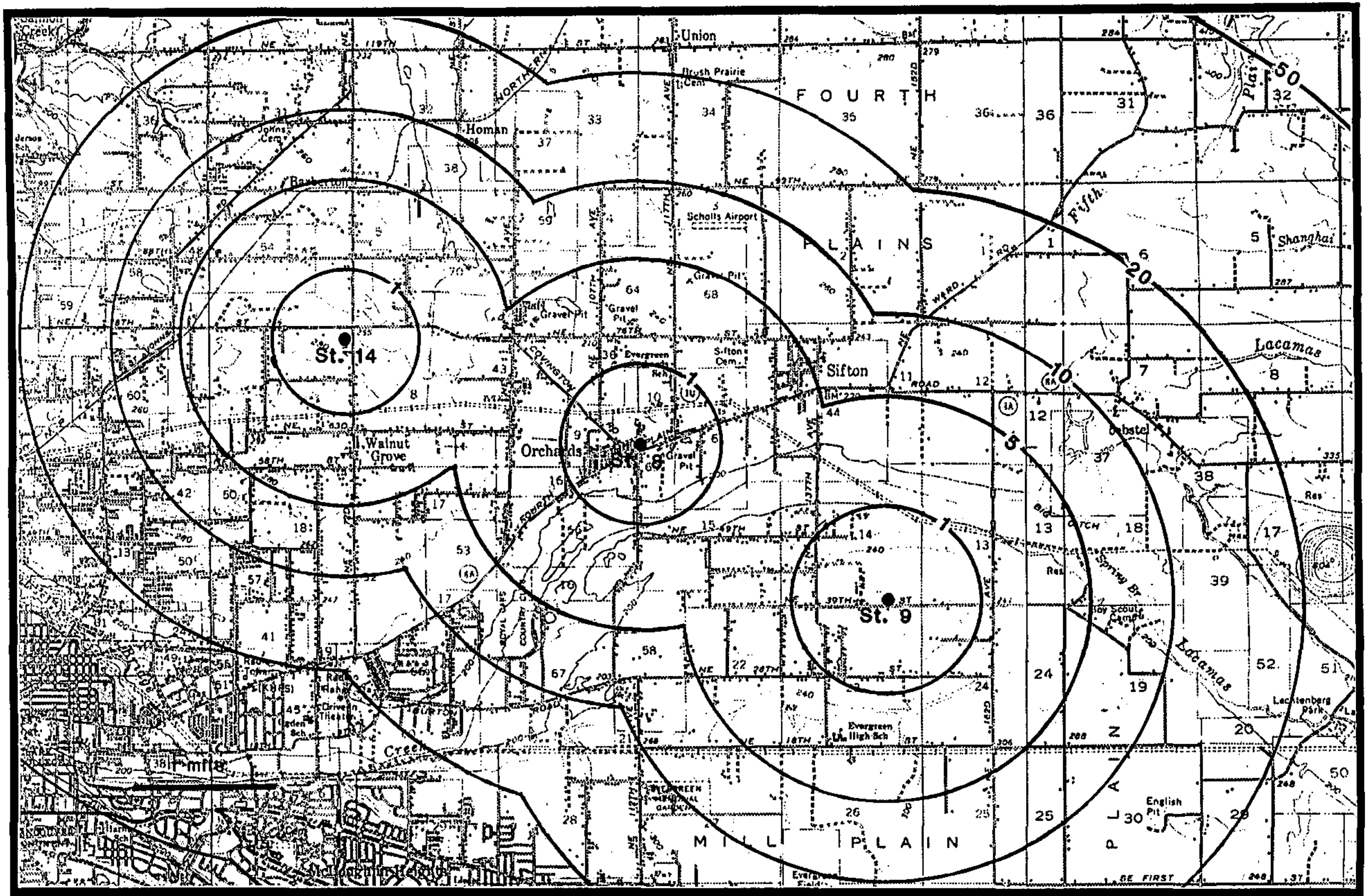

Figure VA-CFR-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation for Vancouver Stations 8, 9, and 14.

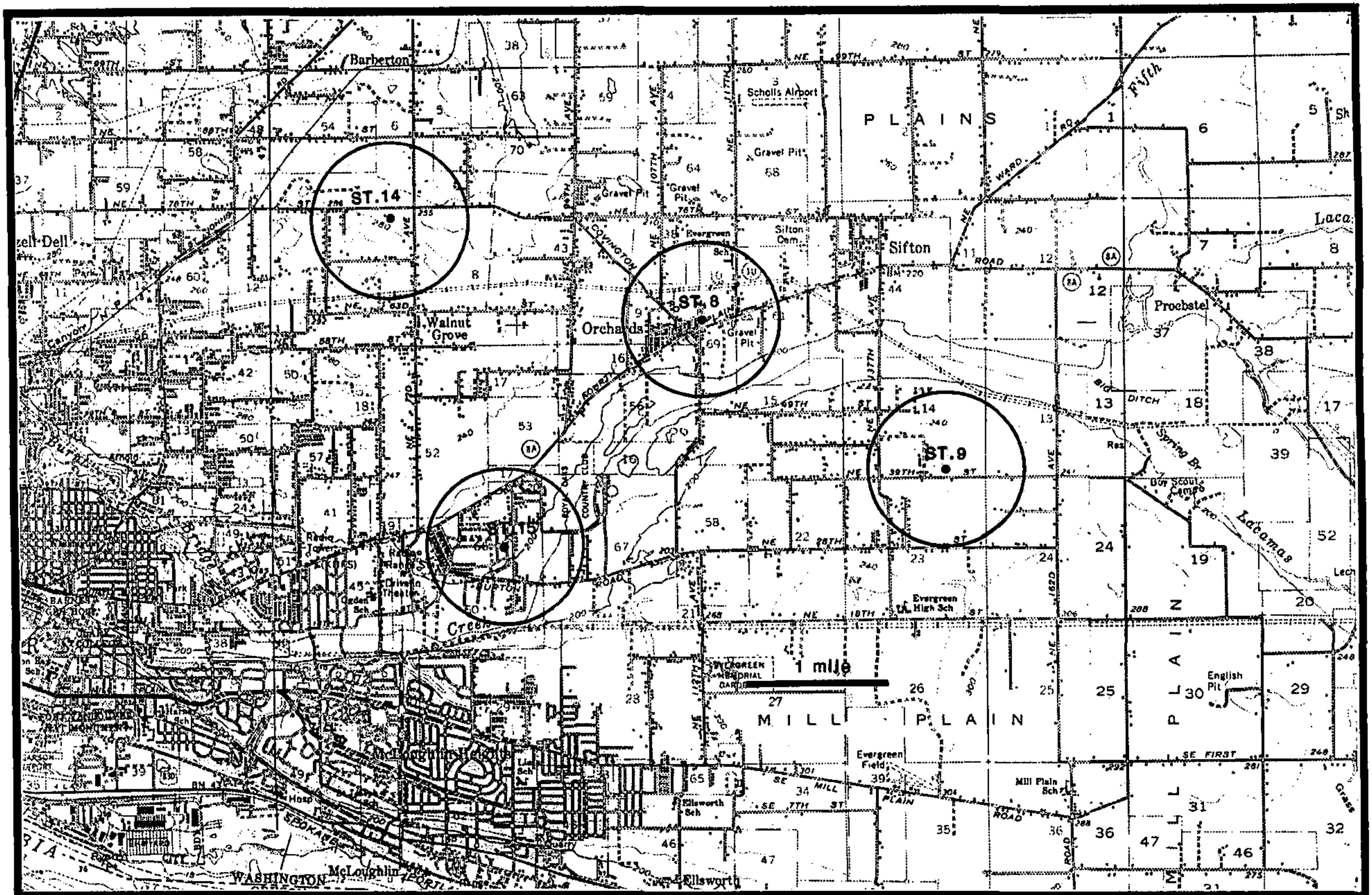

Figure VA-AFR-1. 3000 foot fixed radius delineation for Vancouver Stations 8, 9, 14, and 15.

Appendix N

WELLHEAD PROTECTION AREA DELINEATION REPORT

VANCOUVER WELL STATION 9

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix N
Wellhead Protection Area Delineation Report

Well: Vancouver Well Station 9

Setting: Station 9, the eastern-most Vancouver well station, is on a low rolling hill about two thirds of a mile south of the Burnt Bridge Creek basin. The land surface elevation at Station 9 is between 230 feet and 250 feet above sea level.

Station 9 has five active wells, 3, 4, 5, 6, and 7. Well depths range from about 145 feet to about 230 feet. One well, number 3 is completed in the uppermost part of the aquifer. Well capacities range from 800 gallons/minute to 3,000 gallons/minute.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: The principal water bearing zone at Station 9 is near the contact of the Troutdale Formation and Pleistocene catastrophic flood sandy gravel deposits. The exact stratigraphic position of the aquifer has been debated, but it is part of a regional high transmissivity gravel aquifer that overlies the Troutdale Formation and extends upward to land surface in much of southern Clark County.

Based on available well data, the aquifer extent corresponds to the mapped extent of the Pleistocene catastrophic flood deposits sandy gravel phase mapped by Trimble (1963). In Clark County, this coarse sandy gravel extends from along the Columbia River at Camas and Washougal to as far north as 2 miles north of Orchards. The aquifer is truncated at the east edge of the basin where the underlying Troutdale Formation is exposed.

Both the total aquifer thickness and thickness of the principal water bearing zone at Station 9 were examined. Total aquifer thickness and thickness of the principal water bearing zone were mapped using well data from Vancouver Well Stations and several high specific capacity wells. The total aquifer thickness was determined by subtracting the elevation of the aquifer base from the spring 1988 regional gravel water level map. The principal water bearing zone was mapped using well construction and drill cutting lithology descriptions. At Station 9 the principal water bearing zone is about 60 feet thick. The principal water bearing zone thins to about 40 feet thick away from Station 9. Thickness variation appears to result from the irregular upper surface of the underlying cemented gravel.

The principal water bearing zone at Station 9 is semi-confined by less permeable gravel in the high transmissivity gravel aquifer.

Nitrate levels in the Station 9 wells suggest that septic system effluent and/or fertilizers are entering the aquifer. US Geological Survey recharge estimates for the area suggest that between 15 and 30 inches/year recharge occurs in the area of Station 9. Up to one half of this recharge is estimated to be due to shallow storm water disposal wells (Snyder and others, 1992). No other large scale pumping is identified near Station 9 (Collins and Broad, 1991).

Gradient and Flow Direction: Water level gradient and flow direction were estimated from a water level map for the regional gravel aquifer drawn using spring 1988 water level measurements collected by the US Geological Survey (US Geological Survey, written communication, 1990). The gradient was 0.004 and the flow direction is from the northeast.

Aquifer Properties:

Transmissivity: At Station 9, transmissivity values calculated for several wells by consultants range from 600,000 gallons/day/foot to 3,200,000 gallon/day/foot according to City records. Aquifer properties probably vary greatly in both horizontal and vertical directions depending on the amount of silt, sand, and clay matrix. Estimates of hydraulic conductivity for the principal water bearing zone at Station 9 are 600 to 1,100 feet/day. A transmissivity value for the entire aquifer thickness is likely to be much lower than that of the principal water bearing zone at Station 9 because less permeable silty gravel would be included.

Porosity: A porosity of 0.3 is estimated by comparing well and field observations of aquifer lithology to standard porosity values for aquifer media (Heath, 1983)

Pumping Rate: An average pumping rate for Station 9 of 900,000 feet^3/day (6,730,000 gallons/day or 25,500 meters^3/day) was calculated from an annual total of 2,456,000,000 gallons for the high year of record, 1990. Records of pumpage for individual wells are not available. However, the total was allocated proportional to individual well pumping rate estimates provided by the City (T. McClure, written communication, August, 1991).

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define the extent of the aquifer, aquifer water level surface, and aquifer hydraulic properties. Both existing geologic mapping (Trimble, 1963; Madin, 1990, 1991; and Swanson and others 1991) and water well data were used to define the hydrogeologic setting.

A combination of hydrogeologic maps and analytical models was used to delineate 1 and 5 year time of travel zones of contribution for Station 9 (Figure VA-9-1). The contact between the Pleistocene catastrophic flood deposits and the Troutdale Formation is mapped as a boundary for the time of travel delineation. An analytical model using the EPA WHPA RESSQC model (EPA, March, 1991) was used to define the width of the zone of contribution and the distance of travel in one and five years. Time of travel delineations for over five years time were not done because this time brought the delineation to the exposed contact with the underlying Troutdale Formation. The regional water level map was used to determine the orientation of the zone of contribution.

A buffer was drawn around this delineation due to the degree of uncertainty of the hydrologic parameter values, and the long, thin shape of the zone of contribution. The buffer criteria were selected somewhat arbitrarily because there was no good basis for determining the exact margin of error. First, the distance to the down gradient null point, calculated by the RESSQC delineation, was doubled. Then an expanding lateral buffer was drawn up gradient from the well using a 1 to 5 ratio. In other words, for every 500 feet of distance up gradient, the delineation was widened 100 feet. The expanding buffer uses the doubled null point buffer as the starting point.

An area is delineated where the underlying Troutdale Formation is exposed at the up gradient edge of the aquifer. In this area surface water, and ground water could move to the buffered, 10 year or less travel time zone of contribution area. The boundaries for this area are drawn by extending the buffered delineation along drainage boundaries to the uppermost extent of the Troutdale Formation.

Analytical Models: The EPA WHPA RESSQC model (EPA, March, 1991) was used to simulate zones of contribution for times less than 10 years. Regional hydrogeologic conditions vary to the extent that a simple analytical model cannot be extended far from the well. In addition, the high transmissivity and relatively steep gradient are not ideal for use of analytical models.

The RESSQC model for Station 9 uses average values for transmissivity and gradient. Transmissivity was averaged for Stations 8, 9, 14, and 15. Gradient represents the average gradient between the well and about 5000 feet up gradient. To be conservative, the thickness of the principal water bearing zone was used instead of the total aquifer thickness. The model is also conservative in that recharge to the aquifer is not considered in the RESSQC model. Figure VA-9-2 shows the RESSQC delineation.

Values selected were:

Transmissivity:	4,590 meters^2/day
Pumping rate:	25,500 meters^3/day (allocated by individual well)
Gradient:	0.004
Flow angle:	-140° (230° compass bearing)
Porosity:	0.3
Aquifer thickness:	22 meters
Time of travel:	1, 5, and 10 years

Calculated Fixed Radius: Calculated fixed radii delineations were made using the volumetric flow equation reference by EPA (June, 1987) as the Florida Department of Environmental Regulation (FDER) volumetric flow equation. All pumping was combined to simulate the station as a singe pumping well. The delineation is shown in Figure VA-CFR-1.

Values selected were:

Pumping rate:	900,000 feet^3/year (2,456 mg/y)
Porosity:	0.3

Length of well screen:	29 feet
Times of travel:	1, 5, 10, 20, and 50 years

Arbitrary Fixed Radius: Figure VA-AFR-1 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Well Station 9 is included in a two dimensional model using the FLOWPATH finite difference model. Wells Stations 8, 14, and 15 were also included in the model. A description of the model and model results is in Appendix S.

Three Dimensional Regional Model: Refer to US Geological Survey map report.

References Cited:

Collins, C.A. and T.M. Broad, 1991, Estimated Average Annual Ground-Water Pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 91-4018.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington,D.C., EPA 440/6-87-010.

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Trimble, D.E., 1963, Geology of Portland, Oregon and Adjacent Areas: U.S. Geological Survey Bulletin 1119, 119p., 1 pl.

Snyder, D.T., D.S. Morgan, and T. McGrath, 1991, Estimates of Recharge from Infiltration of Precipitation, On-Site Sewage Disposal Systems, and Dry Wells in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 92-____ .

Swanson, R.D., W.D. McFarland, J.B. Gonthier, and J.W. Wilkinson, 1991, A Description of Hydrogeologic Units in the Portland Basin, Oregon and Washington: U.S. Geological Water-Resources Investigations Report 90-4196.

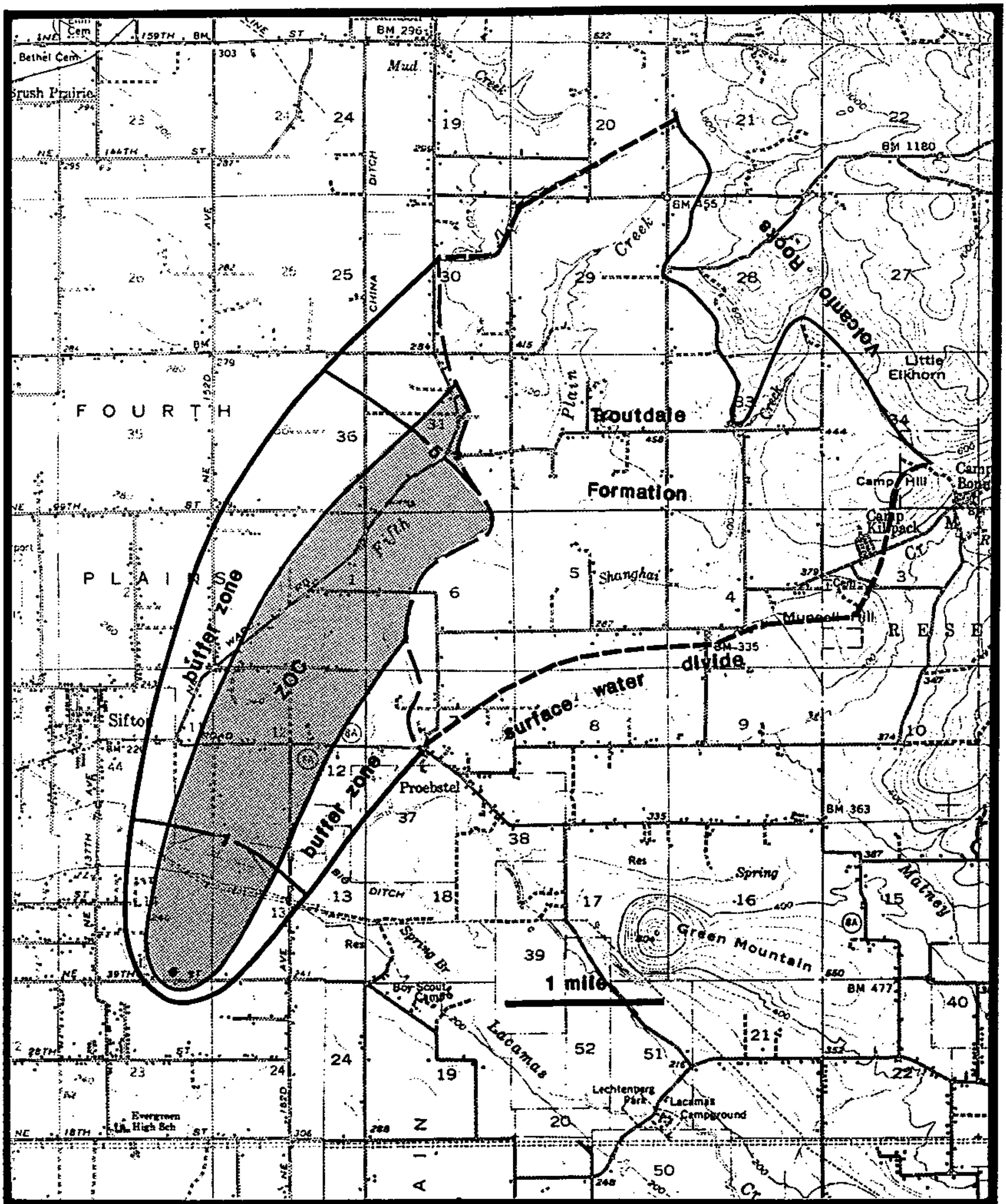

Figure VA-9-1. 1, and 5 year time of travel zones of contribution and buffer zone from hydrogeologic mapping and analytical methods for Vancouver Station 9.

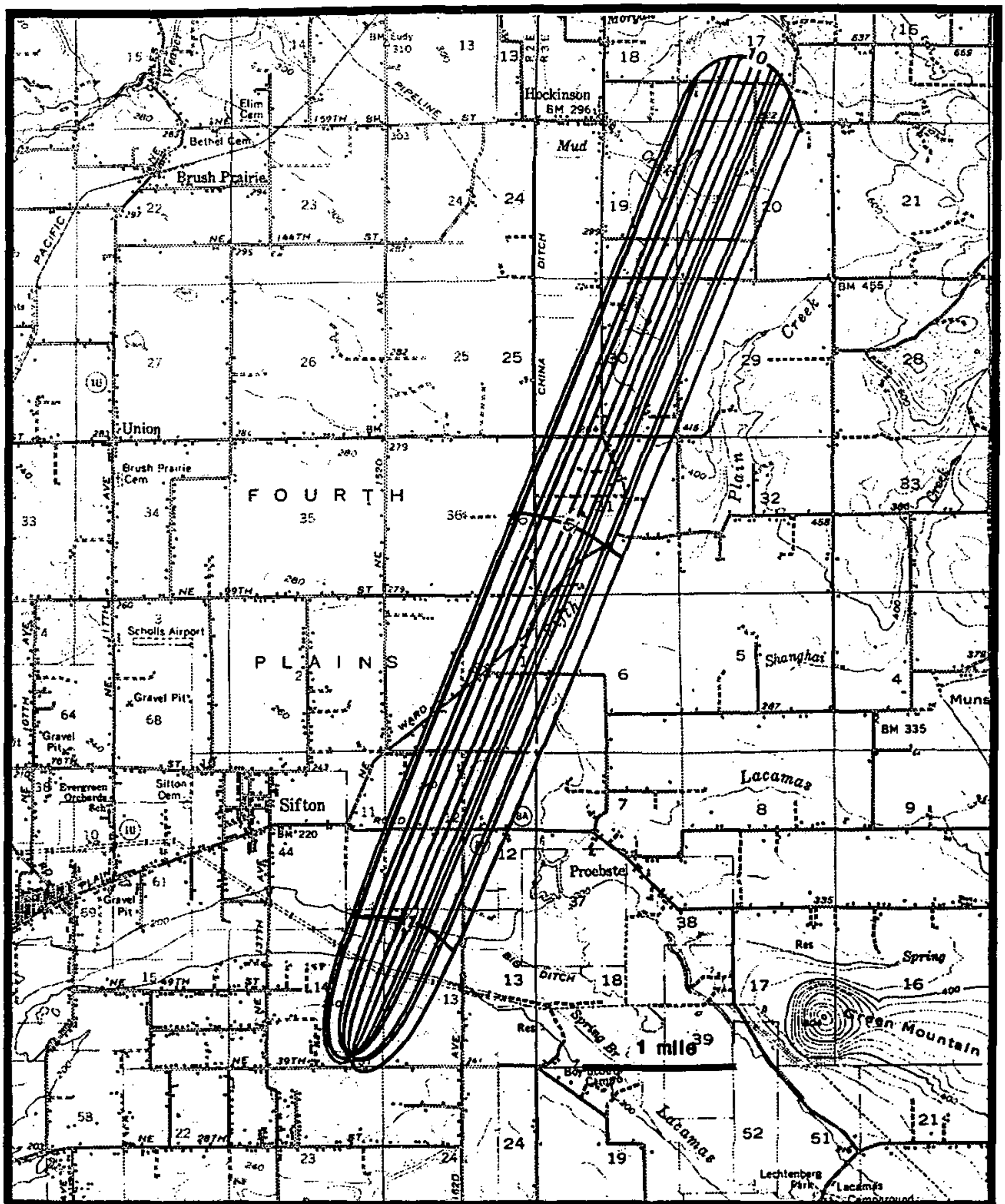

Figure VA-9-2. 1, 5, and 10 year time of travel zones of contribution for Vancouver Station 9 using the EPA RESSQC model.

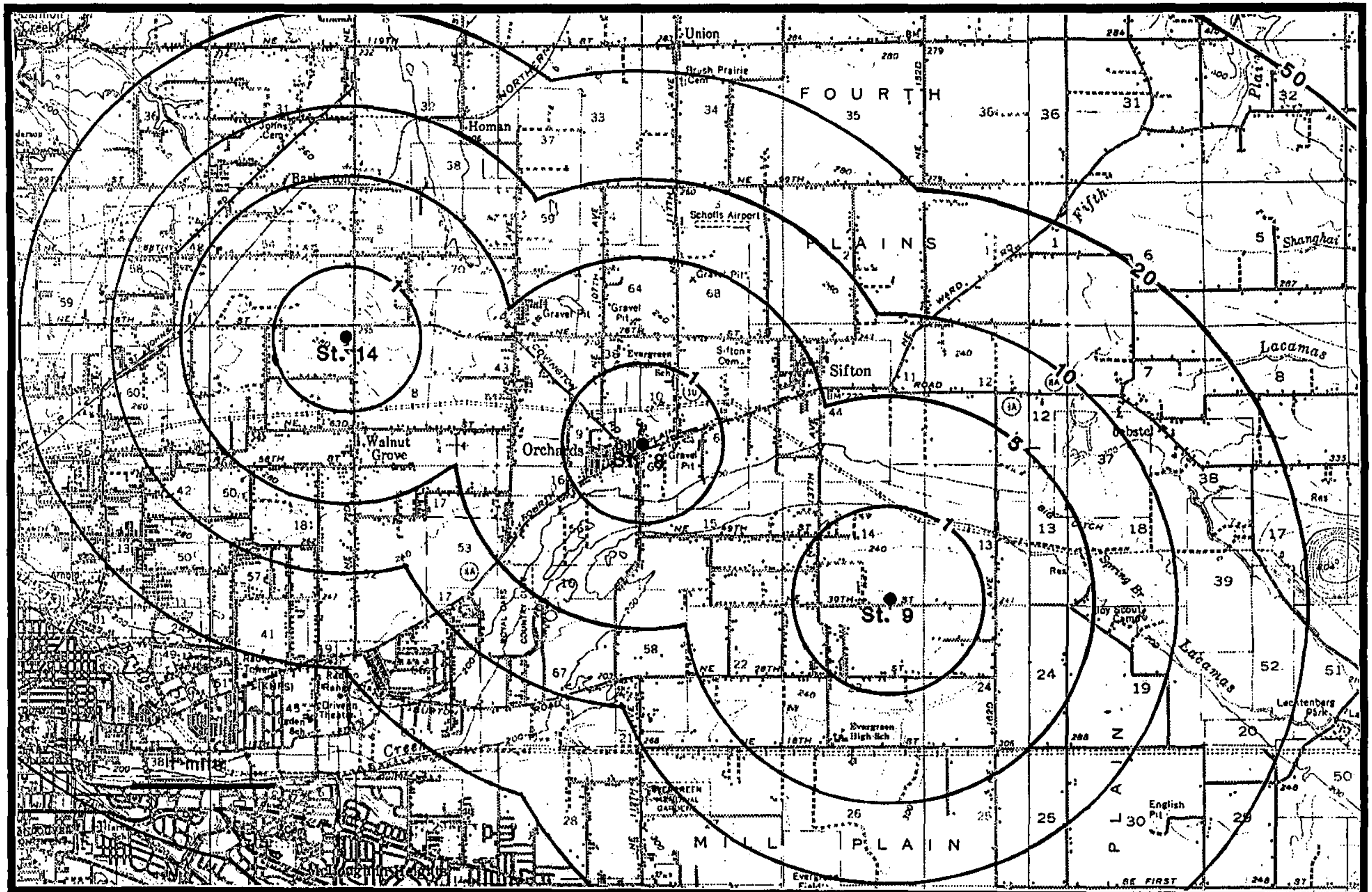

Figure VA-CFR-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation for Vancouver Stations 8, 9, and 14.

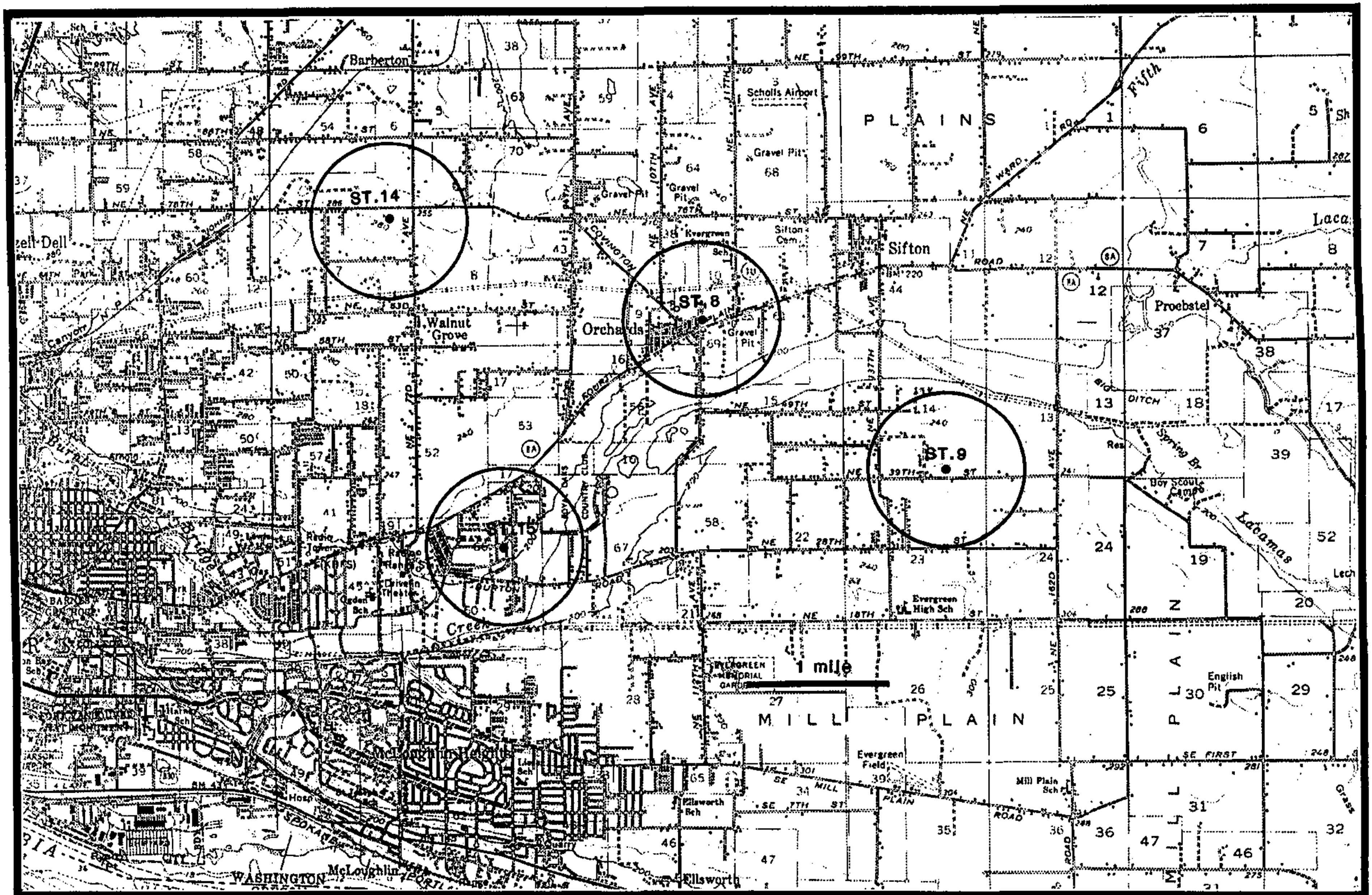

Figure VA-AFR-1. 3000 foot fixed radius delineation for Vancouver Stations 8, 9, 14, and 15.

Appendix O

WELLHEAD PROTECTION AREA DELINEATION REPORT

VANCOUVER WELL STATION 14

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix O
Wellhead Protection Area Delineation Report

Well: Vancouver Well Station 14

Setting: Station 14 is on 78th Street, two miles west of Orchards. The area is gently rolling hills on the upland plain between Salmon Creek and Burnt Bridge Creek. Station 14 wellheads are between 265 feet and 271 feet in elevation.

There are three very similar wells at Station 14 that tap a high yield gravel layer at the interface between the consolidated older gravel and Pleistocene deposits. The wells range in depth from 170 feet to 195 feet. Well capacities are 1,000 gallons/minute for wells 1 and 2 and 1,200 gallons/minute for well 3.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Station 14 taps the same high transmissivity shallow Pleistocene gravel aquifer as Stations 8, 9, and 15. The exact stratigraphic position of the aquifer has been debated, but it is part of a regional high transmissivity gravel aquifer that corresponds to the contact between the Troutdale Formation and overlying Pleistocene gravel.

Based on available well data, the aquifer extent corresponds to the mapped extent of the Pleistocene catastrophic flood deposits sandy gravel phase mapped by Trimble (1963). In Clark County, this coarse sandy gravel extends from along the Columbia River at Camas and Washougal to as far north as 2 miles north of Orchards. North of Orchards, the Pleistocene sand gravel grades into sandier deposits. The aquifer is truncated at the east edge of the basin where the underlying Troutdale Formation is exposed.

Aquifer thickness was mapped using well data from Vancouver Well Stations and several high specific capacity wells. Thickness is not well defined but can be inferred from lithology descriptions of several wells and the regional water table. At Station 14 the aquifer is between 60 and 79 feet thick based on the cuttings description for well 1.

The aquifer is underlain by more cemented sandy gravel of the Troutdale Formation and overlain by less permeable clayey sand. At Station 14 the overlying clayey sand is likely to act as a semi-confining layer.

The aquifer is recharged by infiltration through the overlying clayey sand. Nitrate levels in the Station 14 wells suggest that septic system effluent and fertilizers are entering the aquifer. Other than Vancouver Well Station 8, no other large scale ground water users are in the vicinity of Station 14 (Collins and Broad, 1991).

Gradient and Flow Direction: Gradient and flow direction were estimated from a water level surface map for the regional gravel aquifer. The map was drawn using spring 1988 water level measurements collected by the US Geological Survey (US Geological Survey, written communication, 1990). Water level gradient is 0.002 and flow direction is to the southwest at Station 14.

Aquifer Properties:

Transmissivity: Transmissivity values of 610,000 to 1,300,000 gallons/day/foot were calculated for thin high yield zones (City records for Station 14). These zones were only 5 to 10 feet thick.

Porosity: A porosity of 0.3 was assigned to the aquifer by comparing well record lithology description of the aquifer to tabulated porosity values for aquifer materials (Heath, 1983).

Pumping Rate: An average pumping rate of 2,630,000 gallons/day (9,900 meters^3/day) was calculated from a total annual pumpage of 954,000,000 gallons during the high year of record, 1990. Pumpage was allocated to each well proportional to well pumping rates provided by the City.

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define the extent of the aquifer, aquifer water level surface, and aquifer hydraulic properties. Both existing geologic mapping (Trimble, 1963; Madin, 1990, 1991; and Swanson and others 1991) and water well data were used to define the hydrogeologic setting. In this delineation the total aquifer thickness of the high transmissivity gravel aquifer was used.

A combination of hydrogeologic maps and analytical models was used to delineate 1, 5, and 10 year time of travel zones of contribution for Station 14 (Figure VA-14-1). An analytical model using the EPA WHPA RESSQC (EPA, March, 1991) model was used to define the width of the zone of contribution and the distance of travel in 1, 5, and 10 years. The regional gravel aquifer water level map was used to determine the orientation of the zone of contribution.

A buffer was drawn around this delineation due to the degree of uncertainty of the hydrologic parameter values, and the long, thin shape of the zone of contribution. The buffer criteria were selected somewhat arbitrarily because there was no good basis for determining the exact margin of error. First, the distance to the down gradient null point, calculated by the RESSQC delineation, was doubled. Then an expanding lateral buffer was drawn up gradient from the well using a 1 to 5 ratio. In other words, for every 500 feet of distance up gradient, the delineation was widened 100 feet. The expanding lateral buffer uses the doubled null point buffer as a starting point.

Analytical Models: The principal use of the EPA WHPA analytical models (EPA, March, 1991) in this hydrogeologic setting with large transmissivity and relatively steep ground water gradient, is to simulate pumping conditions near the well. Regional conditions vary to the extent that extending a simple analytical model beyond conditions near the well will result in unacceptably inaccurate zone of contribution delineations.

The analytical model used average values for transmissivity and gradient. Transmissivity was averaged for Stations 8, 9, 14, and 15. Gradient represents the average gradient between the well and about 10,000 feet up gradient. The model is conservative in that infiltration to the aquifer through the overlying clayey sand is not considered in the RESSQC model. Figure VA-14-2 shows the RESSQC delineation. As a comparative tool, a GPTRAC model simulating an unconfined aquifer was done. This delineation is overlaid on the RESSQC delineation in Figure VA-14-2.

Values selected were:

Transmissivity: 4,590 meters^2/day
Pumping rate: 9,900 meters^3/day
Gradient: 0.002
Flow angle: -140° (230° compass bearing)
Porosity: 0.3
Aquifer thickness: 24 meters
Time of travel: 1, and 5 years

Calculated Fixed Radius: Calculated fixed radii delineations were made using the volumetric flow equation reference by EPA (June, 1987) as the Florida Department of Environmental Regulation (FDER) volumetric flow equation. All pumping was combined to simulate the station as a singe pumping well. The delineation is shown in Figure VA-CFR-1.

Values selected were:

Pumping rate: 127,500,000 feet^3/year (954 mg/y)
Porosity: 0.3
Length of well screen: 17 feet
Times of travel: 1, 5, 10, 20, and 50 years

Fixed Radius: Figure VA-AFR-1 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Variable Fixed Shapes: This method was not used.

Two Dimensional Numerical Model: Well Station 14 is included in a two dimensional model using the FLOWPATH finite difference model. Wells Stations 9, 14, and 15 were also included in the model. A description of the model and model results are in a separate document.

Three Dimensional Regional Model: Refer to US Geological Survey map report.

Cited References:

Collins, C.A. and T.M. Broad, 1991, Estimated Average Annual Ground-Water Pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 91-4018.

EPA, June, 1987, Guidelines for Delineation of Wellhead Protection Areas: United States Environmental Protection Agency, Office of Groundwater Protection, Washington,D.C., EPA 440/6-87-010.

EPA, March, 1991, A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0: United States Environmental Protection Agency, Office of Ground Water Protection.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84p.

Madin, I.P., 1990, Earthquake-Hazard geology maps of the Portland Metropolitan Area,Oregon: Oregon Department of Geology and Mineral Industries Open-File Report 0-90-2.

Madin, I.P., 1991, Earthquake-Hazard geology maps for the Vancouver and Orchards Area,Washington, 7-1/2 minute U.S. Geological Survey Quadrangles: IRC map reports.

Swanson, R.D., W.D. McFarland, J.B. Gonthier, and J.W. Wilkinson, 1991, A Description of Hydrogeologic Unit in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90-4196.

Trimble, D.E., 1963, Geology of Portland, Oregon and Adjacent Areas: U.S. Geological Survey Bulletin 1119, 119p., 1 pl.

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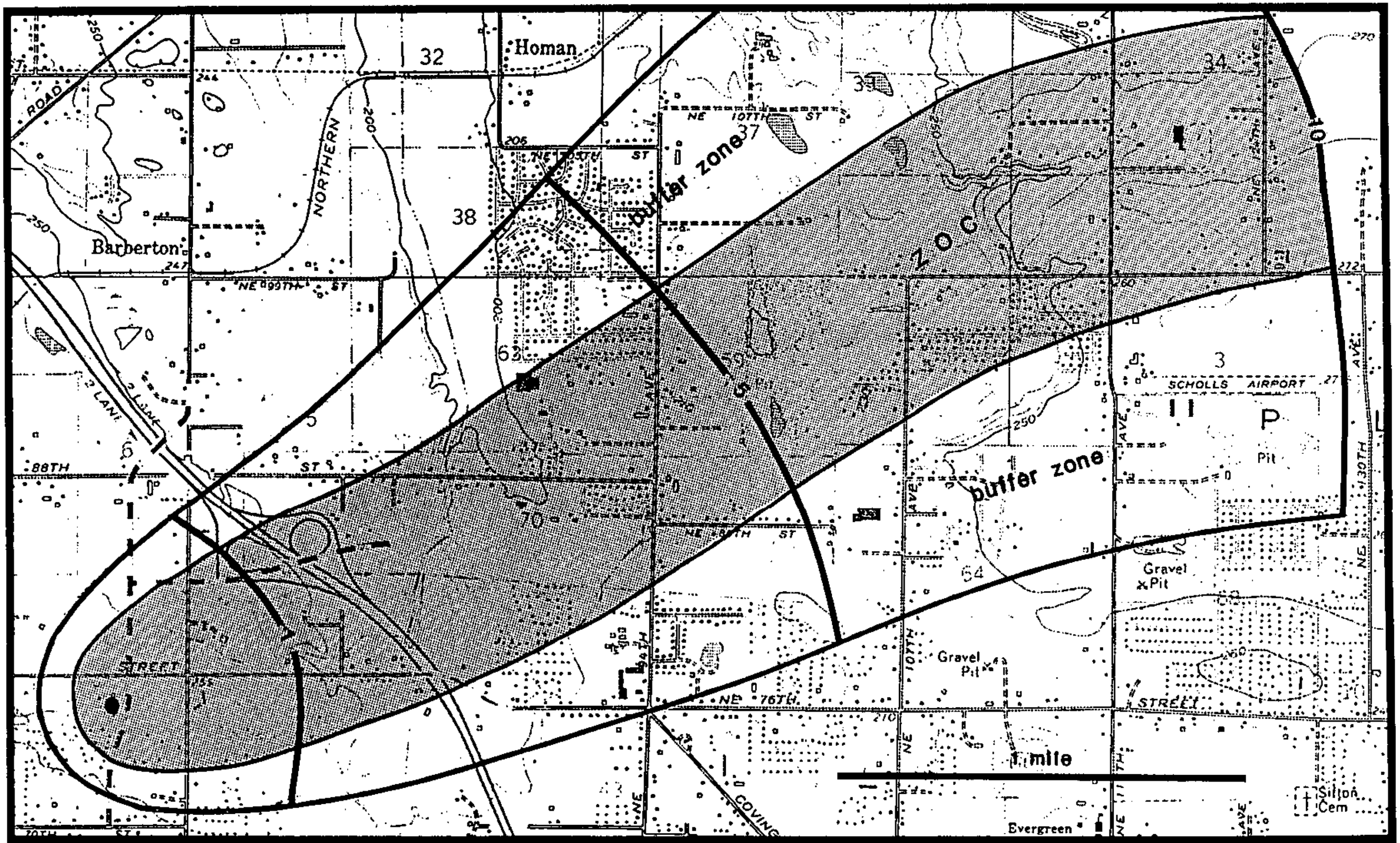

Figure VA-14-1. 1, 5, and 10 years time of travel zone of contribution and buffer zone from hydrogeologic mapping and analytical methods for Vancouver Station 14.

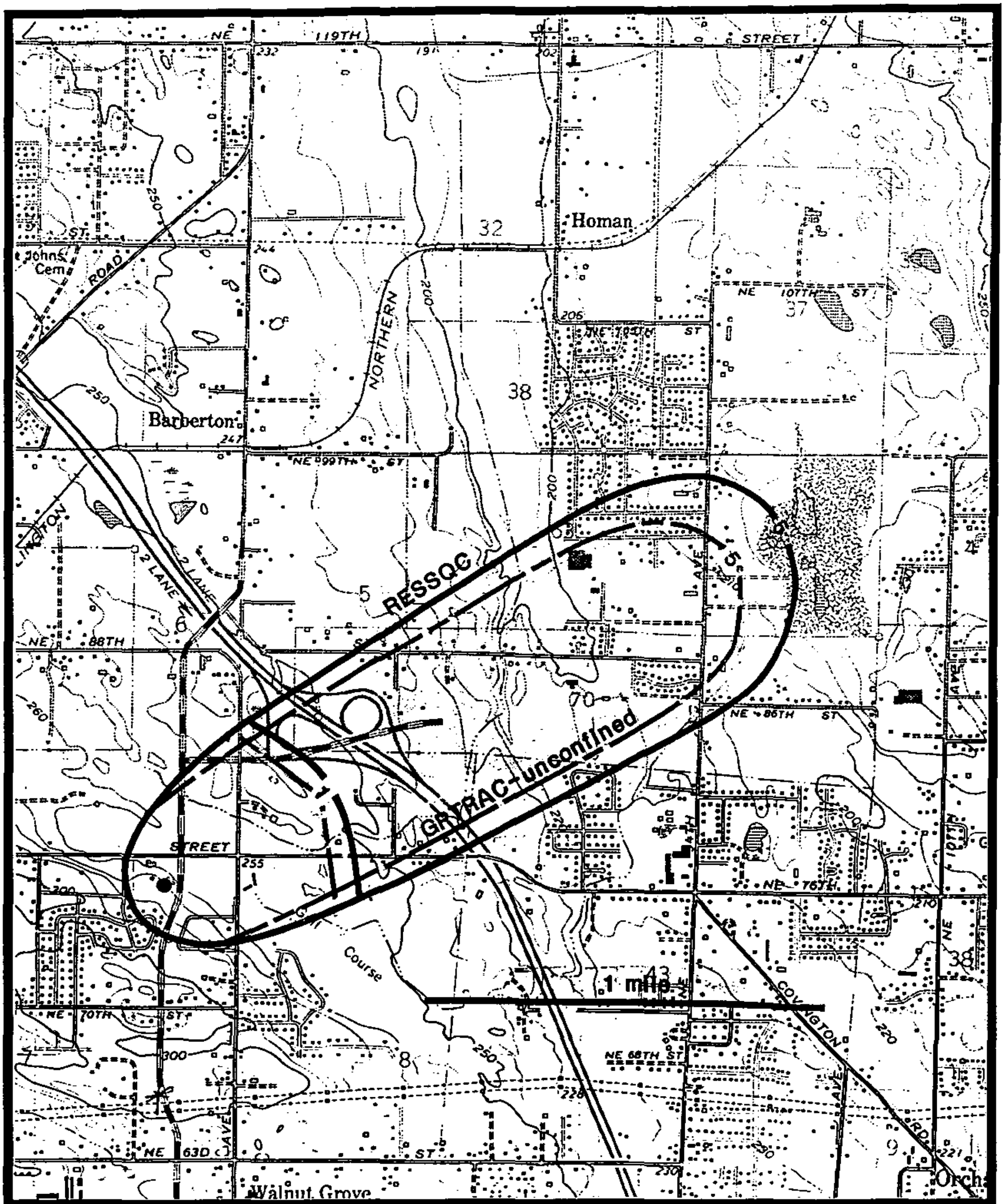

Figure VA-14-2. Comparison of strictly confined RESSQC delineation (solid line) with unconfined GPTRAC delineation (dashed line) for 1 and 5 year time of travel at Vancouver Station 14.

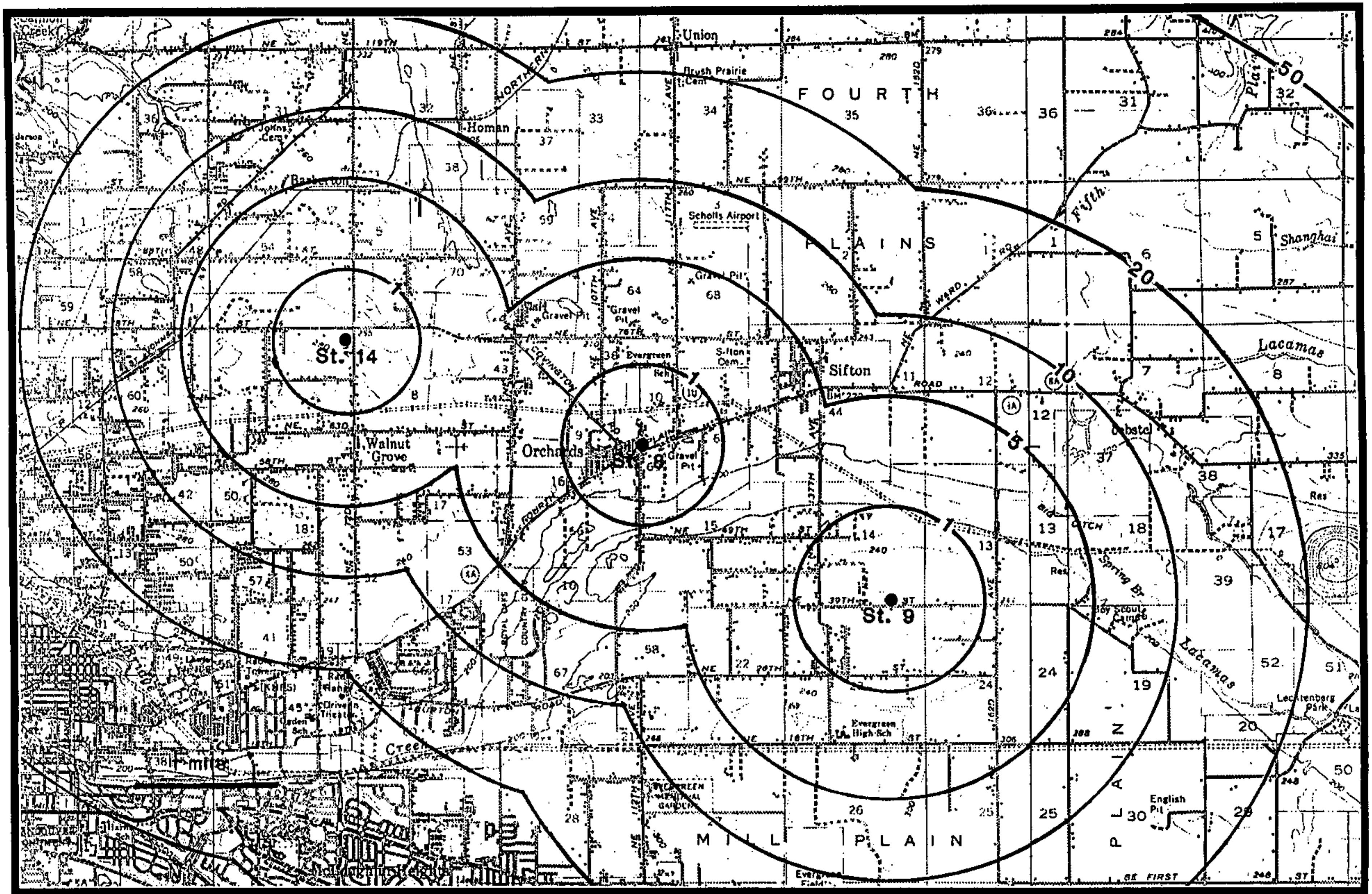

Figure VA-CFR-1. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation for Vancouver Stations 8, 9, and 14.

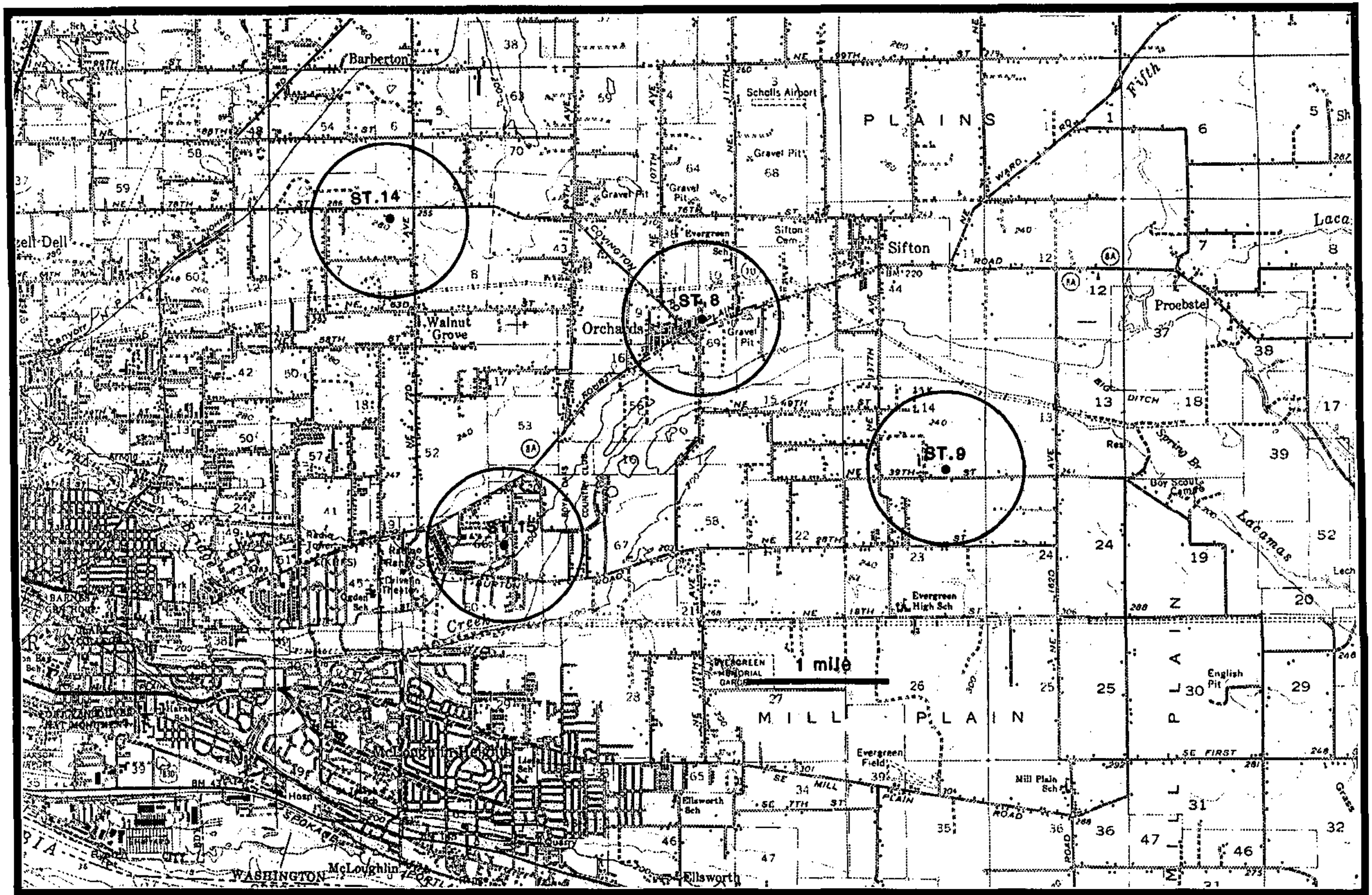

Figure VA-AFR-1. 3000 foot fixed radius delineation for Vancouver Stations 8, 9, 14, and 15.

Appendix P

WELLHEAD PROTECTION AREA DELINEATION REPORT

VANCOUVER WELL STATION 15

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix P
Wellhead Protection Area Delineation Report

Well: Vancouver Well Station 15

Setting: Station 15 is at Ogden School in east Vancouver. The setting is similar to Station 8, with the well situated about one third mile northwest of Burnt Bridge Creek at an elevation about 40 to 50 feet above the creek. The wellhead elevations range from 208 to 210 feet above sea level.

There are four very similar wells at Station 15. Screened intervals are about 40 to 50 feet in length and are from a minimum of 70 feet depth to a maximum of 140 feet depth. Well capacity is 500 gallons per minute for wells 1, 2, and 3, and 1,000 gallons per minute for well 4.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: The aquifer is near the contact of Troutdale Formation and Pleistocene catastrophic flood sandy gravel deposits. The exact stratigraphic position of the aquifer has been debated, but it is part of a regional high transmissivity gravel aquifer that corresponds to the contact between the Troutdale Formation and overlying Pleistocene gravel.

Based on available well data, the aquifer extent corresponds to the mapped extent of the Pleistocene catastrophic flood deposits sandy gravel phase mapped by Trimble (1963). In Clark County, this coarse sandy gravel extends from along the Columbia River at Camas and Washougal to as far north as two miles north of Orchards. The aquifer is truncated at the east edge of the basin where the underlying Troutdale Formation is exposed. North of Orchards, the gravel grades into finer sand and silt deposits.

Aquifer thickness was mapped using well data from Vancouver well stations and several high specific capacity wells. Thickness is not well defined but can be inferred from lithology descriptions of several wells and the regional water table. At Station 15 the aquifer is about 50 feet thick.

The aquifer is underlain by more cemented sandy gravel of the Troutdale Formation and overlain by less permeable sandy silt and gravelly silty sand.

The aquifer is recharged by infiltration through the overlying silty sand and gravelly silty sand. Nitrate levels in the Station 15 wells suggest that septic system effluent and fertilizers are entering the aquifer. No other large scale ground water users are in the vicinity of Station 15 (Collins and Broad, 1991). US Geological Survey recharge estimates for the area are between 1 and 26 inches per year (written communication, USGS, 1990). Large differences in recharge are due to variation in impermeable area, drywell recharge, and septic system recharge.

It is unlikely that Burnt Bridge Creek is directly connected to the aquifer. Water levels at Station 15 at 145 to 150 foot elevation are well below the level of Burnt Bridge Creek at 165 to 170 feet elevation. Some flow from the creek into the aquifer is probable. US Geological Survey low stream flow measurements show that Burnt Bridge Creek is a gaining stream near Station 15 (written communication, USGS, 1990)

Gradient and Flow Direction: Gradient and flow direction were taken from a water level surface map for the regional gravel aquifer drawn from spring 1988 water levels collected by the US Geological Survey. The water level surface gradient is 0.0016 at Station 15, steepening to 0.004 at 15,600 feet up gradient. Flow direction from the regional gravel aquifer water level surface is 240 to 250 degrees (toward the southwest).

Aquifer Properties:

Transmissivity: At Station 15, transmissivity values calculated by consultants range from 580,000 gallons/day/foot to 2,200,000 gallons/day/foot according to City records. Aquifer properties probably vary greatly in both horizontal and vertical directions depending on the amount of silt, fine sand, and clay matrix.

Porosity: A porosity of 0.3 is estimated by comparing well record lithology descriptions of the aquifer to tabulated porosity values for aquifer media (Heath, 1983)

Pumping Rate: An average pumping rate for Station 15 of 701,000 gallons/day (93,800 feet^3/day or 2,700 meters^3/day) was calculated from an annual total of 256,000,000 gallons during the high year of record, 1988. Records of pumpage for individual wells are not available. However, the pumpage total was allocated proportional to estimated well pumping rate (written communication, T. McClure, August, 1991).

Delineation Analysis:

Hydrogeologic Mapping: Hydrogeologic mapping was used to define the extent of the aquifer, water level surface, and aquifer hydraulic properties. Both existing geologic mapping (Trimble, 1963; Madin, 1990, 1991; and Swanson and others 1991) and water well data were used to define the hydrogeologic setting.

A combination of hydrogeologic mapping and analytical models was used to delineate 1 and 5 year time of travel zones of contribution for Station 15 (Figure VA-15-1). An analytical model using the EPA RESSQC WHPA model (EPA, March, 1991) was used to define the width of the zone of contribution and the distance of travel in 1 and 5 years. The regional water level map was used to determine the orientation of the zone of contribution. The upper end of the 5 year delineation overlaps Station 8. The delineations would continue to overlap up gradient from Station 8. Much of the area delineated includes the Burnt Bridge Creek valley.

A buffer was drawn around this delineation due to the degree of uncertainty of the hydrologic parameter values, and the long, thin shape of the zone of contribution. The buffer criteria were selected somewhat arbitrarily because there was no good basis for determining the exact margin of error. First, the distance to the down gradient null point, calculated by the RESSQC delineation, was doubled. Then an expanding lateral buffer was drawn up gradient from the well using a 1 to 5 ratio. In other words, for every 500 feet of distance up gradient, the delineation was widened 100 feet. The expanding lateral buffer uses the doubled null point buffer as a staring point.

Analytical Models: The principal use of analytical models in this hydrogeologic setting characterized by high transmissivity and relatively steep ground water gradient setting is to simulate pumping conditions near the well. Regional conditions vary to the extent that extending a simple analytical model beyond conditions near the well will result in unacceptably inaccurate zone of contribution delineations.

The Station 15 RESSQC model used average values for transmissivity and gradient. Transmissivity was averaged for Stations 8, 9, 14, and 15. Gradient represents the average gradient between the well and about 10,000 feet up gradient. The model is conservative in that infiltration to the aquifer through the overlying clayey sand is not considered in the RESSQC model. Figure VA-15-2 shows the RESSQC delineation.

Values selected were:

Transmissivity:	4,590 meters^2/day
Pumping rate:	2,700 meters^3/day
Gradient:	0.0016
Flow angle:	-160° (250° compass bearing)
Porosity:	0.3
Aquifer thickness:	15 meters
Time of travel:	1, and 5 years

Calculated Fixed Radius: Figure VA-15-3 shows the calculated fixed radius delineation for Station 15 made using the volumetric flow equation referenced by EPA (June, 1987) as the Florida Department of Environmental Regulation volumetric flow equation.

Values used were:

Pumping rate:	34,200,000 feet^3/year (256 mg/y)
Porosity:	0.3
Length of well screen:	46 feet
Times of travel:	1, 5, 10, 20, and 50 years

Fixed Radius: Figure VA-AFR-1 shows the 3000 foot radius delineation. The radius is from an analytical model for 10 years time of travel using average parameter values for the 20 wells included in the Clark County investigation.

Simplified Variable Shapes: This method was not used.

Two Dimensional Numerical Model: Appendix S describes a two dimensional model for the high transmissivity aquifer that underlies the Vancouver area.

Three Dimensional Regional Model: Refer to US Geological Survey map report.

References Cited:

Collins, C.A. and T.M. Broad, 1991, Estimated Average Annual Ground-Water Pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 91-4018.

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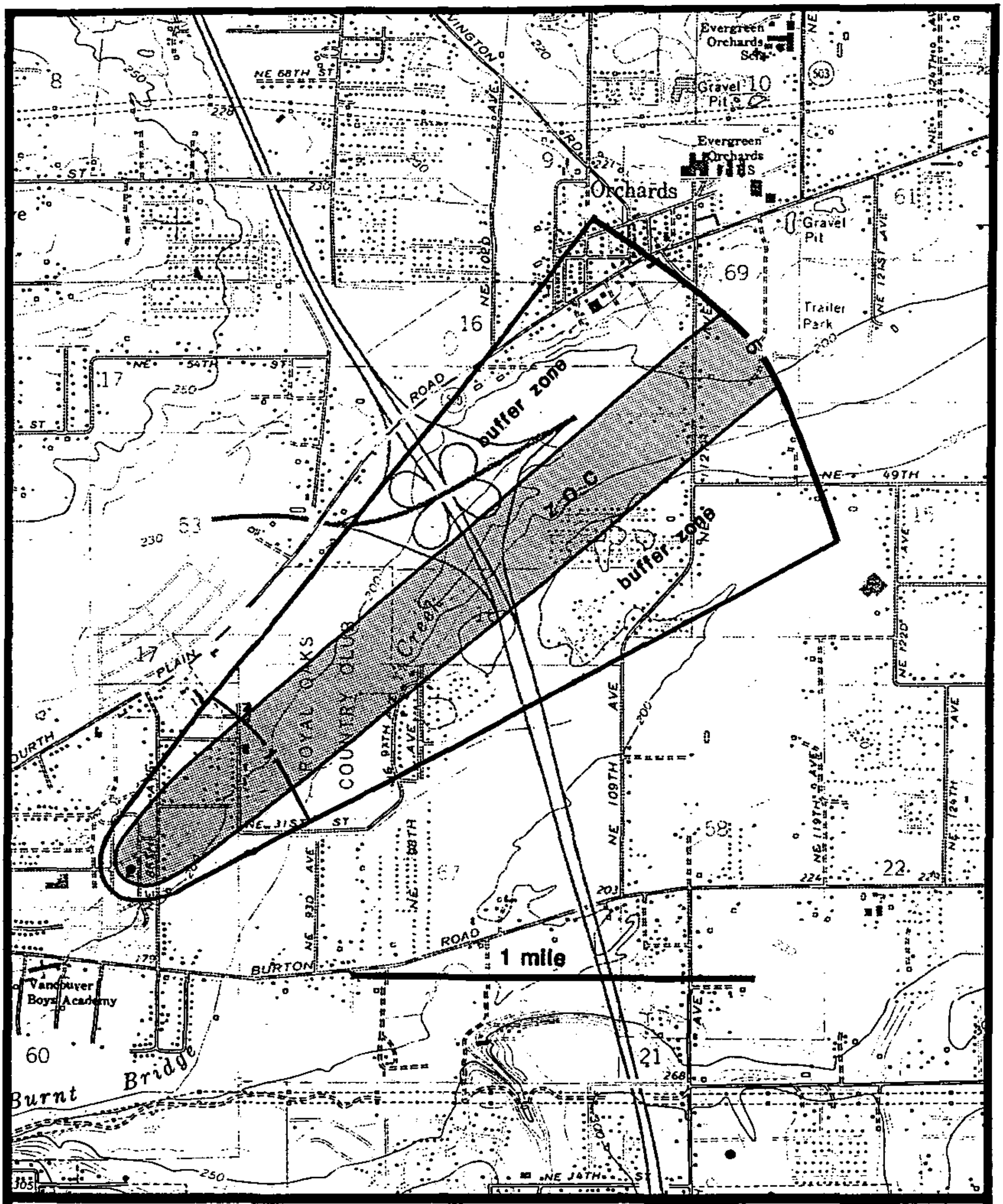

Figure VA-15-1. 1, and 5 year time of travel zones of contribution and buffer zone from hydrogeologic mapping and analytical methods for Vancouver Station 15.

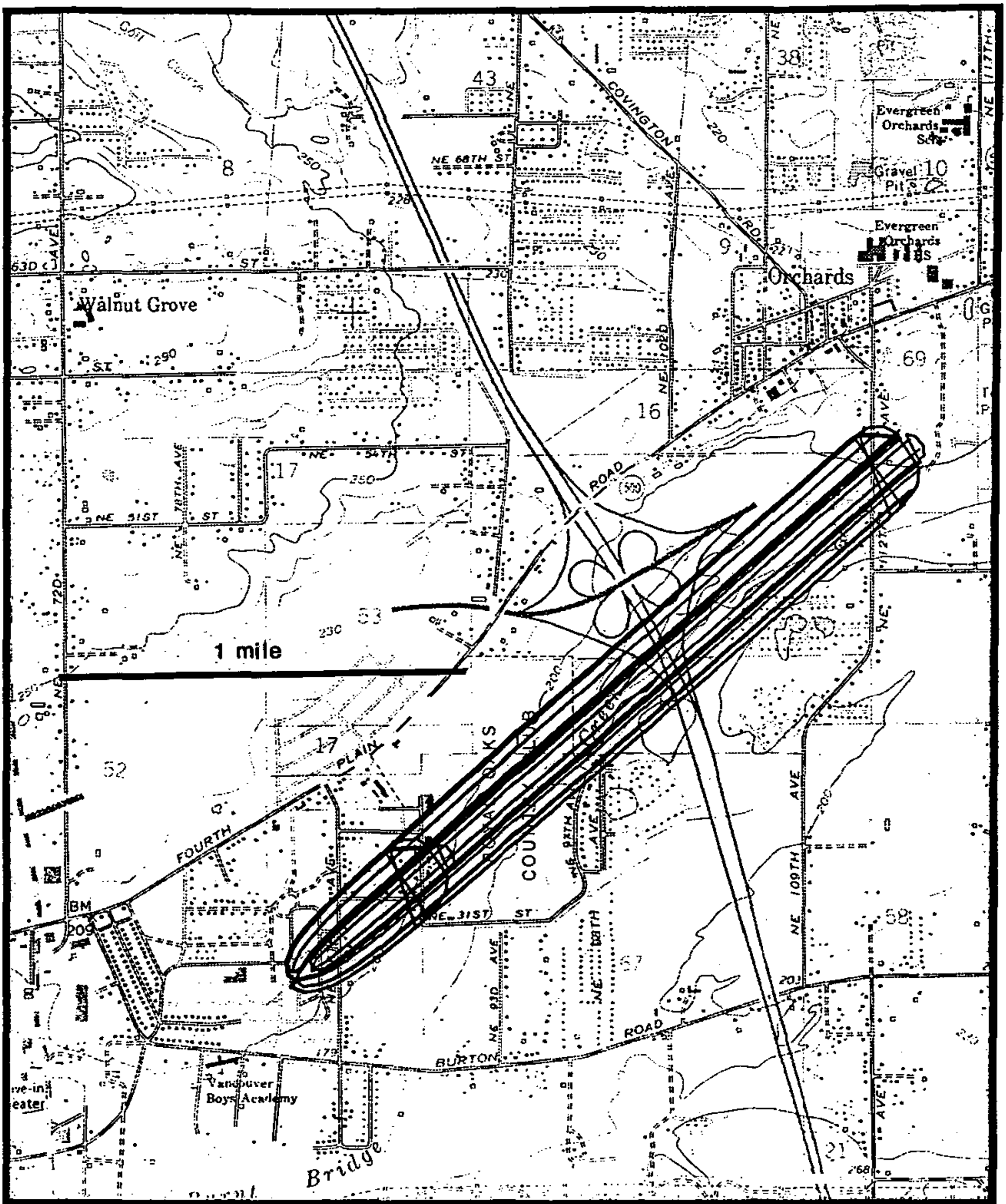

Figure VA-15-2. 1, and 5 year time of travel zones of contribution for Vancouver Station 15 using EPA RESSQC model.

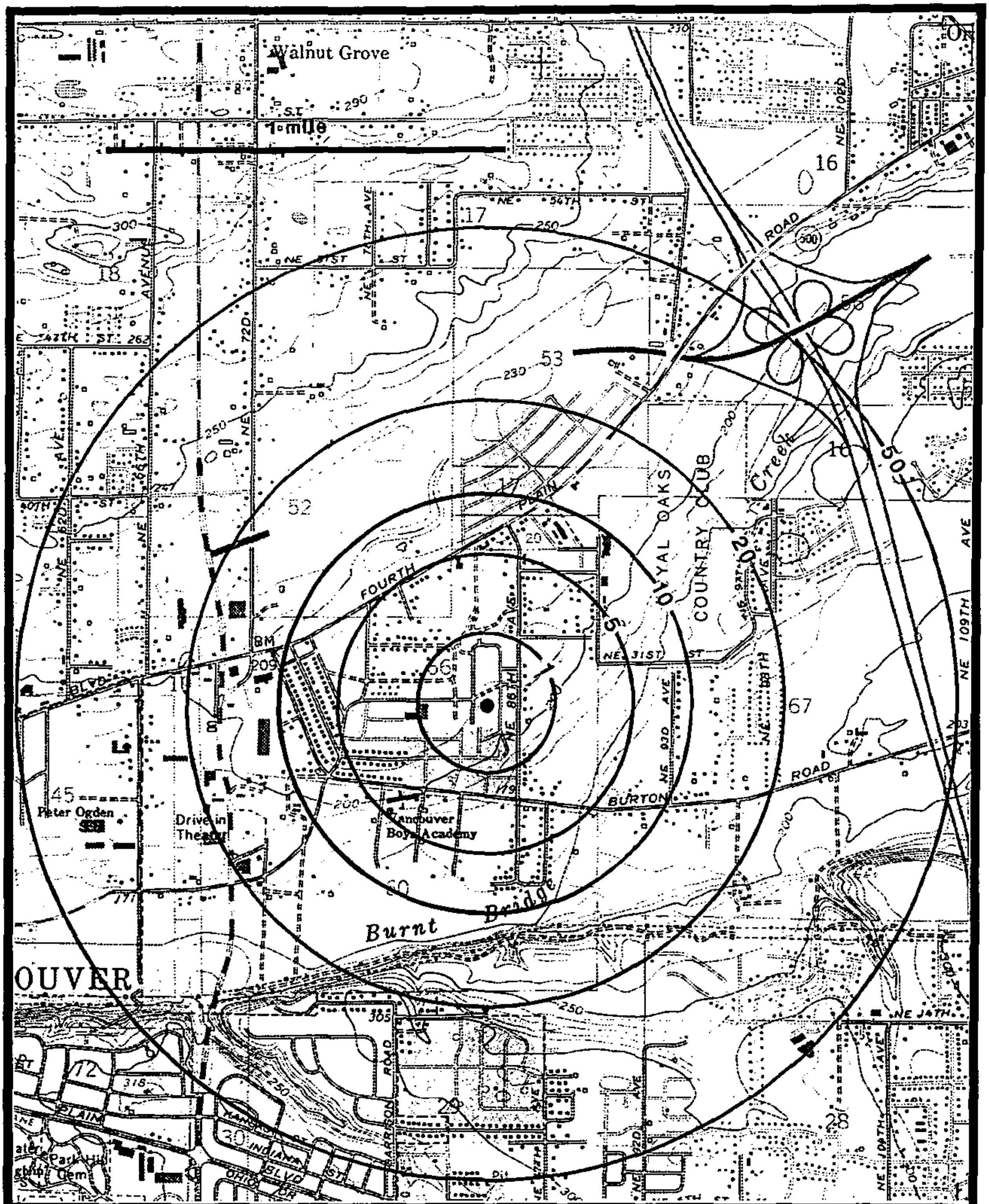

Figure VA-15-3. 1, 5, 10, 20, and 50 year time of travel zones of contribution using the volumetric flow equation for Vancouver Station 15.

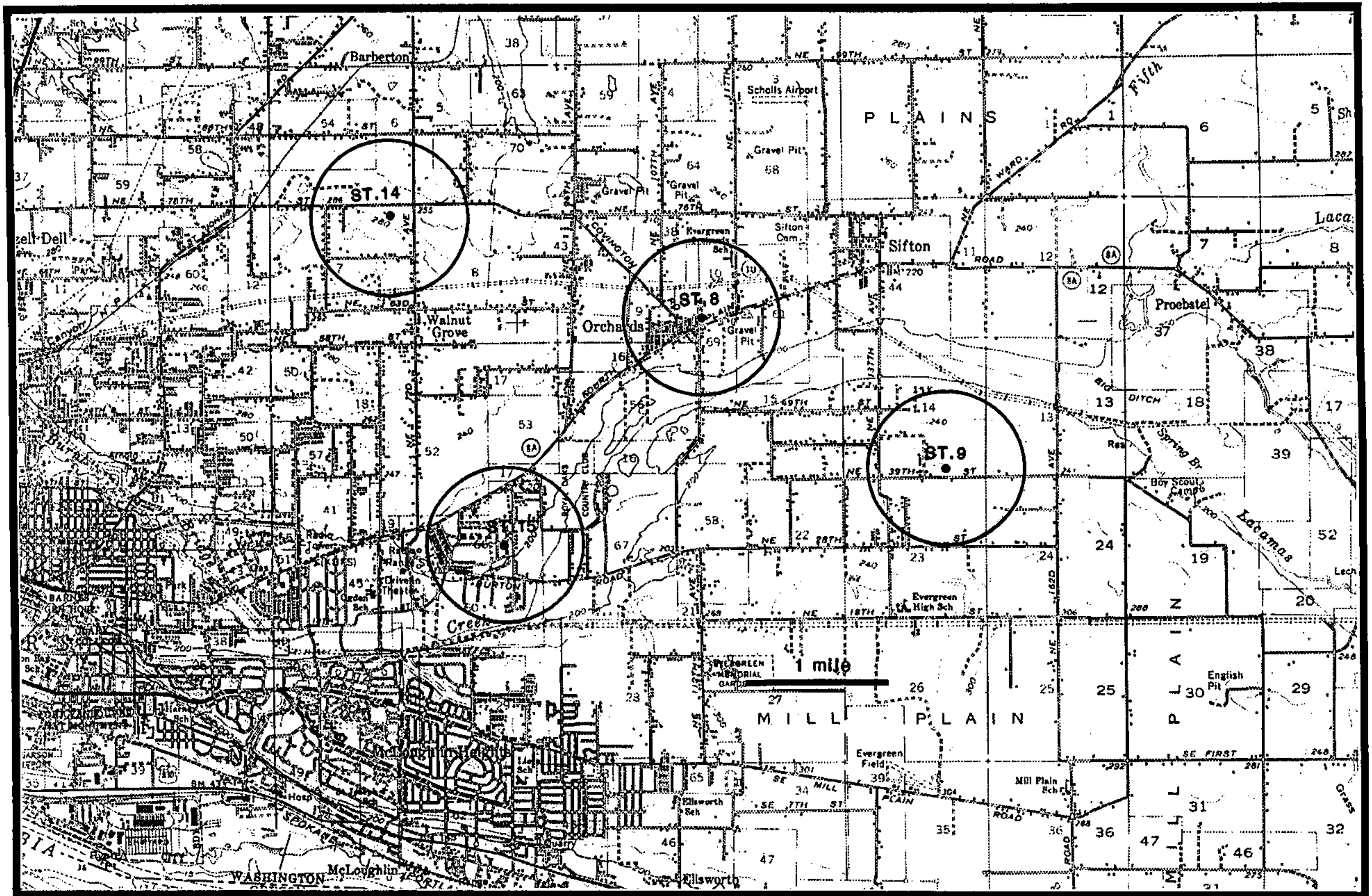

Figure VA-AFR-1. 3000 foot fixed radius delineation for Vancouver Stations 8, 9, 14, and 15.

Appendix Q

WELLHEAD PROTECTION AREA DELINEATION REPORT

YACOLT WELLS 3, 4, AND 6

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

Appendix Q
Wellhead Protection Area Delineation Report

Well: Yacolt wells 3, 4, 5, and 6

Setting: The town of Yacolt is in a small mountain basin tributary to the East Fork of the Lewis River. The elevation of the basin floor is about 700 feet at the north end and about 620 feet at the southern end. The town of Yacolt and the supply wells discussed in this report are in the northwest corner of the basin. There is a large amount of rainfall on the Yacolt area during winter months. However, the summer months are very dry.

The town of Yacolt currently derives all of its water supply from ground water. An older surface water impoundment and diversion is available as an emergency backup system. Town wells are all less than 100 feet deep and draw water from a shallow unconfined aquifer.

Aquifer Extent, Thickness, Saturated Thickness, and Boundaries: Geologic data sources include general regional reports by Mundorff (1964), Phillips (1987), and Swanson (1991). A hydrogeologic report by Carr/Associates (1990) for the town of Yacolt water system summarizes available data for the Yacolt wells and makes some interpretation of ground water flow conditions in the Yacolt area. US Geological Survey 1:24,000 scale topographic quadrangles were used to define the extent of the basin floor gravel deposit that serves as the local aquifer.

The Yacolt basin aquifer is within a 100 foot thick Pleistocene gravel and sandy gravel deposit mantling dense volcanic rock or clayey sediment. The basin floor is about 2.5 miles long and about one mile wide with the long axis aligned at about north 30 degrees west. The east and west sides of the basin are bounded by dense volcanic rock. The north end of the basin is less well defined and appears to be dense volcanic rock with thin overlying glacial drift deposits that predate the basin floor gravel. A wet marshy area occurs at the south or down gradient toe of the basin floor gravel near the contact with underlying volcanic rocks. Creeks draining south out of the Yacolt basin drop 100 feet through a canyon in the underlying volcanic rock into the East Fork of the Lewis River.

Saturated thickness of the gravel aquifer varies greatly with seasonal rainfall. Five years of water level records from the Yacolt wells show high water levels in winter and spring and low water levels in late summer and fall. Typically, winter and spring high water levels are 20 to 26 feet higher than late summer and fall low water levels. Saturated thickness is 25 to 30 feet at low water levels and 50 to 55 feet at high water levels.

Water enters the aquifer from several sources. Direct recharge during the rainy season can be huge. Annual rainfall averages 82.2 inches per year between 1983 and 1990. If half of this amount enters ground water, there would be 40 inches of recharge per year. In addition to direct recharge from rainfall, water probably flows into the valley aquifer margins as shallow ground water moving along the interface between low permeability volcanic rocks and overlying soil and drift.

Streams appear to act as a source of water during the late summer and fall low water level months. Carr/Associates (1990) show a comparison of water levels in wells 4, 5, and 6 with the elevation of nearby Cedar Creek. During the high water level seasons heads in the wells are higher than the elevation of Cedar Creek, indicating flow toward the creek. However, during low water level months water levels in the wells decline to near or below the level of Cedar Creek suggesting the possibility of flow from nearby Cedar Creek to the wells.

Gradient and Flow Direction: The Yacolt basin drains from north to south with tributary streams entering the valley from east, west, and north. Based on the few available wells with water level measurements, ground water flow mirrors this trend. Ground water flows toward wells 4, 5, and 6 from the west, east, and north. Gradient and flow direction may change locally from season to season due to the large fluctuation in water levels. The example of the seasonal change in gradient to Cedar Creek in the winter and away from Cedar Creek in the fall illustrates possible effects of seasonal water level fluctuations.

Gradients toward the Yacolt wells are steep, estimates made using well water levels and stream elevations are between 0.007 (7 feet drop per 1,000 feet horizontal distance) and 0.02 (2 feet drop per 100 foot horizontal distance). At wells 4, 5, and 6 flow direction could be from north, east, and west based on available data. At well 3 flow appears to be chiefly from west and possibly north based on the water levels at wells 2, 3, 4, 5, and 6 and stream elevations. However, inadequate water level data exists to state this with certainty.

Aquifer Properties:

Transmissivity: Analysis by Carr/Associates pump tests at wells 4, 5, and 6 gave transmissivities of 150,000 gallons/day/foot to 250,000 gallons/day/foot (reported by Doug Dow, Sept., 1991). Transmissivity estimates made at IRC using specific capacity data gave values between 150,000 and 200,000 gallons/day/foot.

Doug Dow also reported that during the first well test, pumped water discharged near the well was observed to raise water levels in the pumping well after a few hours. This suggests a very high vertical hydraulic conductivity.

At well 3, a single well recovery test gave a transmissivity of 8,000 gallons/day/foot.

Porosity: A porosity of 0.3 is estimated from standardized tables of aquifer material properties (Heath, 1983).

Pumping Rate: Regular meter readings for each well have been collected by the town of Yacolt since 1983. A high annual pumping rate of 3,173,000 feet^3/year in 1984 was used as a system total for any delineation zone of contribution calculations. The proportion of the total 1990 pumpage that each well produced was used to allocate the high year pumpage to each well.

Average pumping high year rates are 2,500 feet^3/day at well 3; 2,400 feet^3/day at well 4; 1,900 feet^3/day and well 5; and 2,000 feet^3/day at well 6.

Delineation: Hydrogeologic mapping was the principal delineation method applied to the Yacolt wells due to the strong influence of hydrogeologic factors such as aquifer hydraulic properties, aquifer boundaries, recharge conditions, and ground water flow patterns.

Ground water travel times from the upgradient (north, west, and east) edge of the Primary Protection Area are very short. Large aquifer hydraulic conductivity and steep water table gradients result in flow rate estimates of 15 to 40 feet/day. At these velocities, ground water moves from the edge of the aquifer, or Cedar Creek to wells in 50 to 150 days. This means that a contaminant spill or leak could rapidly migrate down gradient to supply wells. However, high recharge rates and rapid flow can act to dilute and move contaminants away from their source area, preventing accumulation of large concentrations in one area.

Primary Protection Area: A Primary Protection Area where all sources of contamination should be carefully managed is designated. The Primary Protection Area (Figure YA-1) is wholly included in the gravel aquifer. Boundaries are determined by the extent of the aquifer, ground water flow direction, ground water divides, and the south boundary of the town of Yacolt. The south boundary is somewhat arbitrary and over protective. Ground water from the southeast part of Yacolt is not likely to flow to town wells based on the limited available data. However, it seemed reasonable to include the entire town for hydrogeologic and management reasons. There is a high level of uncertainty about the direction of flow to wells making delineation of a Primary Protection Area boundary within town arbitrary and subject to revision. The small size of the town, desire for equitable treatment of all town residents, and the possibility of future ground water development within town boundaries argue for including the entire town.

Secondary Protection Area: A Secondary Protection Area was drawn to include areas of the gravel aquifer less likely to contribute to the town wells and areas underlain by older glacial deposits that discharge ground water into the gravel aquifer. These areas should be considered for management to prevent chemical contamination.

Additional Considerations: Because the gravel aquifer is recharged by both rainfall onto the valley floor and water running into the valley from the valley walls, some consideration should be given to managing activities within the valley wall land area from which surface water and shallow ground water drain into the Protection Areas.

During summer months, it is likely that Cedar Creek contributes water to the aquifer. If a contaminant spill into Cedar Creek occurred during the period of creek flow into the aquifer, the aquifer may become contaminated.

Some consideration should also be given to including the entire gravel aquifer south of Yacolt in the Secondary Protection Area with the goal of protecting the resource for future development.

Cited References:

Carr/Associates, Inc. June, 1990, Final Report-Hydrogeological Study for the Town of Yacolt Water System Improvements: Carr/Associates, Inc., Gig Harbor, Washington.

Heath, R.C., 1983, Basic Ground-Water Hydrology: U.S. Geological Survey Water Supply Paper 2220, 84 p.

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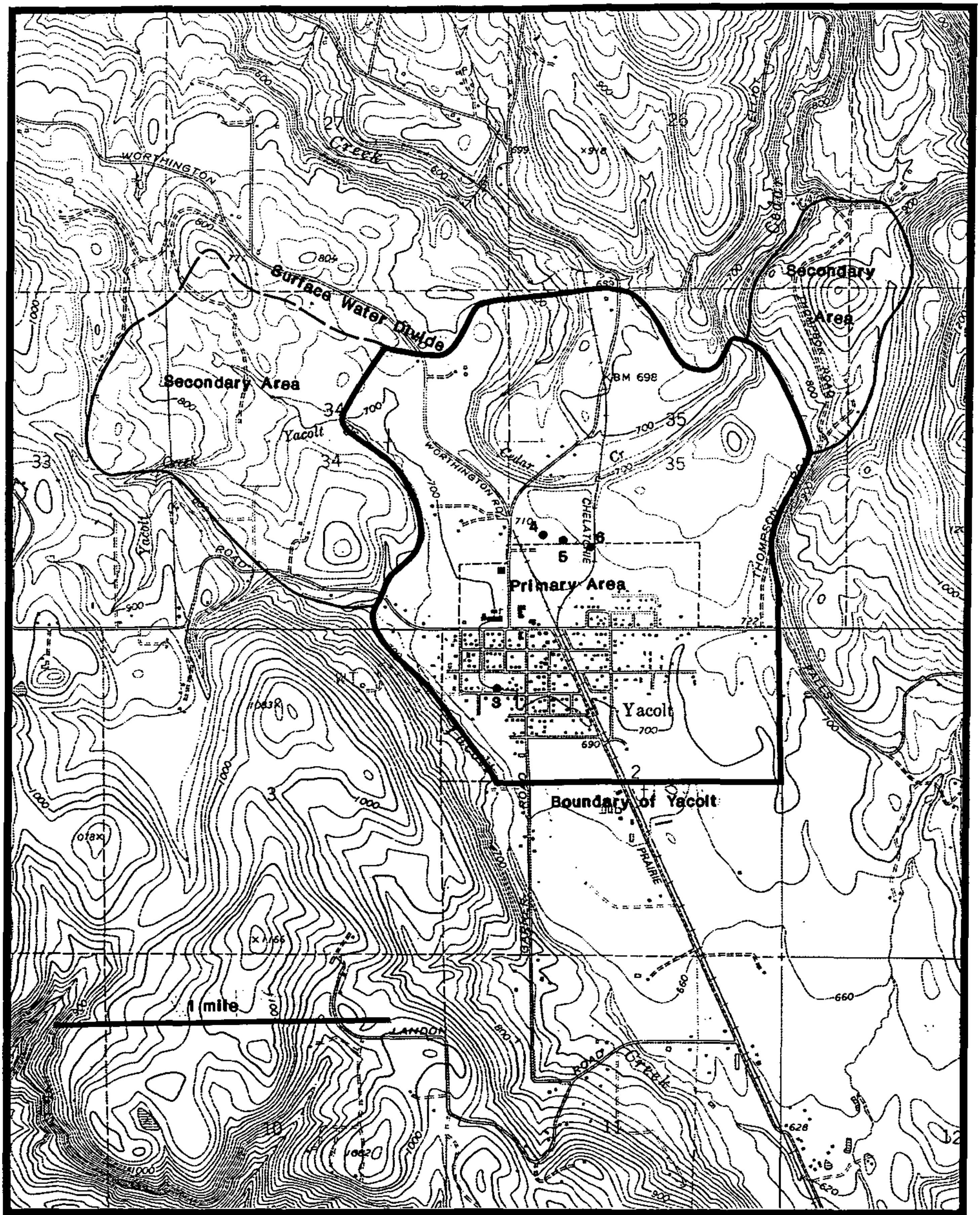

Figure YA-1. Wellhead protection areas for Yacolt, Washington.

Appendix R

WELLHEAD PROTECTION AREA DELINEATION REPORT

150 PERCENT PUMPAGE RATE INCREASE AT

VANCOUVER WELL STATION 15

Intergovernmental Resource Center

Rodney D. Swanson

January 1992

Appendix R

CHANGE IN PUMPAGE RATE DELINEATIONS FOR VANCOUVER STATION 15

Pumping rate at Station 15 was increased by a factor of 1.5 to test the influence on zone of contribution size. Three of the methods applied at IRC respond to changes in pumpage rate: calculated radius, analytical models (EPA WHPA models), and the two-dimensional FLOWPATH model for the Orchards aquifer. Unlike many of the wells examined in this project, each of these methods was applied to Station 15.

Figure VA-15-5 shows the original RESSQC delineation with an overlapping RESSQC delineation with pumpage increased from 700,000 gallons/day to 1,050,000 gallons/day. All other parameters are left as in the original model.

Figure VA-15-6 shows two sets of fixed radius delineations using the volumetric flow equation referenced by EPA (June 1987). The original delineation radii are solid lines, while the radii calculated using increased pumping rates are dashed lines.

The pumping rate of Station 15 was increased in the upper Orchards aquifer two-dimensional finite difference ground water flow model. The resulting capture zones for Station 15 were very similar to the previous model, with only a 10 to 15 percent widening in the one to five year capture zones. There was almost no change in length and little discernable change in capture zones for other modeled stations. The results are not drafted into a figure because there is an almost imperceptible changes at the scale mapped.

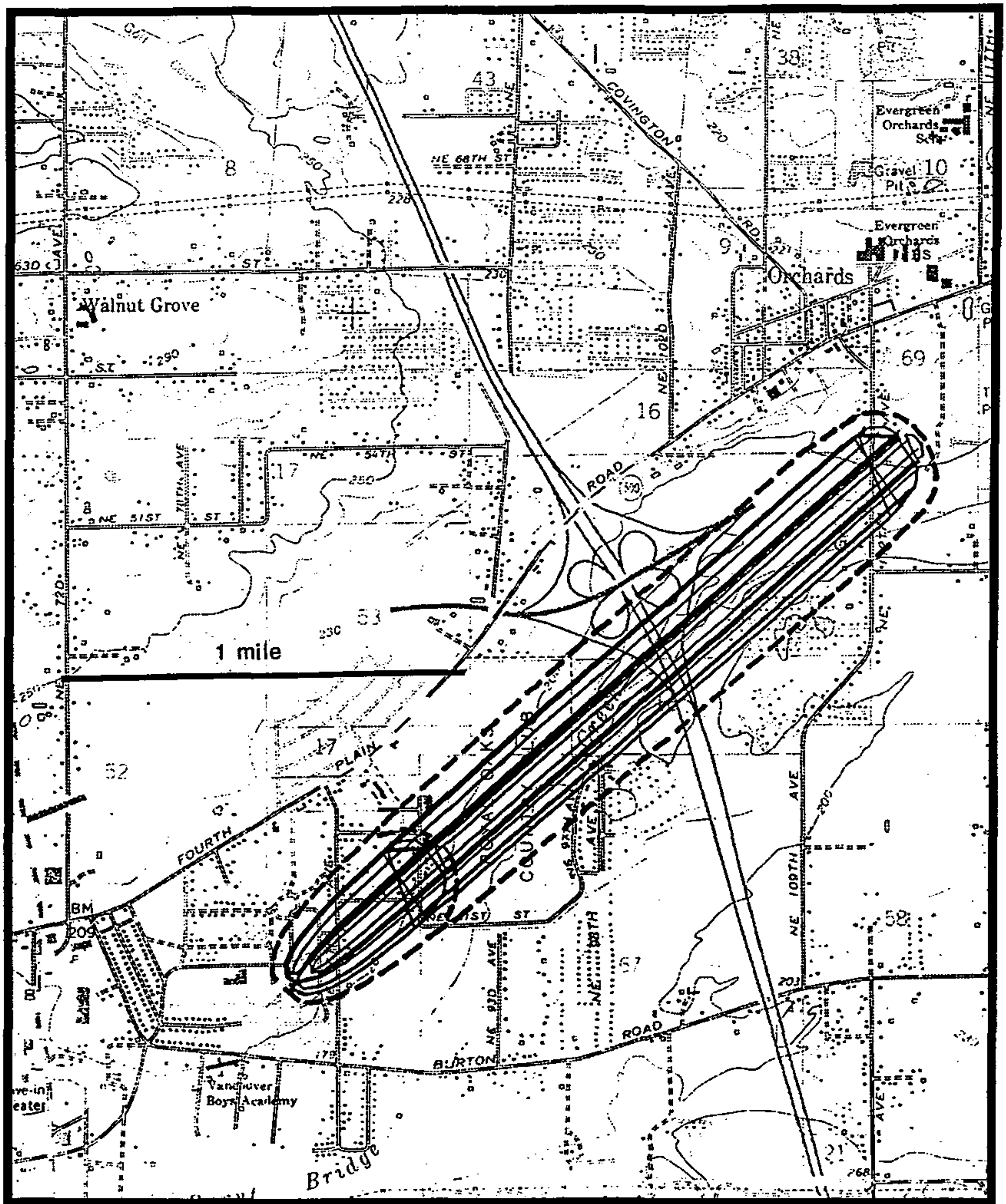

Figure VA-15-5. Comparison of 1 and 5 year RESSQC time of travel zones of contribution delineations with pumping rate increased by 1.5 times (dashed line).

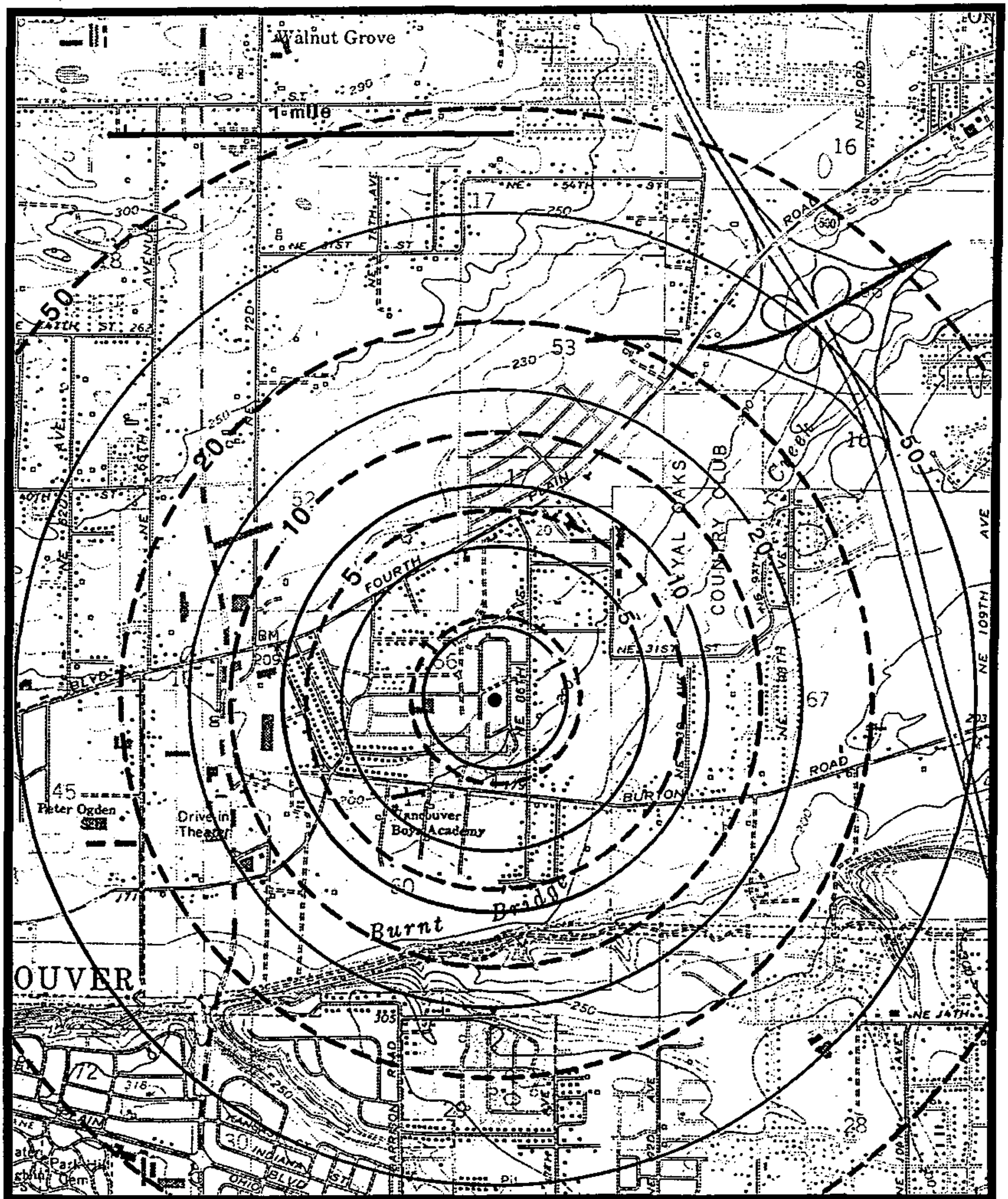

Figure VA-15-6. Comparison of 1, 5, 10, 20, 50 year volumetric flow equation fixed radius time of travel zones of contribution delineations with pumping rate increased by 1.5 times (dashed line).

Appendix S

ORCHARDS AQUIFER
TWO-DIMENSIONAL FINITE DIFFERENCE NUMERICAL MODEL

Intergovernmental Resource Center

Rodney D. Swanson and Irina Leschuk

November 1991

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Orchards Aquifer Two-Dimensional Numerical Model

Modeling Objective: These two-dimensional ground water flow and particle tracking models were produced for comparison to other delineation methods under Washington Department of Ecology Grant TAX 91075. The models identify zones of contribution for Vancouver well stations by simulating two dimensional ground water flow in the shallow high transmissivity aquifer underlying southwest Clark County.

Model Code: The copyrighted ground water flow model, FLOWPATH (Franz and Guiguer, 1989) was used for this investigation. FLOWPATH is one of several commercially available two-dimensional or quasi-three dimensional numerical models that can be applied to horizontal two dimensional analysis of an aquifer. FLOWPATH calculates steady-state head values, ground water velocities, pathlines, and well capture zones. FLOWPATH has been used in several EPA funded delineation investigations and was selected for use in this investigation because of its ease of application to zone of contribution calculation.

Model Construction Methodology: The models described in this report were designed to delineate one year to fifty year wellhead zones of contribution for large capacity City of Vancouver well stations. Models were developed using original interpretation of aquifer properties as well as existing data compiled for the USGS Portland Basin regional ground water flow model (Morgan and McFarland, USGS written communication, 1991).

The models simulate the regional high capacity gravel aquifer overlying the Troutdale Formation as an unconfined aquifer. The high yield water-bearing units used by most Vancouver well stations have been referred to as Orchards aquifer (Robinson, Noble, and Carr, 1980). Robinson, Noble, and Carr (1980) divided the Orchards aquifer into upper and lower units based on the separation of the aquifer into two distinct geographic areas with greatly differing water level elevations. Mundorff (1964) included these units in a regional gravel aquifer that encompassed both the upper Troutdale Formation and the younger gravels that are separated into the Orchards aquifer by Robinson, Noble, and Carr.

Wells in the lower Orchards aquifer have pumping levels near the elevation of the Columbia River at about 10 feet above sea level. Vancouver Well Stations 1, 3, and 4 are in the lower Orchards Aquifer.

The upper Orchards aquifer is described as the part of the Orchards aquifer with water levels above 50 feet elevation (Robinson, Noble, and Carr, 1980). Vancouver Well Stations 8, 9, 14, and 15, were assigned to the upper Orchards aquifer by Robinson, Noble, and Carr (1980). The water level elevation at these well stations is between 150 and 175 feet.

The USGS Portland Basin ground water flow model includes the upper Orchards aquifer in the uppermost part of the consolidated gravel aquifer, and the lower Orchards aquifer in the unconsolidated sedimentary aquifer.

Three separate models were constructed for this project. A general or base model, simulating the entire Orchards aquifer was made at the 3000 foot by 3000 foot grid size of the USGS Portland Basin ground water flow model. The base model was designed to test the conceptual basis of the two-dimensional model. The USGS model grid was used to facilitate transfer of data from the USGS to the two-dimensional model. After the base model was completed, separate models were made for the upper and lower Orchards aquifers by adding more detail to the general model.

Grid: The model grid was chosen to match the USGS grid to facilitate transfer of data to the local model. Also, the 3000 foot square regional model grid is appropriate considering the low density of hydrogeologic data points. The x-axis of the local two-dimensional model was placed at the center of row 50 in the USGS Portland Basin ground water flow model. The y-axis of the two-dimensional model was placed at the center of column 11 of the Portland Basin ground water flow model. Figure VA-2D-1 shows the model grid and model boundaries.

Additional definition of pumping effects near the well areas was gained by further dividing the existing general model cells in the lower Orchards aquifer model (Figure VA-2D-2), and the upper Orchard aquifer model (Figure VA-2D-3). Changing the cell size can change the model results.

Model Edge Boundaries: A no-flow boundary was set just outside the up gradient extent of the Orchards aquifer. A no-flow boundary was set parallel to the east-west ground water divide between Salmon Creek and the Columbia River north shore. A no-flow boundary was also placed at the center of Columbia River.

The Orchards aquifer thins along the bluffs north of the Columbia River. In an area near the I-205 Bridge, the aquifer is completely cut and the underlying Troutdale Formation is exposed in the valley wall. The model does not attempt to represent the aquifer truncation above the Columbia River, but continues the aquifer through to the model edge beneath the Columbia River. This model feature is not within the calculated zones of contribution, but should be considered when using model results.

River Nodes: FLOWPATH can incorporate river leakage into head calculations. River nodes were placed in the model by taking cell conductance and river stage values from the USGS Portland Basin ground water flow model and converting them to the proper units for the two-dimensional model.

Constant Head Nodes: FLOWPATH requires specification of at least one constant head node. One constant head node, matching observed water level, was placed at the up gradient edge of the models.

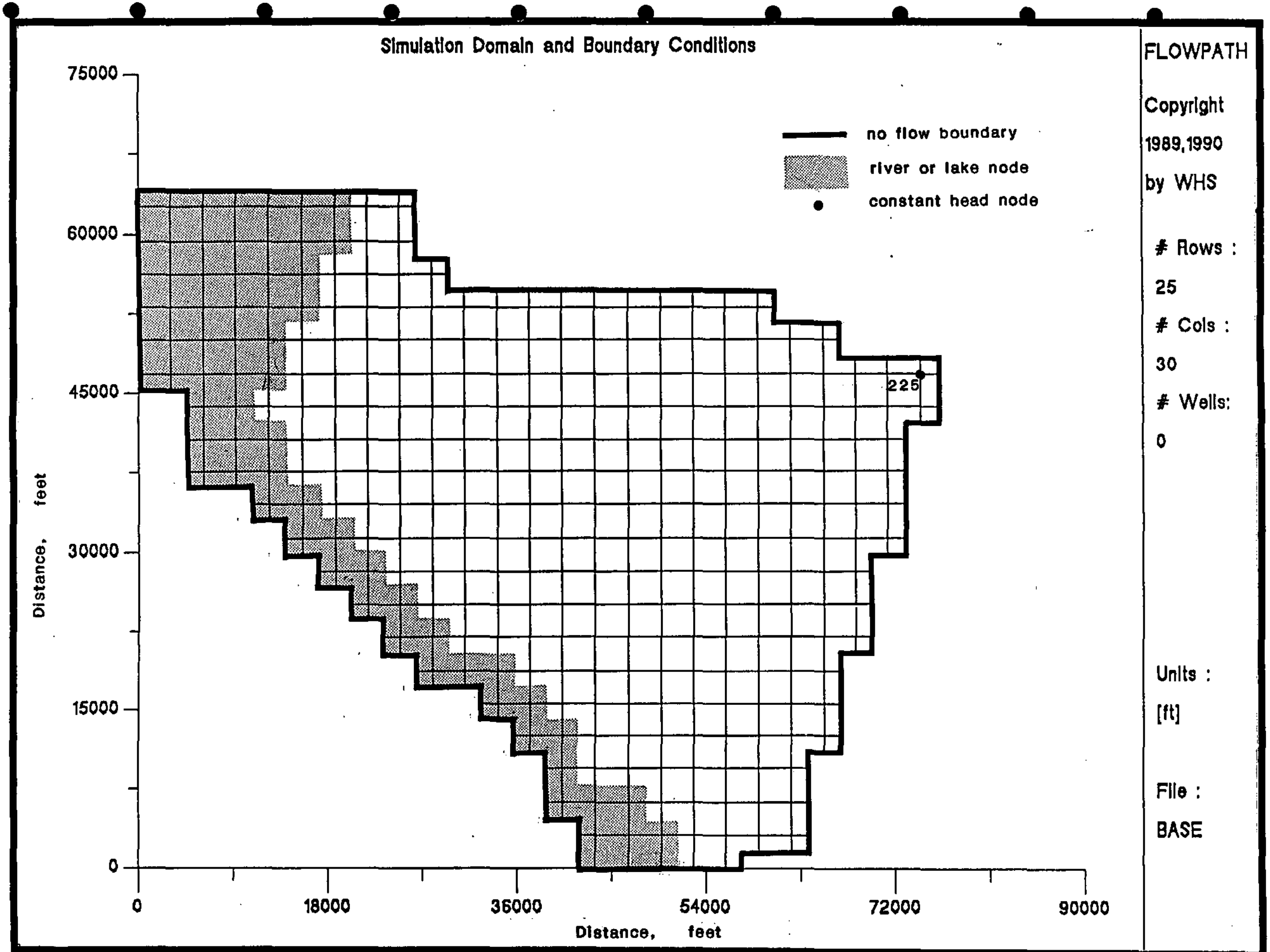

Figure VA-2D-1. Base model grid and boundaries.

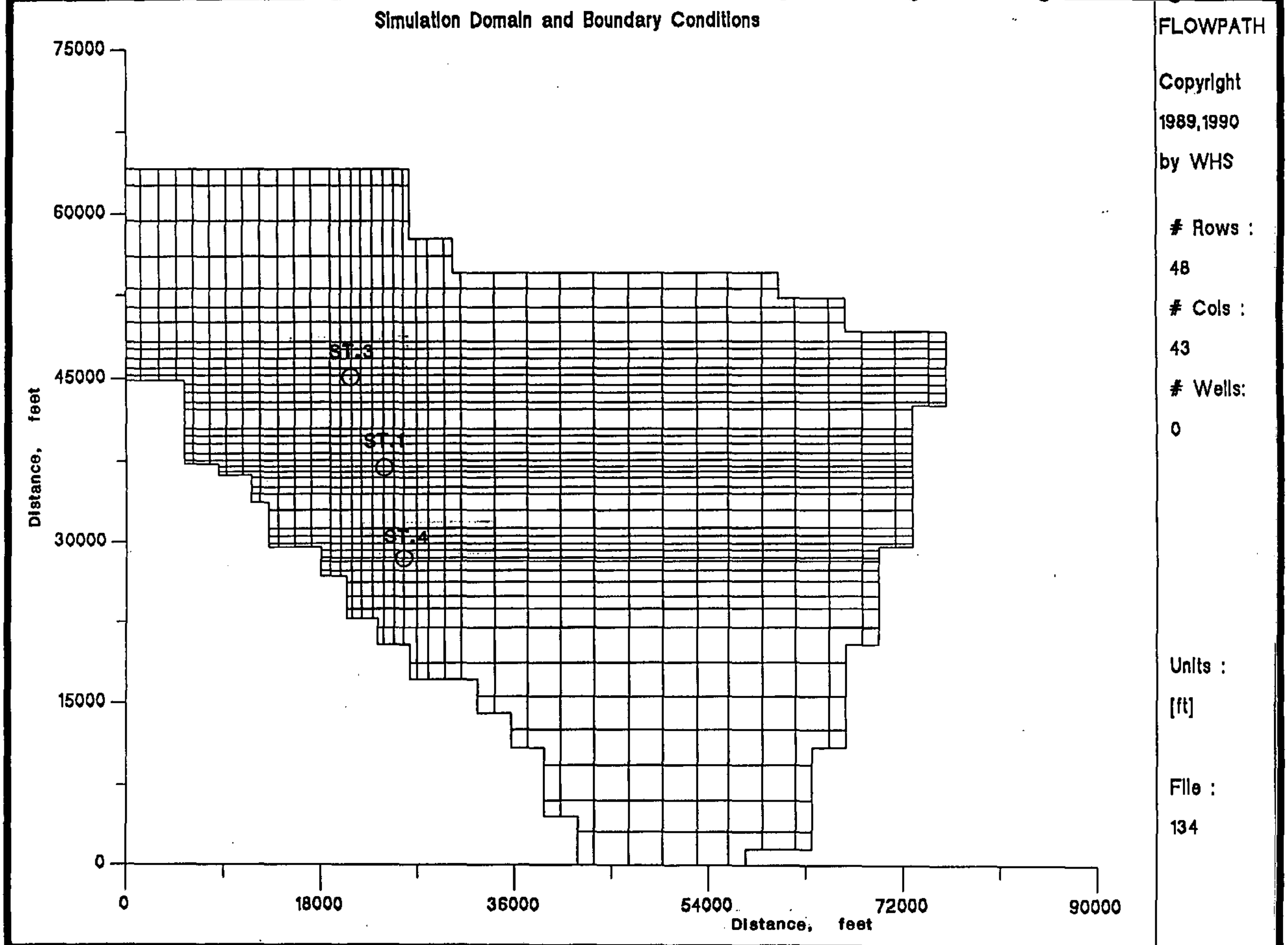

Figure VA-2D-2. Lower Orchards aquifer model grid and pumping wells.

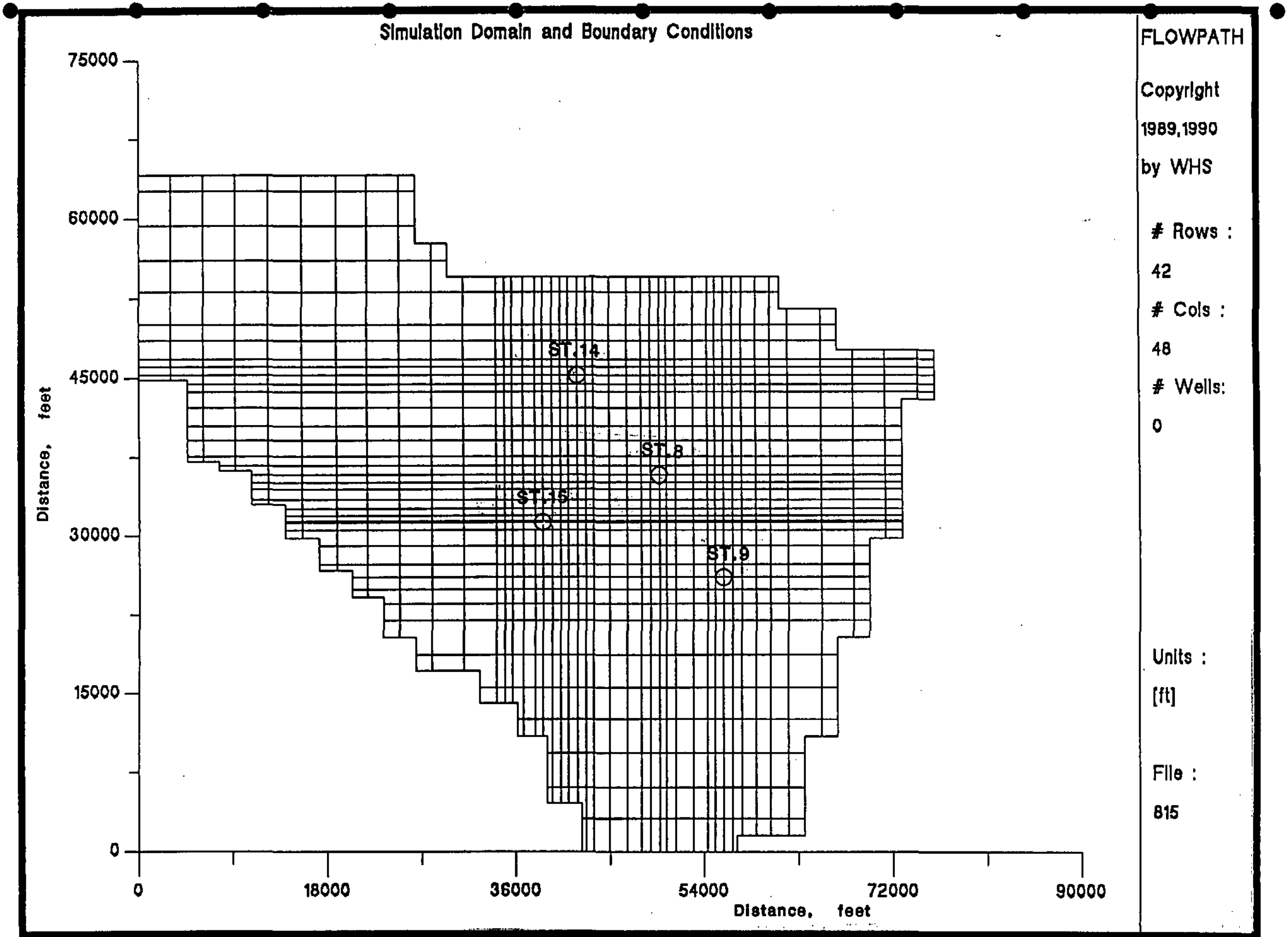

Figure VA-2D-3. Upper Orchards aquifer model grid and pumping wells.

Aquifer Bottom: FLOWPATH uses aquifer bottom elevation to describe the shape of the modeled unconfined aquifer. An aquifer bottom elevation map was drawn using interpreted well records from wells with high yields and specific capacities. Vancouver well stations were used as principal control points because there was more information describing lithology and hydraulic properties for wells at these sites.

The aquifer bottom elevation data for wells was hand contoured. The contoured bottom elevation was transferred to the model by overlaying the model grid on the contoured map, drawing blocks of nodes with like bottom elevations, and entering the bottom elevation blocks into the model data sets. Some simplification of the bottom elevations occurred during this process.

Hydraulic Conductivity: Transmissivities calculated by consultants for the Vancouver well stations, and transmissivities estimated from reported pump test yield and drawdown (specific capacity) were used to estimate aquifer hydraulic conductivity. Modeled hydraulic conductivity values were adjusted downward from well test values to compensate for lower permeability material within the bulk aquifer.

The lower Orchards aquifer was assigned a hydraulic conductivity of 1000 feet/day based on transmissivity values at Stations 1, 3, and 4. The area around Stations 8, 9, 14, and 15 was assigned a hydraulic conductivity of 390 feet/day. The rest of the Orchards aquifer was assigned a hydraulic conductivity of 300 feet/day or 100 feet/day. The lower value was used in areas where the aquifer thinned to less than forty feet or was possibly unsaturated due to the rising elevation of the underlying Troutdale Formation. The area where the Troutdale Formation is exposed at the upper margin of the model were assigned a hydraulic conductivity of 40 feet/day.

Porosity: A porosity of 0.3 (30 percent) was chosen for the aquifer. Porosity is not directly measured for these materials. However, estimates can be made from lithology descriptions. Tabulated observed porosity values for gravels vary from near 20 percent to 40 percent of the rock volume, with typical values between 20 and 35 percent. The porosity range is due to variations in particle sorting in for different gravel samples. The modeled aquifer is primarily coarse sand and gravel with lesser amounts of fine sand and silt, suggesting that it may be in the higher part of the porosity range, 30 to 35 percent.

Recharge and Vertical Flow Through Cells: Usually little data describing recharge rates exists and a single recharge rate is often assigned to an entire model area. The intention with this simple model was to use a single recharge rate for the entire area. Cell by cell recharge estimates have been made by the USGS (written communication, 1990) for the Portland Basin ground water flow model. Values range from near zero in industrial and commercial areas to over 30 inches per year in areas with dry well recharge. Typical recharge rate values are about 17 to 18 inches/year, or 0.004 feet/day in the upper Orchards aquifer and 5 to 15 inches/year (0.001 to 0.0035 feet/day) in the lower Orchards aquifer area.

Since the lower boundary of a simple two-dimensional model aquifer is assumed to be impermeable, vertical leakage out of, or into the aquifer through its bottom needs to be accounted for as a flow into or out of each node. Normally, these values are estimated and incorporated into the model. In this model, vertical leakage through the aquifer bottom is included in the recharge estimates. Cell by cell leakage rates through the base of layer one, calculated by the Portland Basin model were used to get a general estimate of the vertical flow rate through the modeled aquifer. Modeled flow is downward (out of the aquifer) in most of the area. Flow is upward (into the aquifer) in southwest Vancouver and the lowlands along the Columbia River. Most rates are between 0.005 feet/day into the aquifer to 0.005 feet/day out of the aquifer. Much of the area with downward flow had values between 0.0005 and 0.003 feet/day. Upward flow rates in southwest Vancouver and the Columbia River lowlands were typically between 0.0005 and 0.002 feet/day.

After reviewing the recharge rate distribution and vertical flow rate data from the regional model, an initial estimated net recharge rate of 0.002 feet/day was assigned to the entire two-dimensional model.

Well Pumping Rates: Only the delineated Vancouver well stations were incorporated into modeled pumping rates. An initial model with no pumping was made for the general model and the well area models.

Well pumping rates were based on the high year pumping rate at each station. This is the same rate used in the simpler delineation methods described in Appendix A. Table 1 shows the pumping rate used at each well station.

Table 1

Modeled Well Station Pumping Rates

Well Station	Pumping Rate	Base Year
Station 1	9,000,000 gallons/day	1990
Station 3	2,200,000 gallons/day	1990
Station 4	5,400,000 gallons/day	1988
Station 8	1,800,000 gallons/day	1988
Station 9	6,730,000 gallons/day	1990
Station 14	2,600,000 gallons/day	1990
Station 15	700,000 gallons/day	1988

Solution Criteria: FLOWPATH documentation states that model solution convergence is achieved if, for every node, the discrepancy between the current head value and the previous head value is less than 0.2 percent of the total head difference in the system. With a total head difference in the modeled system of about 250 feet, 0.2 percent is 0.5 feet. After calibration, all models reached convergence at 0.2 percent error.

Model Calibration: Model calibration is performed by matching model calculated results to observed values. Separate model calibrations were done for the lower and upper Orchards models. To calibrate these models, calculated aquifer head was matched to water level maps drawn from observed aquifer water levels. Models that included pumping wells were compared to a water level map for the regional gravel aquifer drawn using synoptic water level measurements collected by the USGS in spring 1988. This regional gravel aquifer includes both the upper part of the Troutdale Formation and the Orchards aquifer. Also, modeled drawdown at Vancouver well stations was compared to observed drawdowns reported by the City of Vancouver.

Original parameter values were changed little during calibration. Hydraulic conductivity was decreased from the original estimates at the north, south, and west edges of the model to more closely approximate properties of less conductive aquifers in these areas. Aquifer bottom elevation was decreased in the area just north of the Columbia River to eliminate dry cells, allowing the model to solve itself within specified closure tolerance.

The net water input to the aquifer from recharge and leakage, modeled as a recharge rate of 0.002 feet/day was varied to test the effect of changing this parameter. After trying model-wide values of 0.001 feet/day and 0.003 feet/day, the best fit was determined to be the original estimate of 0.002 feet/day.

Further discretizing the model by adding cells near wells had a significant effect on model results. Generally, water level was smoothed by adding cells, having the effect of raising water levels and steepening gradient in the areas of interest.

A comparison of models with and without pumping wells was done as a crude check to see if the volume of water passing through the model was accurate. Inappropriately small or large differences between pumping and non-pumping water levels indicate that either too much or too little water is flowing through the model. Figure VA-2D-4 shows pumping levels for the lower Orchards aquifer, while Figure VA-2D-5 shows heads calculated without pumping. Pumping and non-pumping model heads for the upper Orchards aquifer are shown in Figures VA-2D-6 and VA-2D-7.

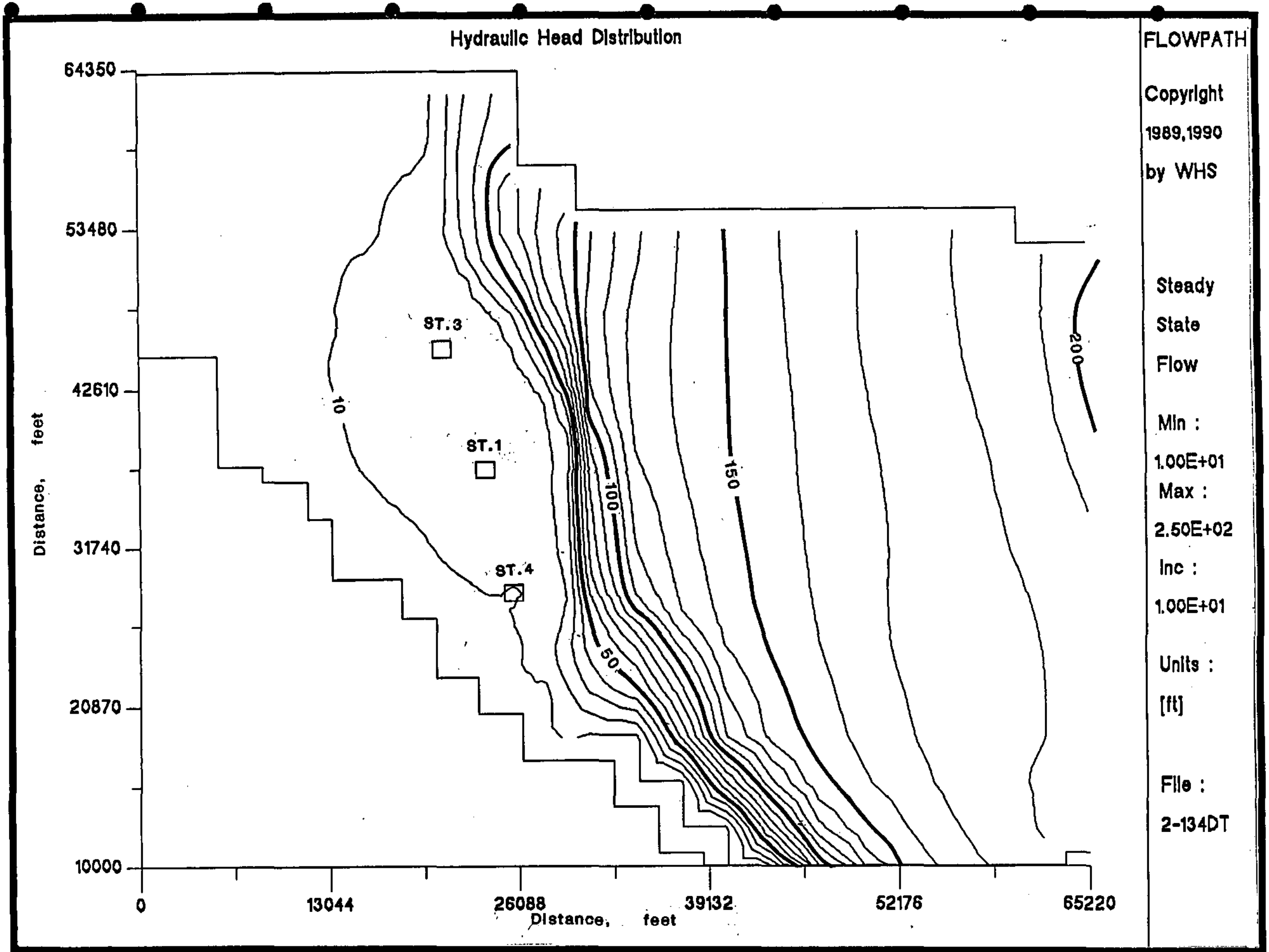

Figure VA-2D-4. Modeled water level surface in the lower Orchards aquifer with pumping at Stations 1, 3, and 4.

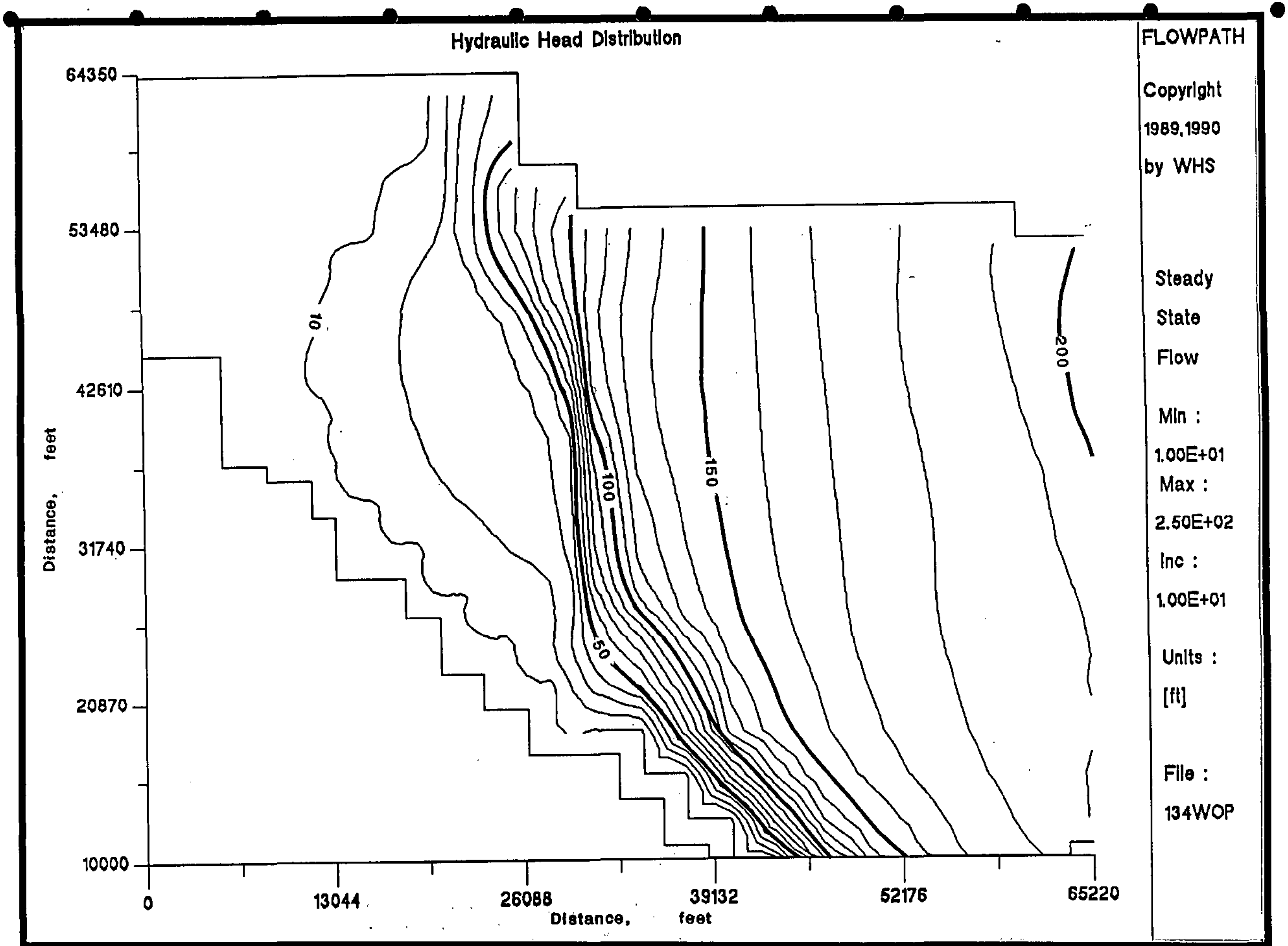

Figure VA-2D-5. Modeled water level surface in the lower Orchards aquifer without pumping.

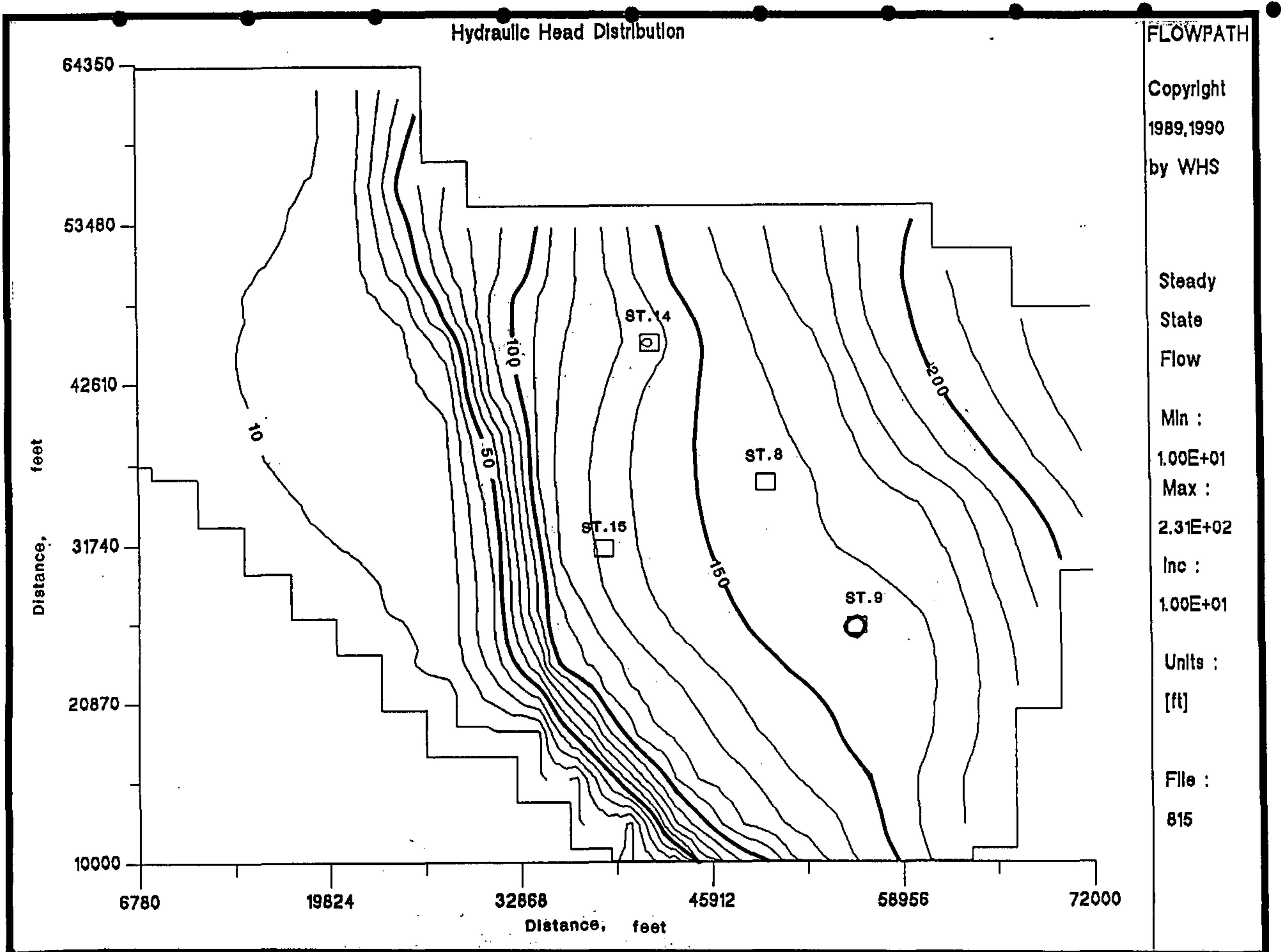

Figure VA-2D-6. Modeled water level surface in the upper Orchards aquifer with pumping at Stations 8, 9, 14, and 15.

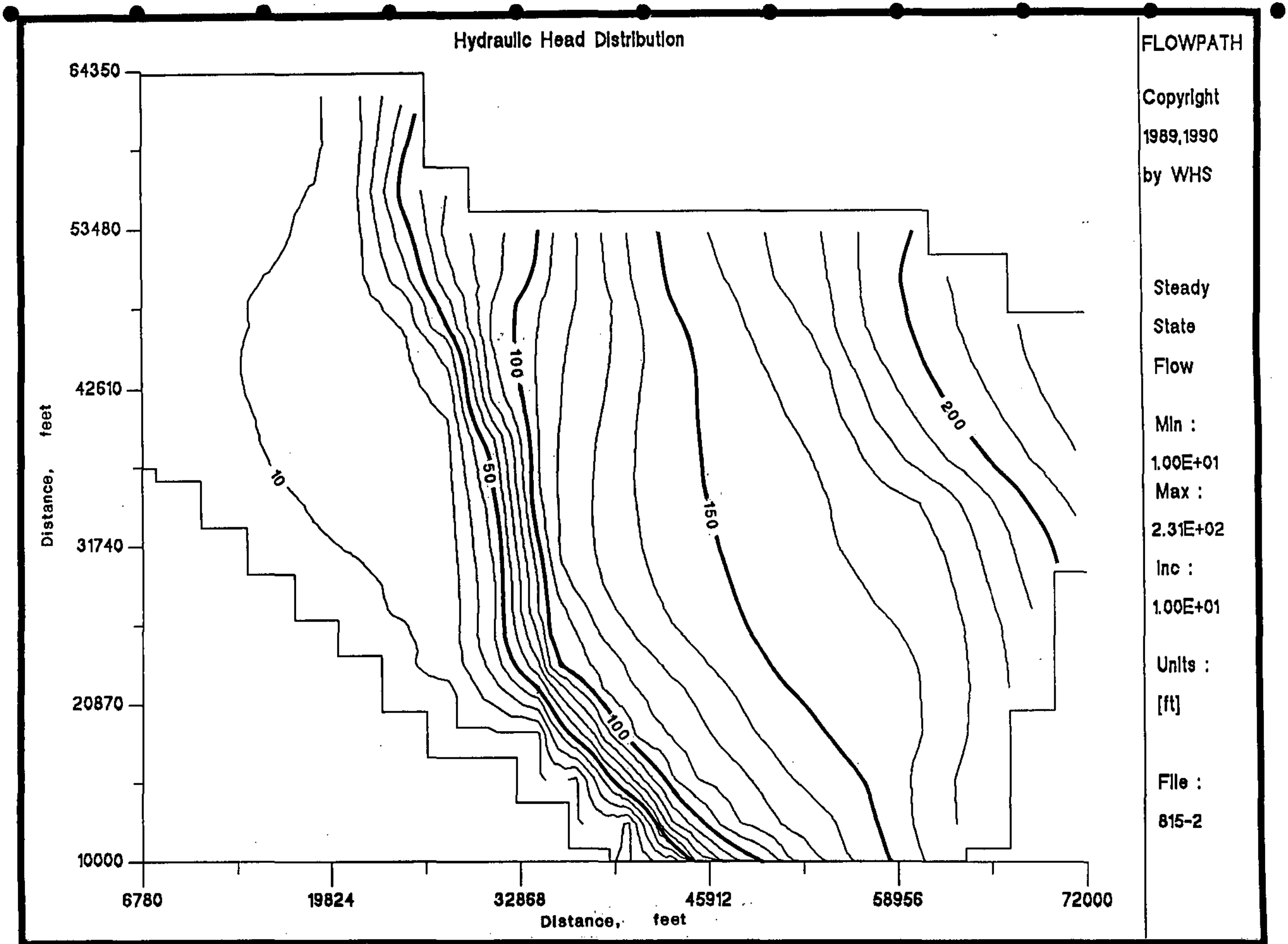

Figure VA-2D-7. Modeled water level surface in the upper Orchards aquifer without pumping.

Modeled drawdown was compared to observed drawdown at Vancouver well stations. Modeled drawdown was taken from the cone of depression depth at each well station. City records were used to obtain values for observed drawdown. Table 2 shows a comparison of observed well drawdown and modeled cones of depression.

Table 2

Observed and Modeled Drawdown

Well Station	Observed Drawdown	Modeled Drawdown
Station 1	2-12 Feet	≈10 Feet
Station 3	3-7 Feet	1 Foot
Station 4	5-11 Feet	8 Feet
Station 8	3-14 Feet	3 Feet
Station 9	5-40 Feet	10-12 Feet
Station 14	3-9 Feet	10 Feet
Station 15	2-5 Feet	1-2 Feet

As an additional check of water level gradient above the delineated wells was made to compare modeled gradients to observed gradients. This is important to assure that the width and length of the zones of contribution are accurate even if modeled water levels did not exactly match observed water levels. Modeled water level gradient above pumping wells were scaled and compared to the observed 1988 water levels. There was good agreement between observed and modeled water level gradients.

Model Limitations: Two types of limitations are described for these models, limitations due to the model code and limitations due to the hydrogeologic information and assumptions used to construct the models. Model code characteristics that significantly influence the accuracy include: limitations of two dimensional flow simulation to characterize vertical flow in pathline calculation, lack of time consideration in steady state solution, and limitations in discretization of model parameters. Results from these models should be used with a clear understanding of the influence of model construction and limitations.

Model Code Limitations: In a practical sense, the assumption of two dimensional flow is the most serious model code limitation for zone of contribution delineation. In areas with low recharge rates or low rates of interaquifer vertical flow, two dimensional models may accurately represent actual time related zones of contribution. However, in areas with high recharge rates and vertical flow through aquifers the two dimensional flow model will be less accurate because water contributing to the well actually may enter the aquifer at a point closer to the well than the modeled two dimensional travel path. The effect of this is that for longer travel times, two dimensional model zones of contribution are likely to be larger than those calculated by a three dimensional model using a three dimensional particle tracking program.

Morrissey (1989) notes that, based on heat distribution, generally two-dimensional models yield smaller zones of influence than three dimensional models. This is due to the relatively high ratio of horizontal to vertical hydraulic conductivity of most aquifers, which, when modeled will result in larger zones of influence.

The degree of discretization, or the number and size of cells in the model area can affect model results. Generally smaller cells in the area of interest allow more accurate solutions. FLOWPATH allows up to 100 nodes or cells in each direction. These models use less, but more could be added. Changing the cell size can have significant effects on model results.

Hydrogeologic Information Limitations: Morrissey (1989) lists what he considers to be minimum hydrogeologic data requirements for a two dimensional model simulation. In order of importance these are: a water level map, aquifer boundary conditions, well field design criteria, aquifer hydraulic properties, and recharge rates.

Water level mapping: There is a good water level map for the modeled area drawn from recently measured (spring 1988) water levels. One limitation of the water level map is that it includes water levels from both the Orchards aquifer and the underlying lower permeability Troutdale Formation. Generally, water levels in the Troutdale Formation are slightly lower than the overlying aquifers.

Boundary conditions: Boundary conditions describe the location and hydrologic conditions at model boundaries. This can include the geometry of the model, the groundwater flow rates across the edges of the model, and conditions that control groundwater flow rates across the edges of the model.

Up gradient model boundaries are located beyond the mapped extent of the modeled unit and at a ground water divide parallel to the direction of flow. The down gradient model boundaries are simulated by leakage to the Columbia River. River bottom conductances are taken directly from the calibrated USGS Portland Basin model and are assumed to be the best data available.

Description of the aquifer bottom elevation is fairly good at Vancouver well stations, but little good data exists in much of the area between the well stations. Accuracy of aquifer bottom elevation is most critical in the area east of Well Stations 1, 3, and 4, where elevation drops rapidly from 50 to 100 feet above sea level to well below the Columbia River. This has a large influence on the rate and direction of simulated ground water flow.

Another boundary condition limitation of the model is the rate of flow across the aquifer bottom. This is not known, but was estimated from USGS model results and incorporated into a single recharge rate for the entire model. Further discretization of this parameter using good estimates could increase model accuracy.

Well field design criteria: Well field pumping rates are averaged from high pumpage year totals. Other pumping is not included in the model but could be added. If additional pumping wells are added, model water levels should be compared to observed to assure model accuracy. In the model, wells are assumed to fully penetrate the aquifer. This is not always the case for Vancouver wells. Screened intervals generally are shorter than aquifer thickness.

Aquifer hydraulic properties: Morrissey (1989) states that analysis of a hypothetical aquifer showed variations in hydraulic conductivity to be less important than other parameters. Hydraulic conductivity was estimated from very few data points and is only described in the horizontal direction. However, blocks of varying conductivity were incorporated into the model based on available data.

Recharge: Recharge is important to this model because rates are high in this area. The model uses a single annual average value and incorporates both recharge and aquifer bottom boundary conditions. This single value is simplistic but produces good results with these models.

Model Results: The model results are two dimensional time related zones of contribution for the Vancouver well stations in the upper and lower Orchards aquifer. Calculated aquifer heads fairly closely matched observed heads. This suggests that the zone of contribution direction of flow is accurate. Model velocities are not as easy to verify. Inaccuracy in velocity calculations could produce zones of contribution that are either too large or too small.

Base Model: This model was designed to test the conceptual model and boundary conditions. It does not include pumpage. Figure VA-2D-8 shows calculated heads from this model compared to 1950 water levels mapped by Mundorff (1964). Mundorff's water level map was chosen because it predates heavy use of the lower Orchards aquifer well stations and installation of the upper Orchards aquifer well stations.

Lower Orchards Aquifer Model: This model delineates 1, 5, and 10 year time related zones of contribution for lower Orchards aquifer Vancouver Well Stations 1, 3, and 4. The model was made by adding more detail to the base model by adding cells around the modeled wells, then making modifications to aquifer bottom and hydraulic conductivity to more accurately reflect our data and conceptual model. Figure VA-2D-9 shows the delineations made by this model, along with water level contours from the 1988 observed water level map.

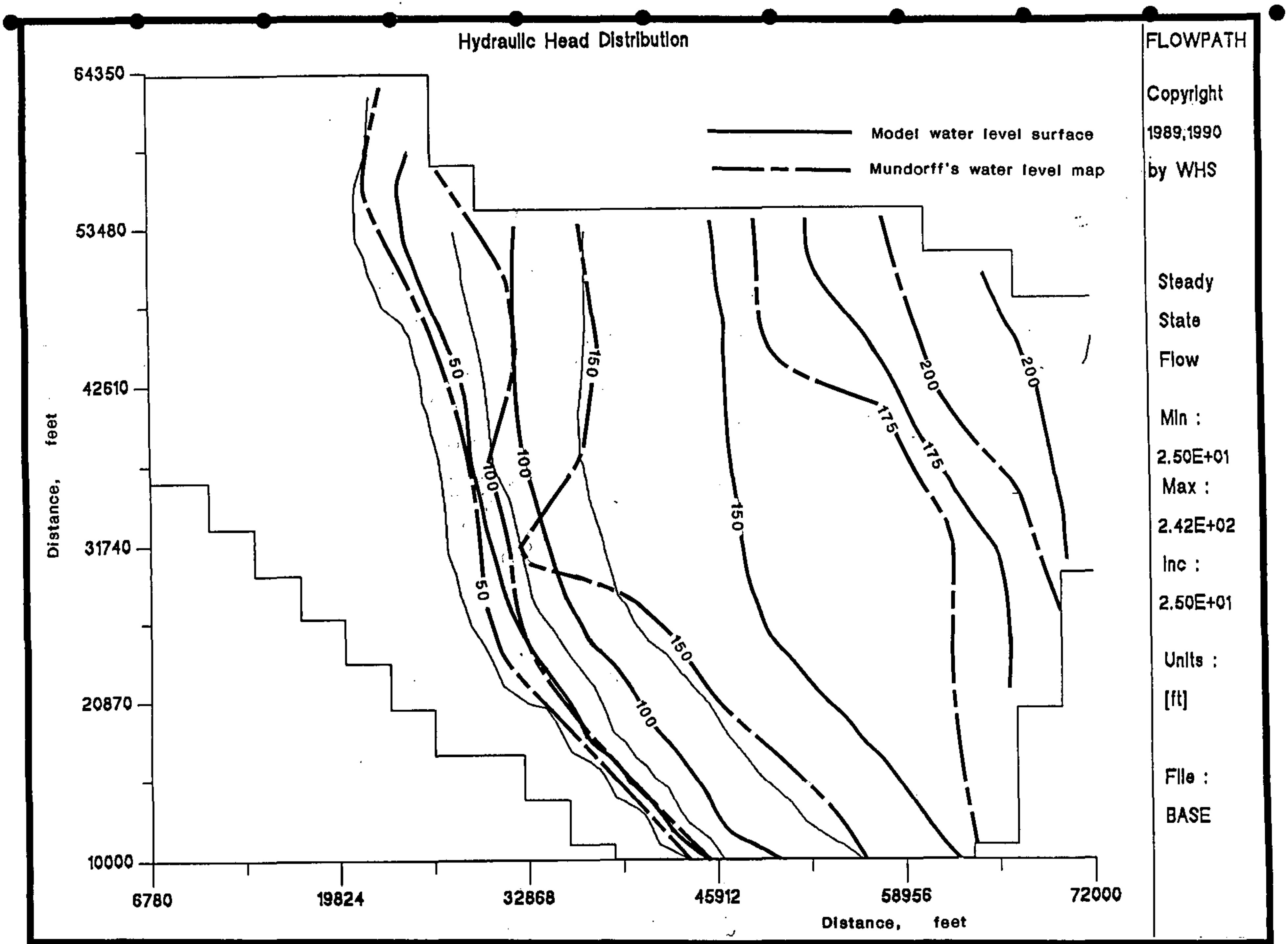

Figure VA-2D-8. Base water level surface compared to Mundorff 's (1964) water level map.

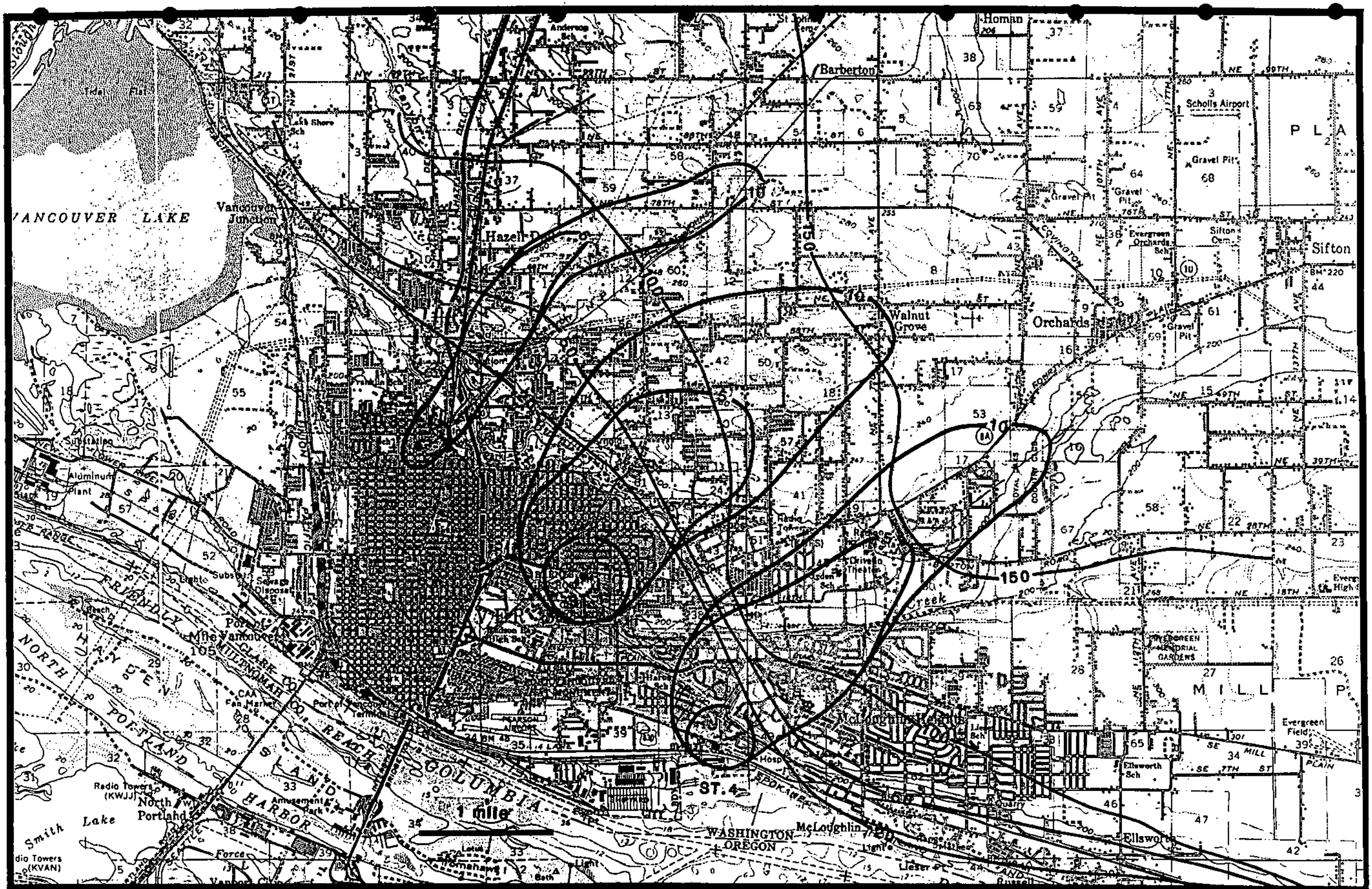

Figure VA-2D-9. FLOWPATH 1, 5, and 10 year zones of contribution for Stations 1, 3, and 4.

The zones of contribution are elongated to the east reflecting the steep gradient in the regional aquifer. According to this model, pathlines do not extend to the Columbia River. This means that the modeled results show that the wells are not pulling water from the Columbia, but are probably decreasing ground water flow to the Columbia.

Zone of contribution delineations using the GPTRAC semi-analytical model (EPA, March, 1991) reported in Appendix J - Vancouver Well Stations 1, 3, and 4 extend farther toward the Columbia River. The lower Orchards aquifer GPTRAC model is designed to be conservative by modeling the up gradient edge of the lower Orchards aquifer as the system boundary, ignoring flow into the aquifer from the northeast. Rittenhouse-Zeman & Associates (1990) modeled the area around Station 4 as a simple two-dimensional model with a very sharp up gradient hydraulic conductivity change at the edge of the lower Orchards aquifer. While the RZA report does not map any zone of contribution, the RZA model may produce a differing capture zone than this two-dimensional model because of this abrupt hydraulic conductivity change.

Upper Orchards Aquifer Model: The upper Orchards aquifer model delineates 1, 5, 10, and 20 year time related zones of contribution for Vancouver Well Stations 8, 9, 14, and 15 in the upper Orchards aquifer. A finer grid was created in the proximity of the delineated wells by adding grid lines to the base model. Aquifer bottom and hydraulic conductivity were slightly modified following creation of the finer local grid. Figure VA-2D-10 shows the delineations along with water level contours drawn from spring 1988 water level observations in the regional gravel aquifer.

A comparison of modeled gradient and observed gradient was made because gradient has a large effect on delineation length and width. Model water level and observed water level gradients compared well. Table 3 shows modeled and observed gradients for well stations in the upper Orchards aquifer.

Table 3

Observed and Modeled Gradient

Well Station	Observed Gradient	Model Gradient
Station 8	0.009 in 5,300 feet	0.009 in 5,300 feet
Station 9	0.015 in 10,500 feet	0.012 in 10,500 feet
Station 14	0.008 in 12,000 feet	0.009 in 12,000 feet
Station 15	0.008 in 9,500 feet	0.011 in 9,500 feet

Generally, a steeper gradient will result in narrower longer zones of contribution and shallower gradients result in more wider shorter zones of contribution.

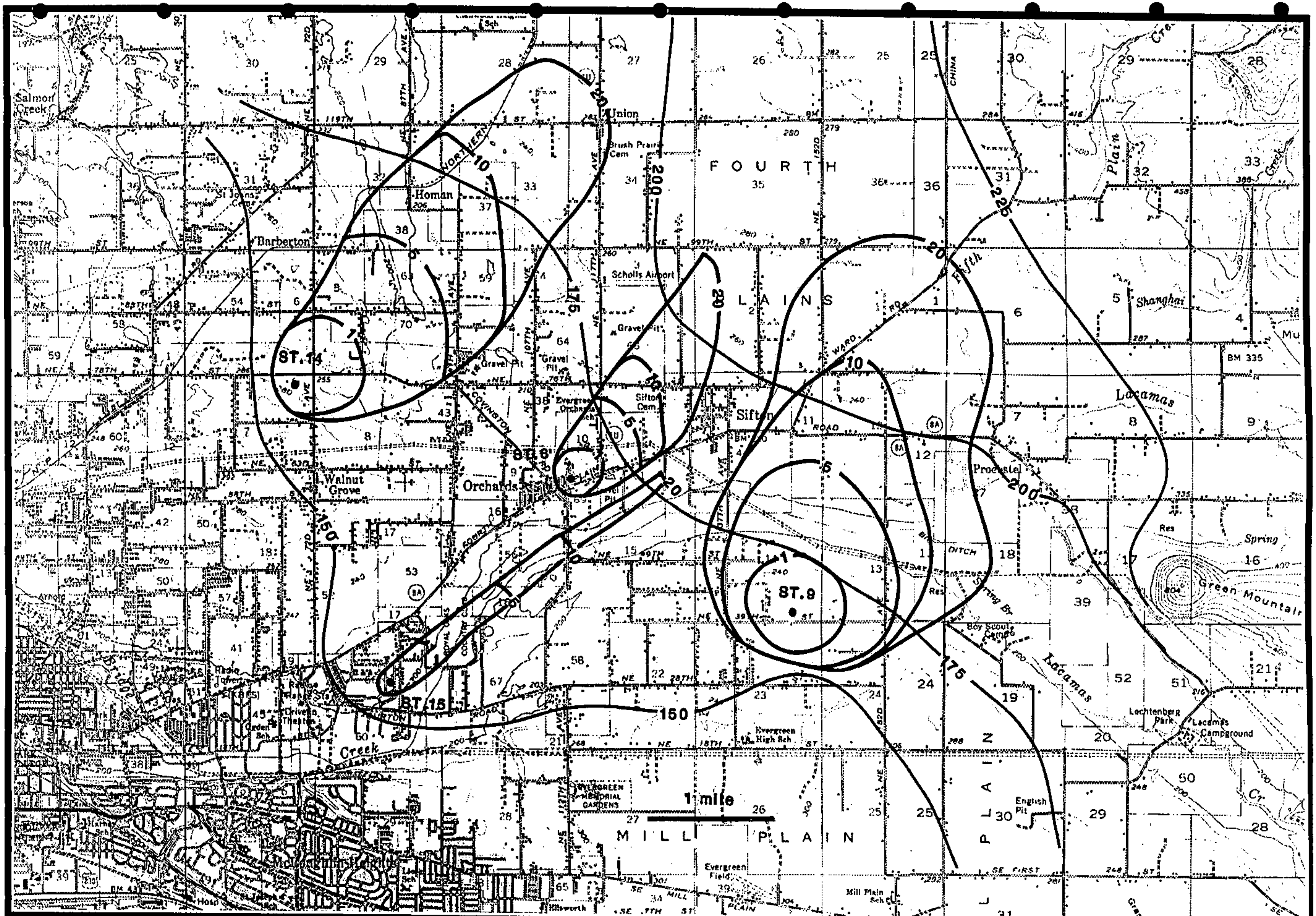

Figure VA-2D-10. FLOWPATH 1, 5, 10, and 20 year zones of contribution for Stations 8, 9, 14, 15, and spring 1988 water level elevation.

References:

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