Comparison of Chlorofluorocarbon-Age Dating with Particle-Tracking Results of a Regional Ground-Water Flow Model of the Portland Basin, Oregon and Washington

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Comparison of Chlorofluorocarbon-Age Dating with Particle-Tracking Results of a Regional Ground-Water Flow Model of the Portland Basin, Oregon and Washington

By STEPHEN R. HINKLE and DANIEL T. SNYDER

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P Eaton, Director

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PLATE [In pocket]

FIGURES

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Length		
foot (ft)	0 3048	meter
mile (mi)	1 609	kilometer
Area		
square mile (mi^2)	259 0	hectare
square mile (mi^2)	2 590	square kilometer
Temperature		

Degrees Fahrenheit (°F) and Degrees Celsius (°C) are related by the following equation

$$°F = 1 8 (°C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929

Comparison of Chlorofluorocarbon-Age Dating with Particle-Tracking Results of a Regional Ground-Water Flow Model of the Portland Basin, Oregon and Washington

By Stephen R Hinkle *and* Daniel T Snyder

Abstract

Chlorofluorocarbon (CFC)-age dating was used to determine the presence or absence of modern water (water containing CFCs) in samples from 54 water wells in the Portland Basin. The accuracy of the CFC-dating method was confirmed by tritium analyses of water from six wells CFC-dating results from 51 of the 54 wells were compared with minimum travel times of the water estimated using particle-tracking-simulation techniques.

Particle tracking was accomplished using a program that combines the results of a regional, ground-water flow model of the Portland Basin with an estimated porosity field, in order to determine ground-water flow paths and to calculate particle travel times The particle tracker can be used to delineate areas that, on the basis of short modeled travel times and known or perceived upgradient-contaminant loadings, may be affected by contaminants.

A sensitivity analysis of various particle densities used in the simulations indicated that about 500 particles per model cell provides an adequate description of the minimum time of travel for water particles tracked from the 51 wells

The CFC results and the particle-tracker results were comparable at 39 (76 percent) of the 51 wells, if water that has entered the ground-water system since 1944 (the limit of detection using CFCs) is considered modern. Furthermore,

although the particle-tracker-model results and the CFC-model results were not comparable at 12 sites, the particle-tracker model appeared to err on the conservative side when compared with the CFC model If the CFC-model results are correct, the particle-tracker results are conservative at 9 of the 12 sites At those nine sites, the particle-tracker model indicated the presence of modern water, but the CFC-model ages were old (pre-1944) At the other three sites, the particle-tracker model failed to indicate the apparent presence of modern water. On the basis of this comparison, it appears that particle-tracking techniques can be used to identify parts of the Portland Basin likely to yield modern water to wells, and that CFC-age dating can provide a useful check on the reliability of the particle-tracker results

Results of both particle-tracking simulations and CFC-age dating indicate that modern ground water flows to depths of hundreds of feet in the Portland Basin Although wells with deep open intervals generally yield old water more often than wells with shallow open intervals, many wells with deep open intervals do produce modern water Because many wells with deep open intervals in the Portland Basin produce modern water, aquifer depth alone is not a reliable indicator of the vulnerability of ground water to contamination Other factors, such as contaminant loadings, and contaminant transport and fate, need to be considered when determining ground-water vulnerability

INTRODUCTION

Population-growth pressures in the Portland Basin in recent decades have increased the potential for ground-water contamination In order to adequately protect ground-water resources, an understanding of the factors affecting ground-water vulnerability is needed Ground-water vulnerability is a function of contaminant loadings, sensitivity of the aquifer to the introduction of these contaminants, and contaminant transport and fate Contaminant loadings can be estimated by characterizing point- and nonpoint-pollution sources Estimates of aquifer sensitivity to contaminant introduction can be made by using a physically based model such as DRASTIC—a standardized system for evaluating ground-water-pollution potential using hydrogeologic settings (Aller and others, 1987) The transport and fate of a contaminant can be modeled using a numerical flow model In recognition of the need to protect and manage the ground-water resource, the Intergovernmental Resource Center (the Council of Governments for Clark County, Washington) began a cooperative study with the U S Geological Survey (USGS) in 1990 to develop a methodology to determine the vulnerability of ground water to contamination in the Portland Basin

The USGS recently completed an extensive study of the hydrology of the Portland Basin (McFarland and Morgan, 1996), which included the development of a three-dimensional, steady-state, numerical ground-water flow model of the Portland Basin (Morgan and McFarland, 1994) In this study, the ground-water particle-tracking computer program of Pollock (1989) was modified by L L Orzol (U S Geological Survey, written commun , 1991) and used in conjunction with the ground-water flow model for the Portland Basin to simulate particle path lines and ages (travel times)

The age of a ground water is defined as the amount of time that has elapsed since the water became isolated from the earth's atmosphere (Freeze and Cherry, 1979, p 135) This age usually approximates the time since recharge of the water occurred (Busenberg and Plummer, 1992). When the age of a ground water is determined from the results of a particle-tracking simulation, the determined age is termed flow-model age In this report, modern ground water is defined as water containing detectable concentrations of chlorofluorocarbons (CFCs)

However, this definition is arbitrary and reflects the tools being used to measure the age of the water In general, modern ground water is more likely to contain anthropogenic contamination than is old (pre-1944) ground water

Although the Portland Basin ground-water flow model and particle tracker are valuable tools for evaluating regional flow patterns, neither had been used to evaluate contributions of modern water to individual wells in the Portland Basin CFCs were used in this study to evaluate results of the flow model and particle tracker The presence of CFCs, which identify modern water in water wells, provided a means of determining the reasonableness of the ground-water flow model

CFCs are stable, synthetic compounds that have been produced since the 1930s There is a short lag time between production and release to the atmosphere Once in the atmosphere, CFCs undergo equilibrium partitioning into water that is in contact with the atmosphere This partitioning is a function of temperature Two CFCs that have gained recent attention as potential age-dating tools are trichlorofluoromethane (CCl_3F) and dichlorodifluoromethane (CCl_2F_2) Atmospheric CCl_3F and CCl_2F_2 concentrations, as a function of time, have been reconstructed by Busenberg and Plummer (1992) Therefore, by measuring CFC concentrations in a ground-water sample and determining or estimating the recharge temperature of the ground water, a CFC-model age can be assigned to the sample Like a flow-model age, a CFC-model age is an estimate of the amount of time that has elapsed since the water entered the ground-water system The difference is that a CFC-model age is based on a measured CFC concentration and a calculated or estimated recharge temperature, whereas a flow-model age is based on an estimate of travel time simulated by a flow model

Two CFCs—CCl_3F and CCl_2F_2—have been successfully used as tracers and as age-dating tools by Thompson and others (1974), Randall and Schultz (1976), Schultz and others (1976), Thompson and Hayes (1979), Busenberg and Plummer (1992), Dunkle and others (1993), Plummer and others (1993), Ekwurzel and others (1994), and Reilly and others (1994) The current (1994) CFC-sampling technology is to collect samples on site in borosilicate glass ampules under a nitrogen atmosphere and to weld the ampules shut for later analysis by purge-and-trap gas chromatography with an electron-capture detector

The current detection limit is less than 1 picogram of CCl_3F or CCl_2F_2 per kilogram of water sample This detection limit enables age-dating of water back to 1948 with CCl_3F and back to 1944 with CCl_2F_2 Busenberg and Plummer (1992) provide a more detailed discussion of the theory and application of CFC-age dating

Purpose and Scope

This report presents the results of an evaluation of the use of CFC analyses to identify modern and old water in selected wells in the Portland Basin and describes the comparison of CFC results with travel times determined by a particle tracker for the Portland Basin regional ground-water flow model

The study involved a three-stage approach

(1) Fifty-four existing wells were sampled for CFCs during the spring of 1991 in order to determine the presence or absence of modern water. Seventeen of these wells were resampled in the fall of 1991 to determine if there were differences in the CFC concentrations Four surface-water sites also were sampled for CFCs in the spring of 1991 Tritium samples from six sites were analyzed to provide a check on the CFC results

(2) Backward particle tracking was performed on 51 of the 54 wells sampled for CFCs Because two of these wells were shallow wells (87 and 128 feet deep) located near the Columbia River, stable isotopes of ground water were analyzed to provide isotopic constraints on particle sources that could be compared with particle-tracking results for these two wells

(3) The results of the CFC sampling were compared with the results of the backward particle tracking, to evaluate results of the particle tracker in detecting the contribution of modern water to wells with the Portland Basin Model

Location and Description of the Portland Basin

The Portland Basin is a structural basin, about 1,280 mi^2 (square miles) in area, located in southwestern Washington and northwestern Oregon The boundaries of the Portland Basin and locations of some of the major physical features in the basin are shown in figure 1 The major aquifers in the basin are consolidated and unconsolidated Miocene, Pliocene, and Pleistocene sedimentary materials deposited on

older, primarily volcanic, bedrock The bedrock is also an aquifer (the "older rocks unit"), but is utilized to a much lesser extent than the sedimentary aquifers (Collins and Broad, 1993) A description of the basin topography, climate, and population can be found in McFarland and Morgan (1996) and in Snyder and others (1994), a description of the hydrogeology of the study area can be found in Swanson and others (1993), McFarland and Morgan (1996) and Morgan and McFarland (1994) The usage of hydrogeologic unit names in this report is consistent with that of Morgan and McFarland (1994)

Acknowledgments

CHLOROFLUOROCARBONS AS AGE-DATING TOOLS AND TRACERS IN THE PORTLAND BASIN

Definition of Modern Water

The definition of modern water is a function of the age-dating tool used The detection limit of less than 1 picogram per kilogram for CFCs provides a measure to age-date water back to approximately 1948 with CCl_3F and back to approximately 1944 with CCl_2F_2 Thus, ground water containing any amount of CCl_3F and CCl_2F_2 contains at least a component of modern water, where modern water has a recharge date no older than approximately 1948 or 1944 for CCl_3F or CCl_2F_2, respectively

The presence of high concentrations of tritium also is frequently used as an indicator of modern water High tritium concentrations in natural water represent tritium associated with above-ground testing of hydrogen bombs, this tritium first entered the global-water cycle in significant concentrations in 1953 When using tritium as a tracer, the term modern water is applied to water containing bomb tritium, and thus implies that at least a portion of water is no older than 1953 (Drever, 1988, p 379)
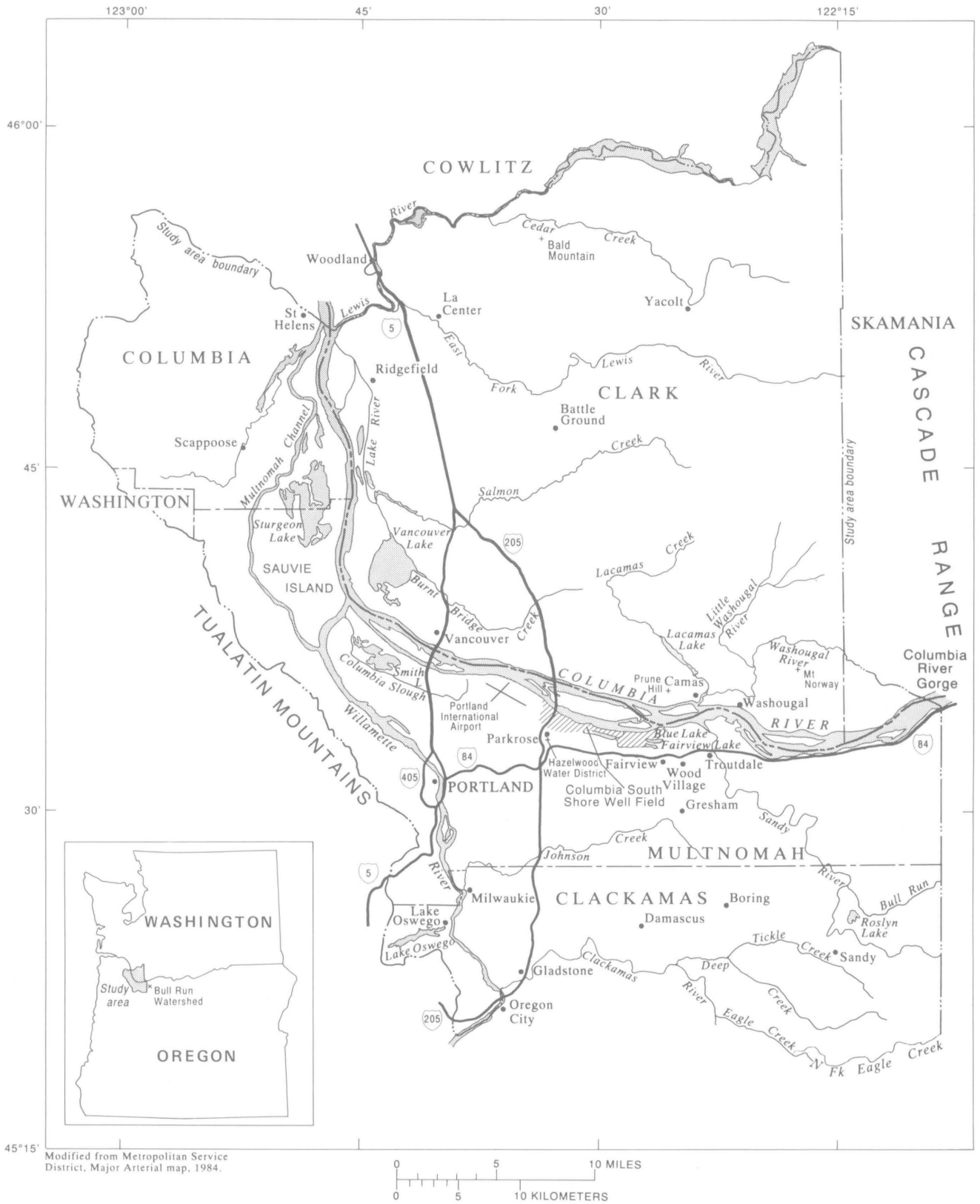
Figure 1. Location and general features of the Portland Basin study area.

Tritium and CFCs, therefore, can be used in a similar manner for tracing modern water, with only a small difference in their respective definitions of old and modern water CFCs have certain advantages over tritium because CFCs are detectable in lower concentrations than is tritium, and are, therefore, more sensitive indicators of modern water where modern and old water mix In addition to acting as tracers of modern water, CFCs can yield actual recharge ages when mixing, environmental contamination, and incidental CFC contributions are insignificant Incidental CFC contributions would be additions of CFCs to a water sample after the water left the ground-water environment

Limitations of Chlorofluorocarbons in Tracer and Age-Dating Studies

Hydrodynamic Dispersion and Mixing

A CFC-model-determined ground-water age represents a composite age because of the hydrodynamic dispersion in an aquifer and the mixing of different flow components in a well A CFC-model-determined age of a mixed ground-water sample is not a weighted mean age because of the effects of hydrodynamic dispersion and because atmospheric concentrations of CFCs do not increase through time in a linear manner This is especially true when part of the mixture is old ground water; that is, ground water recharged before 1944 For example, a small quantity of modern ground water that obtained CFCs from atmospheric exchange, before and during recharge, may mix with a large quantity of old (CFC-free) ground water The resulting mixture will have a low concentration of CFCs, and the CFC-model age will represent a recharge date between 1944 and the date of recharge of the modern water in the mixture It may be that most of the water was recharged before 1944, but the small addition of modern water will result in a modern CFC-model age Ground-water ages, as determined by CFC analyses, do not necessarily represent the weighted mean age of a ground-water sample, and for this reason may be misleading in some ground-water systems For these reasons, CFC-model-determined ages should be considered model ages (herein called CFC-model ages) In the absence of incidental CFC contributions, the presence of CFCs indicates at least a component of modern water in the water sample

Sorption and Biodegradation

CFCs have some affinity for sorption to organic matter, but the degree to which they sorb is not well characterized Sorption of CCl_3F appears to be stronger than CCl_2F_2 (Busenberg and Plummer, 1992, Lovley and Woodward, 1992) Biodegradation of CFCs may occur in reducing environments (Busenberg and Plummer, 1992) Semprini and others (1990) studied the in-situ biotransformation of several halogenated aliphatic compounds in an anoxic aquifer and found that biodegradation of CCl_3F occurred after biostimulation with acetate, CCl_2F_2 was not studied The CFC trichlorotrifluoroethane ($C_2Cl_3F_3$) and carbon tetrachloride (CCl_4) were studied, and biodegradation increased with decreasing fluoride content CCl_2F_2 would seem less likely to undergo biodegradation than would CCl_3F (Busenberg and Plummer, 1992) A significant lack of agreement between CCl_3F- and CCl_2F_2-model ages may, therefore, indicate sorption and (or) biodegradation

Sorption and biodegradation of CFCs in the Portland Basin does not appear to be significant The more frequent absence of CCl_2F_2 than of CCl_3F in samples, assuming that CCl_3F sorbs and biodegrades at a faster rate and (or) more thoroughly than CCl_2F_2 (in spite of the fact that the detection limit for CCl_2F_2 requires older water), contraindicates sorption and biodegradation CFC-model recharge dates, of waters from the population of wells with below-detection-limit data removed, are generally slightly older for CCl_2F_2 than for CCl_3F, also contraindicating sorption and biodegradation Sorption and biodegradation of CFCs cannot be ruled out, as CCl_3F may be predominant because of greater CCl_3F contamination and because much of the ground water in the Portland Basin is reducing—31 percent of the 54 wells sampled yielded water containing less than 1 mg/L (milligram per liter) of dissolved oxygen The data suggest, however, that neither sorption nor biodegradation is significant in the Portland Basin

Environmental Contamination and Incidental Chlorofluorocarbon Contributions

CFCs may be present in ground water because of environmental contamination from sources such as landfill leachate or sewage effluent CFC concentrations as high as 1 3 parts per million have been found in ground water (U S Agency for Toxic Substances and Disease Registry, 1989), much greater than the detection limit of 1 picogram of CFCs per kilogram of

water (1 part per quadrillion) Following the example of Busenberg and Plummer (1992), CFC concentrations greater than those which would be expected for water that is in equilibrium with average global air at the time of sampling are labeled as being at contaminant levels There are no U S Environmental Protection Agency maximum contaminant levels (MCLs) for CCl_3F or CCl_2F_2 (U S Environmental Protection Agency, 1991) The presence of contaminant levels of CFCs could indicate the presence of other anthropogenic organic compounds, and these other compounds may have MCLs and (or) be harmful to human health When discussing the contaminant levels of CFCs in some of the water sampled in this study, the labeling of some CFC concentrations as being at contaminant levels does not imply a violation of U S Environmental Protection Agency MCLs Rather, CFCs at contaminant levels means CFC concentrations were higher than expected in water receiving CFCs solely from atmospheric partitioning from average, global, 1991 air

CFC concentrations above current equilibrium levels (CFC levels that would be found in water in equilibrium with air containing the current, global-average-CFC concentrations) indicate environmental contamination However, environmental contamination of water cannot always be identified because the amount of environmental contamination introduced may have been so small that the concentrations are below current equilibrium levels For instance, water recharged entirely in 1960 may have received some CFC contamination in the recharge area If the contamination was such that the CFC-model age corresponded to a recharge date more recent than 1960, but was older than the date of sample collection, the sample would not be identified as being contaminated Because of the possibility of CFC contamination, CFC-model ages should be treated as minimum ages In other words, the age of the bulk of a water in a sample may be greater than that indicated by the CFC-model age

Incidental CFC contributions (additions of CFCs to a water sample after the water leaves the ground-water environment) also can occur For instance, small bubbles of modern air can become introduced through leaky plumbing connections into water travelling through a water-supply system during sampling, or CFCs can be introduced into ground water cascading through modern air within a well

When interpreting multiple samples from a site, the oldest CFC-model age is chosen to represent the

ground water, because of the possibility of environmental contamination and (or) incidental CFC contributions

Methods

Field

Sixty-six existing wells, primarily domestic and public-supply wells, were visited in the spring of 1991 Twelve of these sites could not be sampled for CFCs Difficulties encountered were (1) air bubbles migrating through the existing plumbing system, thought to have been introduced by a pump intake point located above the production water level in the well bore or through a leak in the plumbing system, and (2) excessive silt and (or) sand in the pumped water that could potentially clog or damage the sampling apparatus Fifty-four wells were sampled for CFCs Although the emphasis of this study was the part of the Portland Basin in Clark County, Washington, several wells in Oregon were sampled in order to compare the results of the CFC-age dating with the results of the flow model in an area greater than that encompassed by Clark County A total of 46 wells in Clark County, Washington, 6 wells in Multnomah County, Oregon; and 2 wells in Columbia County, Oregon, were sampled Additionally, four surface-water sites in Clark County, Washington, were sampled as grab samples during this time period In the fall of 1991, 17 of the ground-water sites were resampled

Strict criteria for well selection were implemented Each well had to have an existing driller's well log with well construction information so that hydrogeologic interpretation could be made Each well had to be open across only one hydrogeologic unit in order to simplify the interpretation and particle-tracker definition of the zone-of-contribution to those wells One well, open in two hydrogeologic units, was inadvertently sampled To preserve sample integrity, water had to be obtained using submersible- or vertical-turbine pumps, or artesian pressure Finally, selected wells had to be more than 1,000 feet from a known landfill or municipal dump in order to minimize contamination of samples from leachate Locations of known landfills and waste dumps were provided by R.D. Swanson, Intergovernmental Resource Center, Washington (written commun , 1991) The process for assigning site-location numbers is shown in figure 2, sampled sites are located in figure 3; site data, well
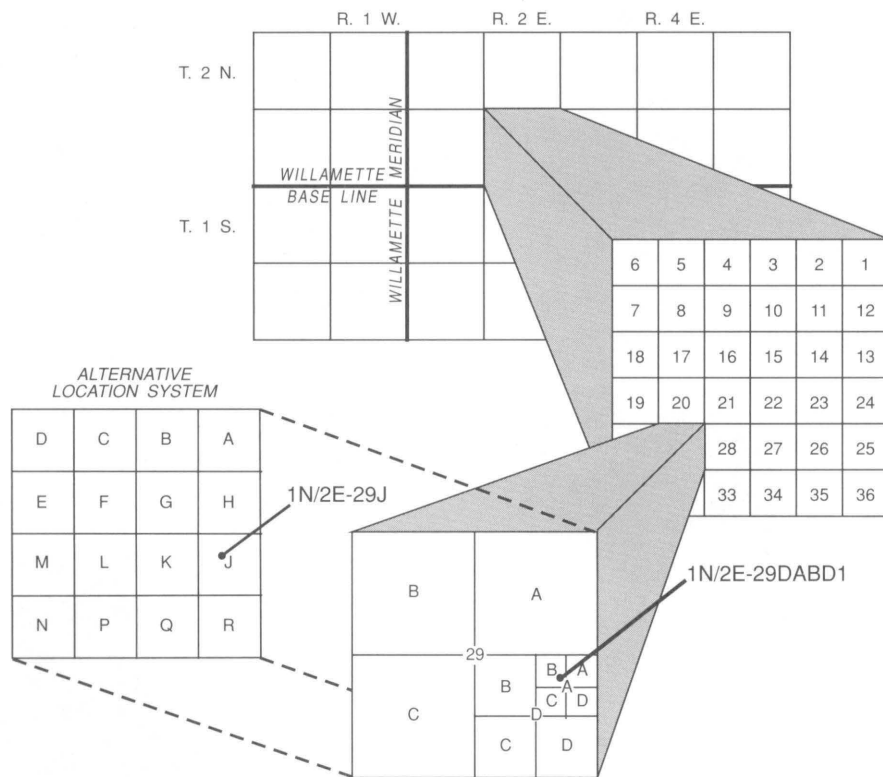
Figure 2. Site-location system.

data, and measured field parameters are listed in table 6 (at back of report).

Ground-water samples were usually collected after a minimum of three well-bore volumes of water had been purged and readings of field parameters (temperature, pH, specific conductance, and dissolved oxygen) had stabilized. Ground-water samples were collected from existing water-supply systems upgradient from pressure tanks, chlorinators, filters, and (or) water softeners. Procedures for collection and processing of samples for CFCs are given by Busenberg and Plummer (1992).

Samples for stable isotopes of ground water also were collected at the ground-water sites in the spring of 1991 to aid in interpretation of ground-water flow and age; five samples were analyzed for deuterium (D) and oxygen-18 (^{18}O), and six were analyzed for tritium. The locations of these sites are shown in figure 4.

The procedure for collection of samples for analyses of isotopes was:

(1) a piece of silicone or teflon tubing was connected to a hose bibb affixed at the wellhead or as close to the wellhead as possible;

(2) the tubing was placed at the bottom of a glass bottle;

(3) the bottle was filled and several volumes were allowed to overflow;

(4) enough sample volume was removed to leave a small air bubble (about 0.5 cubic centimeters) in the bottle when capped, allowing the sample to expand upon exposure to thermal and pressure changes without breaking the bottle or cap; and

(5) bottles were capped with conical-seal caps and sealed with electrical tape.

In the spring of 1991, 11 samples for dissolved-nitrogen and -argon gas analyses were collected so that recharge temperature calculations for CFC-age dating could be made. Samples were collected at nine sites in Clark County, Washington; and at one site in Multnomah County, Oregon; in addition, one replicate sample was collected to verify reproducibility. The locations of these sites are shown in figure 4. Sample-collection flasks and sample-collection procedures were identical to those used by Hobba and others (1977) and Pearson and others (1978) to collect dissolved-gas samples.
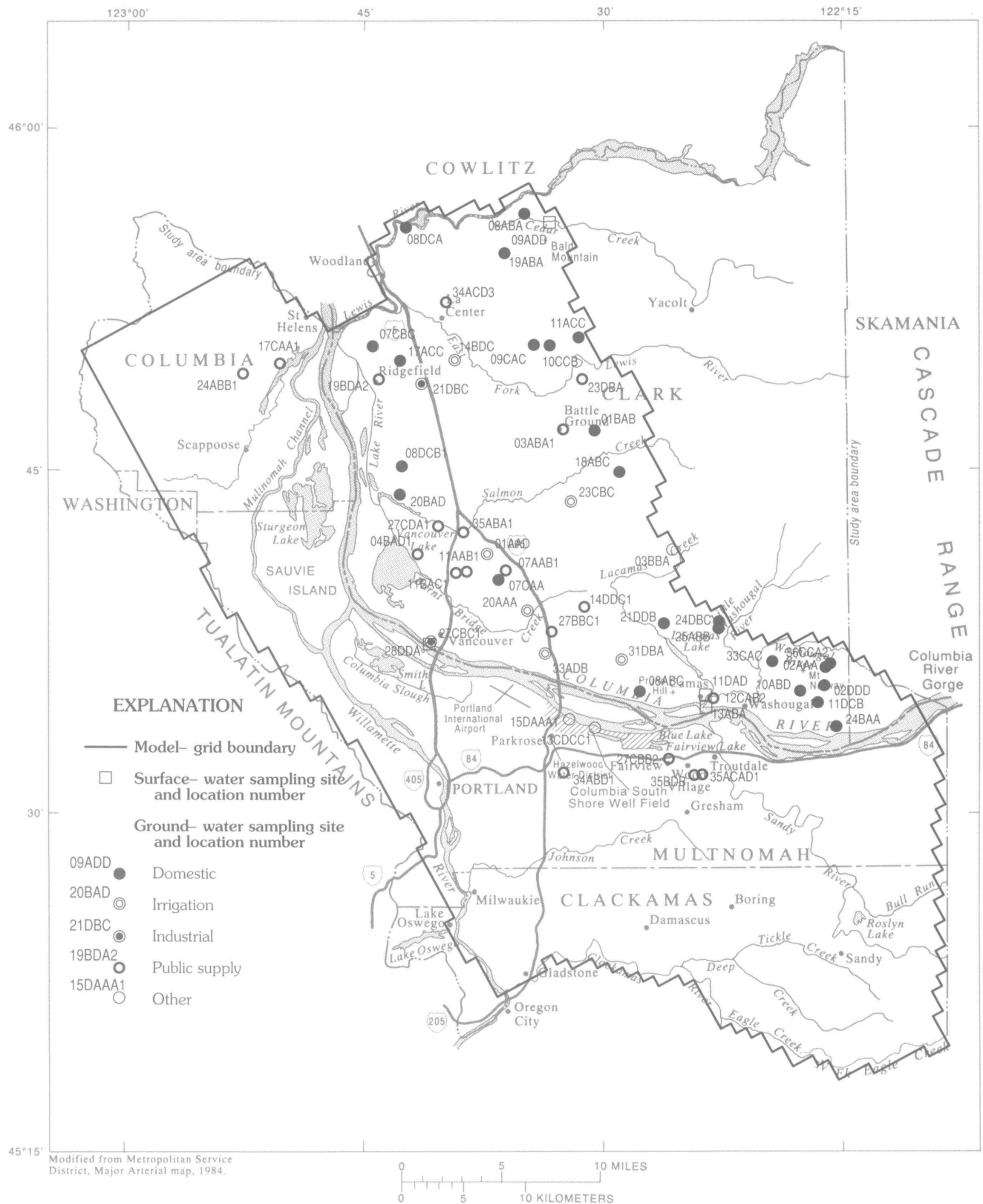
Figure 3. Locations of sites sampled for chlorofluorocarbons.
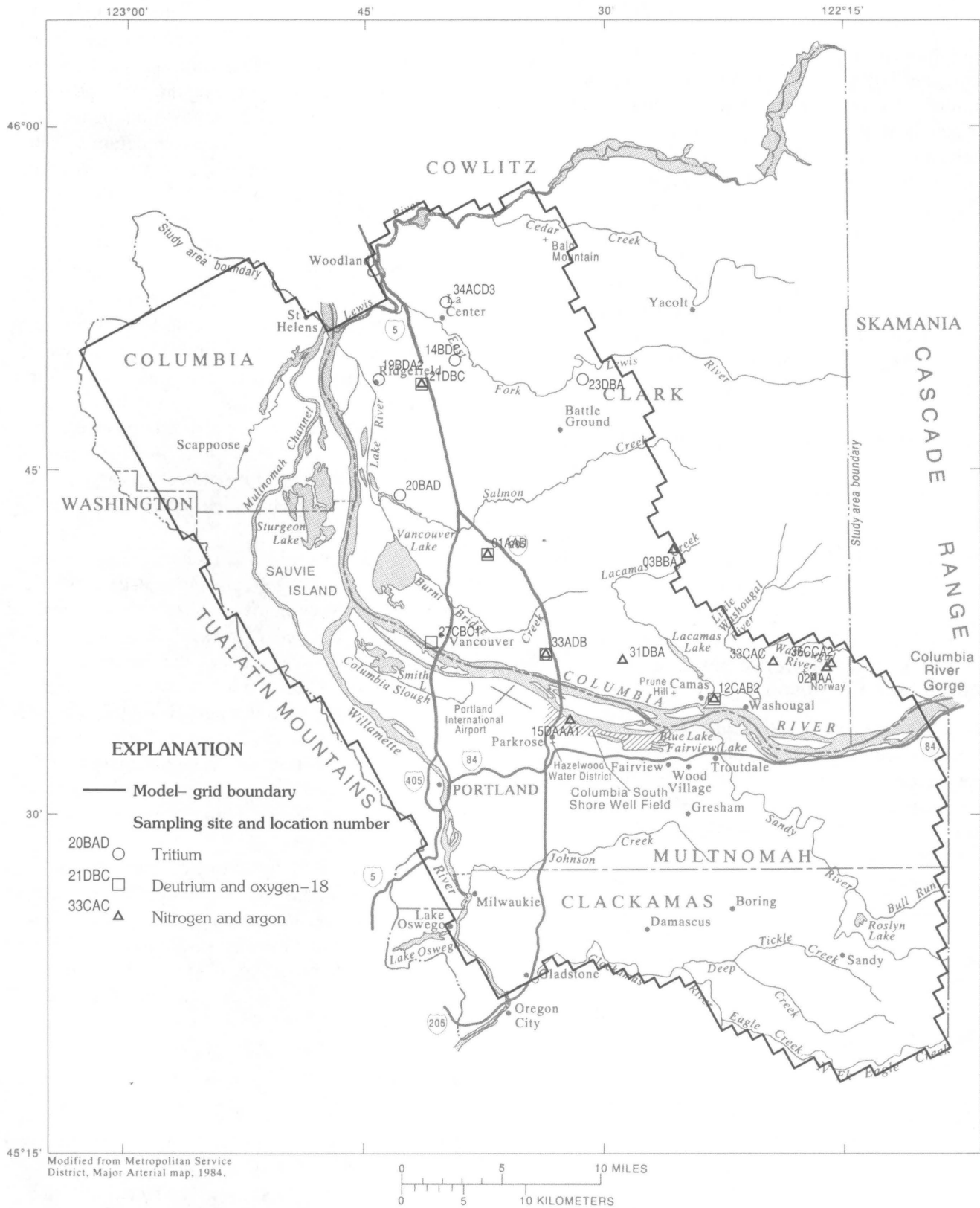
Figure 4. Locations of sites sampled for tritium, deuterium and oxygen-18, and nitrogen and argon.

Laboratory

Samples for CFCs were analyzed in triplicate by purge-and-trap gas chromatography with an electron-capture detector, see Busenberg and Plummer (1992) for details of the analytical techniques Tritium was analyzed by electrolytic enrichment with gas counting and is reported in units of picocuries per liter Dissolved nitrogen and argon were analyzed by gas chromatography, analytical procedures are described in Hobba and others (1977) Deuterium and ^{18}O were analyzed by mass spectrometry The amount of stable isotopes of water (D and ^{18}O) in a water sample is expressed as a deviation from the reference standard, Standard Mean Ocean Water, (SMOW) [Craig, 1961b] using the delta (δ) value

$$\delta = [(R_{sample} / R_{standard}) - 1] \times 1000 \qquad (1)$$

Where

δ = ‰ (per mil or parts per thousand) for D or ^{18}O, and

R = D/H or $^{18}O/^{16}O$

Results

Chlorofluorocarbon Concentrations and Recharge Temperatures

CFC concentrations for the 54 ground-water sites sampled are given in table 7 (at back of report) These concentrations can be related to CFC-model ages using the solubility relations of Warner and Weiss (1985) and reconstructed atmospheric CFC data as a function of time, as discussed in Busenberg and Plummer (1992) A measurement or estimate of recharge temperature is required because water entering an aquifer undergoes final equilibration with atmospheric CFCs during recharge, and this equilibration is a function of water temperature

Recharge temperatures were calculated from dissolved-nitrogen and -argon gas concentrations using equations of Wilhelm and others (1977) One sample, which yielded high dissolved-nitrogen and -argon gas concentrations that may represent the presence of excess air (Heaton and Vogel, 1981) or may indicate a leaky sample container, was not used in recharge temperature calculations

Results of the recharge-temperature calculations are presented in table 1, along with minimum- and maximum-recharge altitudes above sea level as calculated by the particle-tracker model. (The recharge

altitude for a given particle is the altitude of the particle at the point where the particle entered the water table) The mean recharge altitude, also presented in table 1, is calculated by summing the recharge altitudes for all of the particles and dividing the total by the number of particles Recharge temperatures calculated from dissolved-nitrogen and -argon gases ranged from 5°C (degrees Celsius) to 12°C, both the mean- and median-recharge temperatures were 8°C The uncertainty of this method is ± 2 °C

Although there is a general trend toward cooler recharge temperatures with higher mean-recharge altitude, the 7°C range in recharge temperatures cannot be explained by differences in altitude alone Effects of urbanization may play a part in the observed recharge temperatures However, accounting for the effects of changing urban size over time and that effect on recharge temperatures is not feasible, and the mean calculated recharge temperature of 8°C was assigned to all ground water being modeled with CFC-age-dating techniques

The validity of the 8°C recharge temperature is supported by recharge-temperature estimates calculated for three representative subbasins in the Portland Basin Salmon and Cedar Creeks in Clark County, Washington, and Johnson Creek in Multnomah County, Oregon These three subbasins were used to model recharge in the Portland Basin (Snyder and others, 1994). The monthly mean-recharge temperatures in these three subbasins were calculated for the period of record and then weighted by monthly precipitation to arrive at a precipitation-weighted recharge temperature of 8°C

Any errors introduced to CFC-model ages through uncertainty in recharge temperature would be small For instance, an error of 2°C in the recharge-temperature estimate would result in the following errors in the CFC-model ages 3 years for a 1990 water, 1 year for a 1970 water, and 0 years (for CCl_3F) or 1 year (for CCl_2F_2) for a 1950 water

Chlorofluorocarbon-Model Ages

CFC-model ages for the ground-water sites, calculated for an 8°C recharge temperature, are presented in table 7 (at back of report) as CFC-model recharge dates. Because the samples were collected in 1991, the CFC-model age is simply the difference between the CFC-model recharge date and the year 1991 Each site has several CFC-model recharge dates, listed in table 7 (at back of report) Because of the possibility

Table 1. Recharge temperatures from dissolved-gas analyses

[Site-location number see figure 2 , date is date of sample collection, dissolved gas concentrations given in milligrams of gas per liter of solution, recharge temperatures calculated using the equations of Wilhelm and others, (1977), given in degrees Celsius, particle-tracker model backward particle tracking estimates of minimum, maximum and mean recharge altitude given in feet above sea level, altitudes in brackets [ ] represent altitudes of particles that reached model cells adjacent to the model boundary before reaching the water table]

Site-location number	Date	Dissolved nitrogen	Dissolved argon	Dissolved oxygen	Dissolved carbon dioxide	Recharge temperature	Particle-tracker-recharge altitude		
							Minimum	Mean	Maximum
1N/2E-15DAAA1 (J)	5/16/91	18 32	0 7011	0 37	0 102	10	345	436	728
1N/3E-12CAB2(L)	4/24/91	20 50	7664	5 5	19 5	6	20	[297]	[624]
1N/4E-2AAA (A)	4/22/91	18 68	7384	9 6	11 7	5	981	981	981
2N/1E-1AAD (A)	5/15/91	19 12	7215	2 8	9 51	8	248	260	266
2N/2E-33ADB(H)	5/16/91	17 55	6653	6 1	15 1	12	182	207	251
2N/3E-3BBA(D)	5/15/91	19 19	7212	2 9	472	8	(1)	(1)	(1)
2N/3E-31DBA(K)	4/23/91	17 36	6788	4 4	1 59	10	198	237	248
2N/4E-33CAC(L)	4/22/91	24 77	8583	9 5	20 0	(2)	479	526	635
2N/4E-36CCA2(N)	4/24/91	19 88	7429	9 8	18 9	5	891	903	981
4N/1E-21DBC(K)	5/16/91	20 16	7666	32	11 1	5	[23]	[233]	[556]
4N/1E-21DBC(K) [3]	5/16/91	20 33	7744	24	11 4	5	[23]	[233]	[556]

[1] This well is located in a model cell that lies adjacent to the model boundary Particles could not be reliably backtracked from this well

[2] The dissolved nitrogen/argon ratio of this sample indicates that the sample contained excess air, and thus it should not be used to estimate recharge temperature

[3] Serial replicate

of environmental contamination and (or) incidental CFC contributions, the oldest CFC-model recharge date for any given site is considered the most reliable and was used for analysis in this study Thirty-five of the sites yield modern CFC-model recharge dates, and 19 have old CFC-model recharge dates Of the 17 sites resampled, negligible differences are seen between the spring-season and fall-season samples Seventeen of the 54 sites that were sampled yielded one or more samples with contaminant levels of CFCs, and 11 of 17 yielded contaminant levels of both CCl_3F and CCl_2F_2 for all three samples Contaminant levels of CFCs, when present, were usually at levels significantly above those that would be in equilibrium with 1991 air In those cases where contaminant levels were close to those that would be expected for 1991 water, using a recharge temperature of 5°C in calculating the CFC-model recharge dates would not change the number of sites yielding contaminant levels of CFCs

Comparison with Tritium Results

Samples analyzed for tritium at six of the ground-water sites provide partial, independent verification of the usefulness of CFCs as tracers of modern water The comparison of the CFC-model recharge dates with tritium results is shown in table 2 Three samples with CFC-model recharge dates prior to 1944 also had pre-bomb tritium concentrations, and three samples with modern CFC-model recharge dates also had modern tritium concentrations

Surface-Water Chlorofluorocarbon Data

In addition to the 54 ground-water sites, grab samples were collected in the spring season of 1991 at four surface-water sites as a part of this study (table 7 at back of report) Three sites were on the Columbia and Washougal Rivers; the fourth site was located at an ephemeral pond located about 1,000 feet from Cedar Creek in Clark County, Washington, at the edge of a flat field lying at the foot of a hill (fig 3). The ephemeral pond appeared after a heavy rainstorm, was sampled within 48 hours of the end of the rains, and disappeared within 6 days of sampling All four sites yielded contaminant levels of CCl_3F and some sites also yielded contaminant levels of CCl_2F_2. The presence of contaminant levels of CFCs in these surface-water samples exemplifies the pervasive extent of contaminant levels of CFCs in natural water

Table 2. Tritium concentrations at six ground-water sites with corresponding chlorofluorocarbon-model recharge dates and maximum particle-tracker-model recharge dates

[Site-location number see figure 2 , tritium concentrations and standard deviations are in picocuries per liter and indicate modern or old time frame for recharge, where modern water contains "bomb" tritium and contains at least a portion of water recharged since 1953, chlorofluorocarbon-model dates calculated based upon 8 degrees Celsius recharge temperature estimate, " < 1944 " indicates older than 1944]

Site-location number	Well depth (feet)	Sample collection date	Tritium concentration	Tritium standard deviation	Tritium time frame	Chlorofluorocarbon model recharge date	Maximum particle-tracker-model recharge date
2N/2E-33ADB(H)	277	5/16/91	30 4	2 3	modern	1978	1983
3N/1E-20BAD(C)	183	4/29/91	1 3	1 9	old	<1944	1906
4N/1E-14BDC(F)	320	4/30/91	1 0	1 6	old	<1944	1736
4N/1E-19BDA2(F)	208	4/08/91	- 0 3	1 9	old	<1944	1948
4N/2E-23DBA(K)	370	4/09/91	43 5	2 9	modern	1970	1957
5N/1E-34ACD3(G)	257	4/10/91	25 9	2 6	modern	1966	1987

CFC-model recharge dates were calculated using the field-water temperatures measured at the time of sampling, and are presented in table 7 (at back of report) Most of the samples contained CCl_2F_2 at concentrations close to 1991 levels—when concentrations were not at contaminant levels Pre-1991 CFC-model recharge dates could reflect non-equilibrium between water and atmosphere, inaccuracies in field-temperature measurements or laboratory analytical measurements, or the presence of ground-water discharge to these surface-water bodies

Interpretation of General Trends in Chlorofluorocarbon Data

When interpreting CFC data, it is sometimes useful to separate the results into modern and old ground-water groups In this report, an old ground water as dated by the CFC-age-dating technique is defined to be one in which CCl_3F and (or) CCl_2F_2 were not detected in at least one sample, and thus has a CFC-model age prior to 1944 (for CCl_2F_2) or prior to 1948 (for CCl_3F) For these data, all but one of the wells yielding old water have CFC-model ages of prior to 1944 Similarly, the data were separated into groups on the basis of the presence or absence of contaminant levels of CFCs If one or more samples from a well contained contaminant levels of CCl_3F and (or) CCl_2F_2, the well was considered to be contaminated with respect to CFCs

CFC data for water from wells were related to depths to the tops of the open intervals of those wells in order to determine the relation between depth to top of open interval and the presence of modern or old water (fig 5) It is evident that of the wells sampled,

water from deep zones (from deep open intervals) tends to be free of modern water more often than water from shallow zones With increasing depth of open interval, there is an increase in the percentage of wells without modern water. More than one-half of the wells with open intervals greater than 300-feet deep do not contain modern water A similar relation also is seen with respect to the occurrence of contaminant levels of CFCs (fig 6), Most of the wells with open intervals less than 100-feet deep contain water with contaminant levels of CFCs, whereas fewer than one-half of the wells with open intervals greater than 100-feet deep contain water with contaminant levels of CFCs Ground-water vulnerability is a function, in part, of ground-water age. Physical characteristics of aquifers, as they relate to flow paths and flow rates, are important controls on ground-water vulnerability Because modern water is more frequently absent in water from wells with deep open intervals (open intervals several hundreds of feet deep) than in water from wells with shallow open intervals, water from wells with deep open intervals may be better protected at present from potential contamination

The results indicate, however, that Portland Basin wells with the greatest open-interval depths often produce modern water Four out of the nine wells (44 percent) with open intervals greater than 400 feet below the land surface yielded modern water Although the physical properties of these aquifers do not seem to greatly impede movement of modern water to depth in at least some parts of the Portland Basin, it is possible that well construction and well abandonment practices in the Portland Basin could have some effect on movement of modern water to
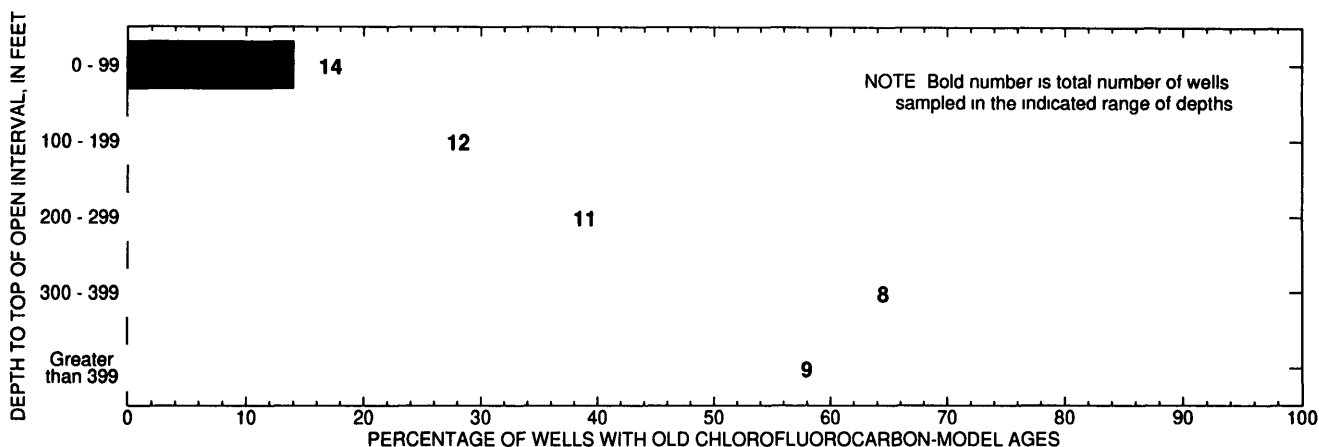
Figure 5. Relation between percentage of wells with old chlorofluorocarbon-model ages (recharged prior to 1944) and depth to top of open interval
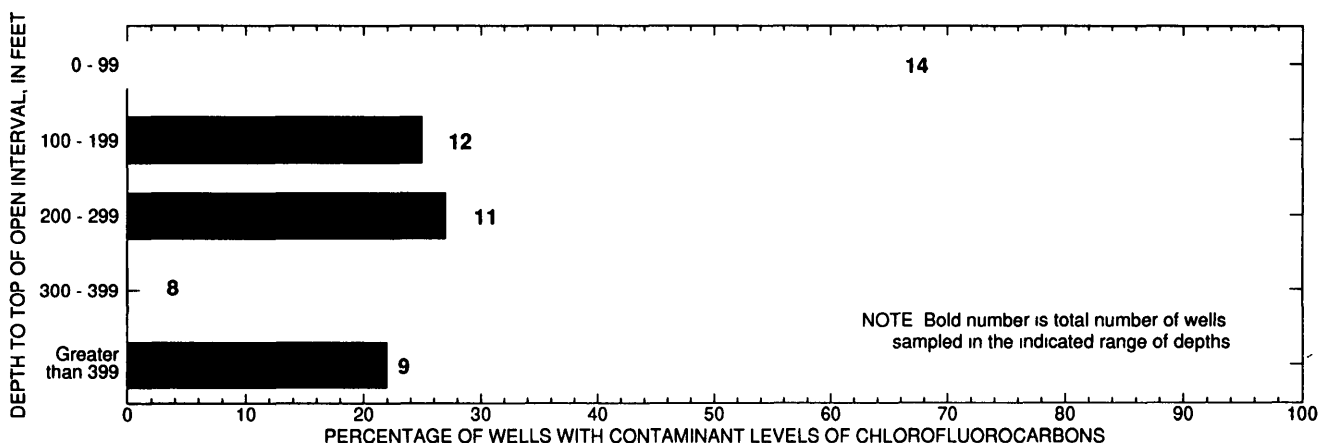
Figure 6. Relation between percentage of wells with contaminant levels of chlorofluorocarbons and depth to top of open interval (Chlorofluorocarbon concentrations greater than those which would be expected for water in equilibrium with average global air at the time of sampling are labeled as being at contaminant levels)

depth Regardless of the pathway, however, significant vertical flow is indicated by the CFC data Because modern water is present in at least some of the deep parts of the Portland Basin, contaminant loadings and contaminant transport and fate are important factors to consider in assessing ground-water vulnerability in the Portland Basin.

PARTICLE TRACKING

Particle tracking is a method of simulating ground-water movement by calculating particle flow paths on the basis of information about the distribution of hydraulic gradient, hydraulic conductivity, and effective porosity Information describing particle paths—starting, intermediate, and ending positions, travel times, and velocities—can be determined

The method can be used to start and follow a particle forward in time from any point as it moves downgradient towards a discharge area, this is defined as forward particle tracking Conversely, a particle can be tracked backward in time from any point upgradient towards a recharge area, this is defined as backward (or reverse) particle tracking This information can then be used to estimate the age of the ground water that might be discharged from a well

Methods

The particle-tracker software used in this study is the USGS three-dimensional, particle-tracking, post-processing program developed by Pollock (1989) and is referred to as MODPATH MODPATH is designed to utilize input data and results from the

USGS modular three-dimensional, finite-difference, ground-water flow model by McDonald and Harbaugh (1988) The plotting portion of MODPATH, called MODPATH-PLOT, was modified by L L Orzol (U S. Geological Survey, written commun , 1991) to facilitate the output of data and results in ARC/INFO data files and coverages ARC/INFO is a geographic information system which is capable of displaying and performing operations on spatial features and associated attributes The modified version of MODPATH-PLOT, known as MODTOOLS, does not change the method used to calculate particle path lines or attributes, but does enhance the ability of ARC/INFO to display and analyze the results of the particle-tracking simulations

The particle-tracking analyses used the input data and results of a regional ground-water flow model developed for the Portland Basin by Morgan and McFarland (1994) The three-dimensional, time-averaged, steady-state model encompasses an area of 981 mi^2 The model consists of eight layers each containing 3,040 active grid cells which are 3,000 feet on a side and of variable thickness (see fig 7)

Effective Porosity Distribution

Effective porosities for the model grid cells are used along with the results of MODFLOW in the particle-tracking simulations to calculate the velocity distribution of the ground-water flow system which can then be used to determine ground-water flow paths and travel times The effective porosity values will not have any effect on the location of the path lines or the points of recharge. The three-dimensional distribution of effective porosity for the model was estimated in this study using an empirical relation between hydraulic conductivity and effective porosity developed by Ahuja and others (1989) and modified using information available from Morris and Johnson (1967)

Many particle-tracking studies assign a single value of effective porosity for each hydrogeologic unit on the basis of values for various lithologies published in the literature such as Cohen (1963), Davis and DeWiest (1966), Johnson (1967), and Morris and Johnson (1967) Because the model for the Portland Basin simulates a layered, three-dimensional aquifer system with an area of nearly 1,000 mi^2, a method was sought that would yield a spatial distribution of effective porosity for each of the nine hydrogeologic units

Ahuja and others (1989) utilized effective porosity data to evaluate the spatial distribution of hydraulic conductivity Using a regression analysis of 473 soil samples across a wide variety of soil types they derived an empirical relation between effective porosity and hydraulic conductivity The regression equation derived by Ahuja and others (1989) was

$$K_s = 764 \, 5\phi_e^{3 \, 29} \qquad (2)$$

Where,

K_s is saturated hydraulic conductivity, in centimeters per hour,

ϕ_e is effective porosity (dimensionless)

Ahuja and others (1989) reported that the regression resulted in an R^2 (the coefficient of determination) of 0 67 and a root mean square error ($\log_{10}K_s$) of 0 613 Solving for ϕ_e yields.

$$\phi_e = \left(\frac{K_s}{764 \, 5} \right)^{1/3 \, 29} \qquad (3)$$

This relation was applied to the modeled hydrogeologic units in the Portland Basin to solve for effective porosity using hydraulic conductivity values for each model grid cell as calculated from the cell thickness and the calibrated transmissivity values The principle advantage of this method is that it utilizes the transmissivities calibrated by the flow model to estimate the spatial distribution of effective porosity The calibrated transmissivities are the best source of information regarding the regional hydraulic characteristics of the aquifer materials in the Portland Basin and are directly proportional to effective porosity

The regression was developed using hydraulic conductivities with a range of over five orders of magnitude, however, the linear regression begins to deviate from the data for large values of hydraulic conductivity For this reason, an effective porosity of 0 31 was assigned to any cells having a hydraulic conductivity greater than or equal to 15 feet per day. Maps of the spatial distribution of porosity for each of the nine hydrogeologic units defined by Morgan and McFarland (1994) and used in the ground-water flow model are provided in the Appendix, figures A1–A9
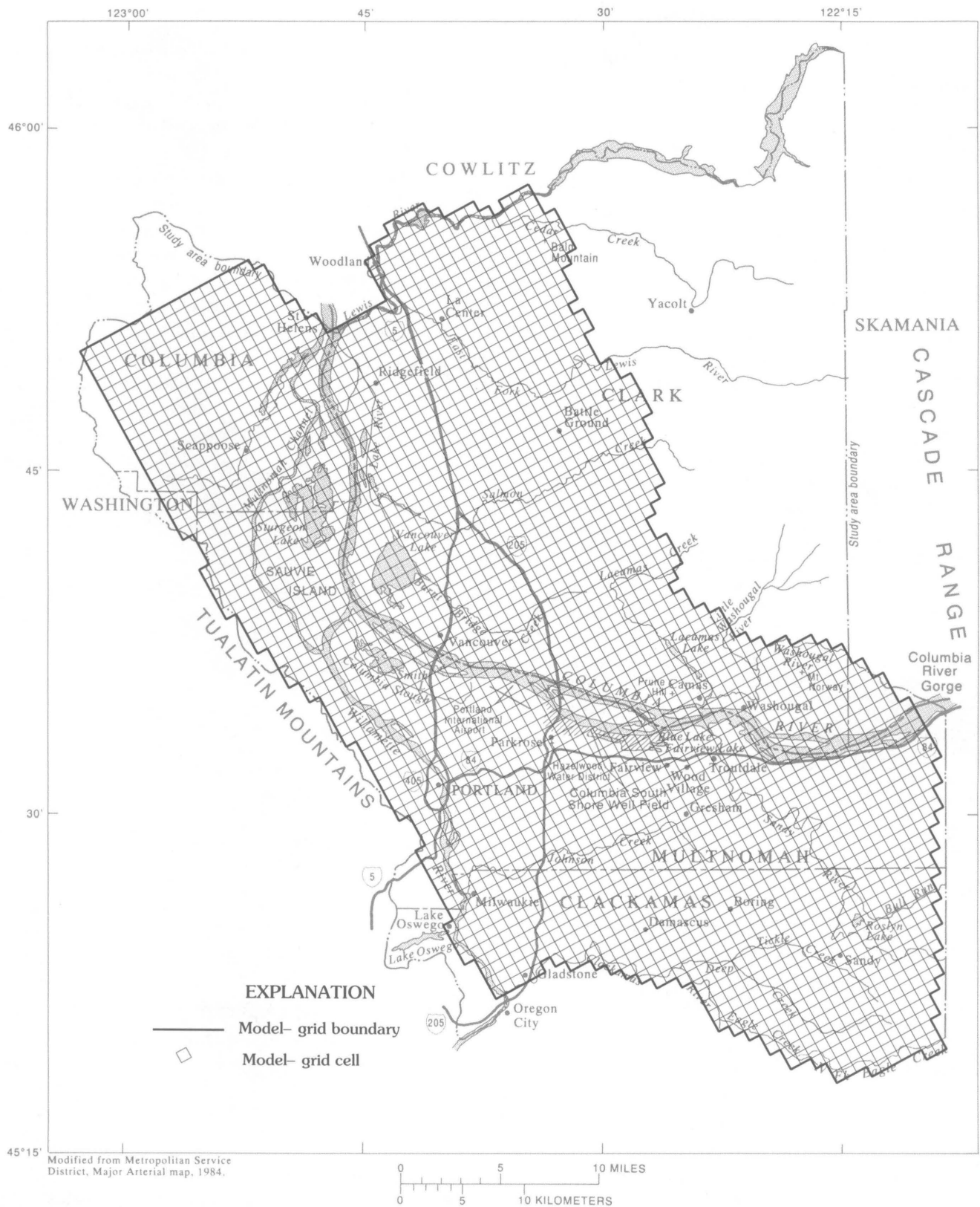
Figure 7. Grid for ground-water flow model of the Portland Basin.

Particle-Density Sensitivity Analysis

An infinite number of possible starting positions exist for particles that could be located on the faces of the model grid cells to be tracked backwards. Ideally, as many particles as possible should be started to increase the probability of modeling all possible flow paths. However, hardware and software limitations, as well as the logistics of handling very large data sets, require the utilization of some subset of starting particles. To enable the selection of the density of starting particles on the faces of the model grid cells, a sensitivity analysis was performed. The goal of the sensitivity analysis was to determine the effect of different particle densities on the distribution of minimum travel times between the model grid cells representing the wells sampled for CFCs and the points at which the particles were recharged. For the purposes of this report, the point of recharge is defined as the point at an inflow boundary at which the particle enters the ground-water-flow system.

The sensitivity analysis used the cells representing the 54 wells sampled for CFC-age dating. Each well location consisted of one to eight model layers representing the hydrogeologic unit(s) to which the well is open. Six modeling runs were made using either 1, 4, 9, 16, 25, or 81 particles on each of the 6 faces per model cell. The result was 6, 24, 54, 96, 150, and 486 particles per cell, respectively, for the cell in each model layer representing the well. The particles were uniformly distributed on the cell faces as described by Pollock (1989, p. 32–33). The particles were tracked backwards in time, upgradient to their recharge points, to determine the time of travel from recharge point to model cell. Particles were stopped if they encountered a model cell adjacent to a no-flow boundary, resulting in a more conservative estimate of minimum travel times (refer to "Limitations and Factors Contributing to Uncertainties" in subsequent section of this report). For example, younger travel times would be estimated than if the particles were allowed to continue. Travel times that are underestimated provide a greater measure of protection from erroneously designating the age of water within a model cell as being older; older water would be less likely to contain anthropogenic contamination. Three of the 54 wells (2N/3E-3BBA, 2N/3E-24DBC, and 4N/2E-11ACC) were located within the cells adjacent to the model boundary, and were not used in the sensitivity analysis.

The minimum travel times for each well were determined for each model run. The data were statistically analyzed using the Kruskall-Wallis test, to test the null hypothesis that the mean ranks of the minimum travel times between each particle-density distribution were equal. This robust test, a one-way analysis of variance on rank-transformed data, is not sensitive to outlying values or to the assumptions of equal variance or normality.

If the null hypothesis was rejected by the Kruskall-Wallis test, indicating that at least one mean rank minimum time of travel value differed, Tukey's "honest significant difference test" was performed to determine which means differed. The alpha value (level of significance) for all hypothesis testing was 0.05.

The results of the model runs from the backward tracking of 51 wells using distributions of starting particles of either 6, 24, 54, 96, 150, or 486 particles per cell are summarized in figure 8 and presented in table 3.
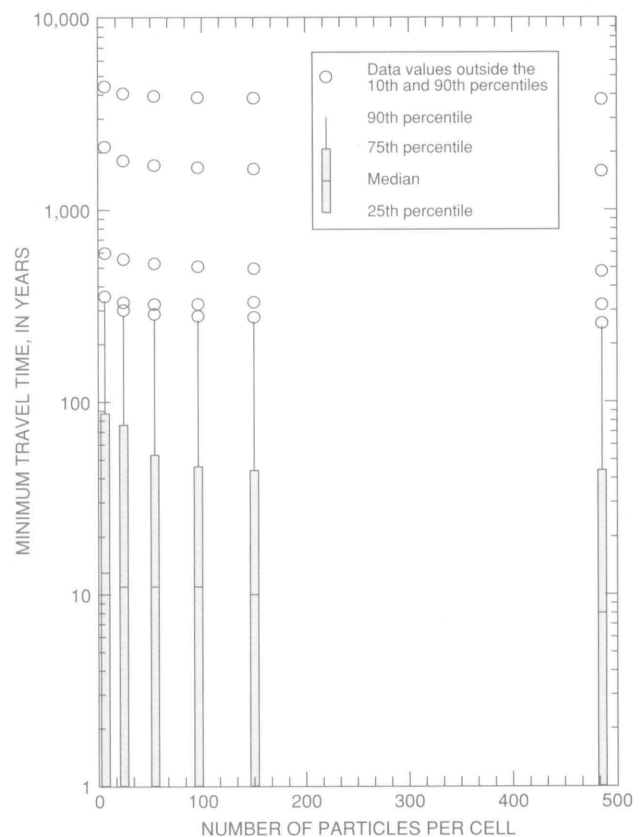
Figure 8. Distribution of particle-tracking-indicated minimum travel times for 51 wells in the Portland Basin sampled for chlorofluorocarbons, by the number of particles per cell.

The mean values of the minimum travel times for the 51 wells decrease exponentially with increasing particle density. However, the Kruskall-Wallis test fails to reject the null hypothesis that the mean rank minimum travel times are equal and, therefore, there is no evidence to suggest that any of the mean rank minimum travel times differed from one another.

Table 3. Minimum particle-tracker-model travel times, in years, for ground water intercepted by 51 wells in the Portland Basin sampled for chlorofluorocarbons

["<" indicates less than]

Location	Number of particles per cell					
	6	24	54	96	150	486
01N/02E-13CDCC1	596	555	526	507	494	478
01N/02E-15DAAA1	355	330	323	323	330	320
01N/02E-34ABD1	10	9	9	9	9	9
01N/03E-08ABC	<1	<1	<1	<1	<1	<1
01N/03E-12CAB2	18	10	9	9	8	<1
01N/03E-27CBB2	147	24	18	15	13	12
01N/03E-35ACAD1	274	214	213	220	218	213
01N/03E-35BDB	121	108	106	105	104	104
01N/04E-02AAA	<1	<1	<1	<1	<1	<1
01N/04E-02DDD	19	18	18	18	18	18
01N/04E-10ABD	6	6	6	6	6	6
01N/04E-11DCB	15	14	14	14	14	7
01N/04E-24BAA	<1	<1	<1	<1	<1	<1
02N/01E-01AAD	<1	<1	<1	<1	<1	<1
02N/01E-04BAD1	217	202	189	168	156	144
02N/01E-11AAB1	87	87	53	46	42	35
02N/01E-11BAC1	49	33	30	27	27	23
02N/01E-27CBC1	<1	<1	<1	<1	<1	<1
02N/02E-07AAB1	13	12	11	11	10	9
02N/02E-07CAA	16	13	12	12	11	11
02N/02E-14DDC1	<1	<1	<1	<1	<1	<1
02N/02E-20AAA	9	7	7	6	6	<1
02N/02E-27BBC1	12	11	10	9	9	9
02N/02E-33ADB	14	9	9	9	8	8
02N/03E-21DDB	<1	<1	<1	<1	<1	<1
02N/03E-25ABB	<1	<1	<1	<1	<1	<1
02N/03E-31DBA	11	10	10	10	10	9
02N/04E-33CAC	<1	<1	<1	<1	<1	<1
02N/04E-36CCA2	<1	<1	<1	<1	<1	<1
03N/01E-08DCB1	13	12	11	11	11	<1
03N/01E-20BAD	151	108	100	95	90	85
03N/01E-27CDA1	<1	<1	<1	<1	<1	<1
03N/01E-35ABA1	7	5	5	5	5	<1
03N/02E-01BAB	251	212	201	189	187	184
03N/02E-03ABA1	<1	<1	<1	<1	<1	<1
03N/02E-23CBC	81	76	74	71	70	70
03N/03E-18ABC	<1	<1	<1	<1	<1	<1
04N/01E-07CBC	<1	<1	<1	<1	<1	<1
04N/01E-14BDC	355	301	287	280	276	256
04N/01E-17ACC	44	36	34	33	33	33
04N/01E-19BDA2	48	45	45	44	44	44
04N/01E-21DBC	93	89	87	86	86	85
04N/01W-17CAA1	4,405	4,056	3,929	3,866	3,834	3,771
04N/02E-09CAC	<1	<1	<1	<1	<1	6
04N/02E-10CCB	15	13	12	12	12	11
04N/02E-23DBA	57	45	40	37	36	34
04N/02W-24ABB1	2,139	1,813	1,714	1,667	1,638	1,591
05N/01E-08DCA	<1	<1	<1	<1	<1	<1
05N/01E-34ACD3	18	12	11	11	11	4
05N/02E-08ABA	<1	<1	<1	<1	<1	<1
05N/02E-19ABA	12	11	11	11	10	<1
Mean	190	167	159	156	154	149

The results indicate that increased particle densities (from among those tested) do not result in sample populations with significantly different minimum travel times Any of the distributions of starting particle densities tested will adequately describe the population of minimum travel times for all 51 wells With only a few exceptions, however, the minimum travel times for individual wells decreased with increased particle density, the magnitude of change also decreased with increased particle density It was expected that particle densities greater than 486 particles per cell would yield only small differences in the minimum travel times for individual wells For these reasons, the minimum travel times determined using 486 particles per cell were used for comparison with the ground-water ages determined using CFCs

Limitations and Factors Contributing to Uncertainties

The results of the particle-tracking simulations are based on specific limitations and assumptions Some specific limitations and assumptions arise from the use of the results of the regional ground-water flow model, while others are inherent in the method of particle tracking

Portland Basin Ground-Water Flow Model

Morgan and McFarland (1994) identified the major simplifying assumptions for the Portland Basin ground-water flow model as (1) steady-state simulation of time-averaged conditions for the period 1987–88, (2) transmissivities of hydrogeologic units do not change when the saturated thickness of the units change, and (3) simplification of some boundary conditions as "no-flow " The most restrictive limitations for this study that result from the above assumptions are that the model cannot be used to evaluate the transient response of the flow system and that some boundaries form a barrier to ground-water flow which, though the flux across may be insignificant relative to the model as a whole, may affect the tracking of particles near that boundary Because of the limitation of using a steady-state model, it is not possible to incorporate the effects of changes in springs, streamflow, recharge, and pumpage in the modeled area since predevelopment However, it is more appropriate to use the 1987–88 time-averaged conditions for comparison with CFC-model ages because these are, perhaps, more representative of the prevailing conditions since

1944 when measurable quantities of CFCs became present in the atmosphere The limitation relating to the boundary conditions is discussed in the subsequent "Particle Tracker" section of this report

Another limitation of the regional flow model for the Portland Basin is spatial discretization The model grid cells are 3,000 feet on a side and are of a variable thickness Each model grid cell contains a typical value for characteristics such as the altitude of land surface, hydrogeologic unit thickness, depth to water, and hydraulic conductivity However, heterogeneities in some parameters, such as geologic framework and lithology, may result in variations in the actual range of values present for a particular parameter within a model grid cell These heterogeneities are not reflected in the model input data In addition, the grid-cell size may be large enough that local flow system characteristics, which can affect CFC concentrations, may not be discernible

Additional limitations may arise from uncertainties associated with the data used to construct the flow model for the Portland Basin, including aquifer geometry, hydraulic characteristics, heads, and stresses. These limitations can result in modeled heads and fluxes which differ from observed values and could influence estimated travel times determined by the particle-tracking simulations

Particle Tracker

The use of the particle tracker is subject to the limitations of the ground-water flow model as well as limitations in the particle-tracking methodology The limitations of MODPATH (Pollock, 1989, p 19–21) include two that require further discussion—boundaries, and spatial discretization and the representation of internal sinks

Care must be used interpreting the results of particle-tracking simulations when particles, which are tracked backwards towards their recharge points, encounter model cells adjacent to a no-flow model boundary If the boundary is represented as a no-flow boundary, the particle is unable to pass through that cell face However, boundaries that are simulated as no-flow may actually have small ground-water fluxes entering from outside the model This situation arises along the eastern boundary of the ground-water flow model in Clark County (see Morgan and McFarland, 1994) The effect of not modeling these fluxes may be insignificant for most uses of the regional ground-water flow model; however, it may cause deflection or

truncation of path lines Particles that enter cells adjacent to no-flow boundaries at depth may, therefore, move laterally until they reach the surface—resulting in particle paths and travel times that are not representative of actual ground-water flow. For these reasons, particles were stopped if they encountered a model cell adjacent to a no-flow boundary

A problem in particle-tracking simulations may arise in the representation of internal sinks, such as discharging wells, springs, gaining streams or rivers, and general-head boundaries due to spatial discretization Pollock (1989 p. 19–20) describes this problem

> The effect of spatial discretization on the representation of internal sinks is especially important for particle-tracking analyses because of the ambiguity associated with the movement of particles through weak sink cells These cells contain sinks that do not discharge at a large enough rate to consume all of the water entering the cell The net result is a flow-through cell in which water enters the cell across some faces and leaves it across others Path lines computed for these cells are consistent with the assumption of a uniformly distributed sink within the cell, however, it is difficult to interpret the results of particle tracking analyses in systems with weak sink cells because
>
> 1 There is no way to know whether a specific particle should discharge to the sink or pass through the cell That means individual particles will not correspond to a fixed volume of water, nor will flow tubes defined by adjacent path lines represent a fixed quantity of flow
>
> 2 Path lines through weak sink cells may not accurately represent the path of any water in the system if they contain point sinks that cannot be represented accurately as being uniformly distributed throughout the cells

In this study, all sinks were treated as weak sinks, thus allowing any particle which entered a cell with a sink to pass through that cell

Uncertainty in travel times also may result from representation of the wells sampled for CFCs as model grid cells The open interval along a well is represented by particles populated along the faces of a model cell or cells, rather than along a line segment Unless the well is located along a cell face, the travel time between the cell face and the actual position of the well is not accounted for, resulting in an under-estimate of the travel time Additionally, wells which partially penetrate a hydrogeologic unit are represented as fully penetrating. This representation would most likely result in underestimating the travel time, however, overestimating the travel time also is possible

An additional limitation in using the particle-tracking simulations to estimate possible flow lines and travel times for chemical constituents is that the constituents are assumed to be conservative A conservative constituent is defined as a nonreactive, dissolved constituent These constituents also are assumed to move as a particle of water and are not subject to the effects of hydrodynamic dispersion or retardation

Results

The backward particle-tracking results for 51 wells are presented in maps A–D on plate 1 (Note that the wells were arbitrarily divided into four groups and plotted on separate maps to prevent overlapping of flow lines from adjacent wells) Because of the large number of particles used in the particle-tracking simulations, plotting all of the particle flow paths for display was not possible Instead, a subset of backward-tracked particles was selected for plotting on plate 1 The subset of particles for each cell consisted of five of the original 81 particles on each face of the cell. The five particles selected were those closest to each of the four corners on each face, plus the center-most particle on each face Because each well is represented by using between one and eight model cells, the resultant subset of particles for plotting ranged from 30 to 240 particles per well

Path lines for particles tracked backward from the 51 wells illustrate the presence of local, intermediate, and regional ground-water flow systems and emphasize the three-dimensional nature of the ground-water flow system in the Portland Basin. For the purposes of this report, the characterization of local, intermediate, and regional flow systems as described by Fetter (1988, p 221–225) will generally be applied Fetter characterizes a local ground-water flow system as having its recharge area at a topographic high spot, and its discharge area at an adjacent topographic low Intermediate flow systems have at least one local flow system between their recharge and discharge areas Regional flow systems have the recharge area in the basin divide and the discharge area at the valley bottom

Local flow systems are generally shallower, with shorter flow paths, and more rapid circulation of ground water compared with regional flow systems Intermediate flow systems have properties falling between those of local and regional flow systems

The well located at 2N/1E-1AAD (map B, plate 1) is an example of a well that withdraws water from a local ground-water flow system This shallow well, completed within the unconsolidated sedimentary aquifer to a depth of 65 feet, is located about four miles east of Vancouver Lake in an area of low relief The path lines to recharge areas for particles tracked from this well range from near 0 to 0 6 miles in length and are contained entirely within the unconsolidated sedimentary aquifer, the surficial unit in this area

Well 1N/2E-13CDCC1 (map B, plate 1) is located east of the Portland International Airport along the Columbia River and withdraws ground water from an intermediate flow system, as delineated by particle path lines This well is 569 feet deep and is screened in the sand and gravel aquifer unit The particle path lines for this well are from 7 1 to 17 8 miles long, traverse as many as seven different hydrogeologic units, and originate in topographically high areas between the Johnson Creek and Clackamas River drainages

Regional ground-water flow is illustrated by the path lines for the well at 4N/1W-17CAA1 (map B, plate 1) located in a low-lying area between St Helens and Scappoose, Oregon This well is screened within the older rocks hydrogeologic unit and has a completed depth of 327 feet The path lines for particles tracked from this well range from 5 4 to 7 6 miles long, travel entirely within the older rocks, and originate along the northwestern boundary of the Portland Basin in the Tualatin Mountains

Well 4N/1E-19BDA2, located near Ridgefield, Washington (map A on plate 1), provides an example of a well that withdraws water from multiple but distinct source areas This well may receive components of water from a local flow system originating from the east and southeast, an intermediate flow system that recharges in the vicinity of Bald Mountain to the northeast, and a regional flow system that recharges along the eastern boundary of the Portland Basin along the western flank of the Cascade Range The path lines from the various source areas range in distance from 0 8 to 13.6 miles and illustrate that local, intermediate, and regional flow systems can all contribute to the discharge from a well This well also demonstrates the

three-dimensional nature of the ground-water flow system The well is screened in the undifferentiated fine-grained unit which, at this location, is represented by five model layers each populated with particles. The trajectories for these particles are calculated using the hydraulic parameters for each model layer, which can vary with depth. Path lines within the undifferentiated fine-grained unit that appear to cross each other in map view actually occur at different depths within the unit and are calculated on the basis of the hydraulic conditions present at that depth

Comparison of Particle-Tracking Results with Stable-Isotope Data at Two Sites

Most ground water in the Portland Basin is significantly less depleted in D and ^{18}O than is water from the Columbia River. These distinct isotopic signatures allow stable isotopes of water to be used to calculate the fraction, if any, of ground water that has traveled through the ground-water environment to a given well from the Columbia River. McCarthy and others (1992) used stable isotopes of water in this manner in their analysis of several City of Portland public-supply wells in Multnomah County, Oregon, and these techniques were used in a similar manner in this study

Samples for stable isotopes of ground water were collected from two shallow wells (2N/1E-27CBC1 and 1N/3E-12CAB2) located in Clark County, Washington, near the Columbia River (table 4) Values from three ground-water sites (2N/1E-1AAD, 2N/2E-33ADB and 4N/1E-21DBC), that are located far from the Columbia River in Clark County, Washington, are listed in table 4. Ten values from the Columbia River at the USGS National Stream Quality Accounting Network (NASQAN) station at Warrendale, Oregon (gaging number station 14128910), located 6 miles upstream from the eastern edge of the study-area boundary, also are listed in table 4 The 3 ground-water sites located far from the Columbia River were sampled as part of this study, and the 10 Columbia River samples were collected as depth-integrated samples by USGS personnel during routine NASQAN sampling (T B Coplen, U.S. Geological Survey, written commun , 1991). The three values of stable isotopes of ground water, for sites located far from the Columbia River, represent one end member for mixing calculations

Table 4. Stable isotopes of ground water and Columbia River surface water

Analyses run at the U S Geological Survey laboratory in Reston, Virginia, are reported to the nearest 0 5 o/oo (per mil, or parts per thousand) for D (deuterium) and 0 1 o/oo for ^{18}O (oxygen-18) Analyses run at the U S Geological Survey laboratory in Menlo Park, California, are reported to the nearest 1 o/oo for D and 0 1 o/oo for ^{18}O Results of analyses are reported relative to the reference standard, Standard Mean Ocean Water (Craig, 1961b)

Site	Sample date	$\delta^{18}O$ (o/oo)	δD (o/oo)
	Ground water		
1N/3E-12CAB2 (L)	4/24/91	-9 6	-67 0
2N/1E-1AAD (A)	5/15/91	-8 5	-62
2N/1E-27CBC1 (M)	5/07/91	-13 4	-99 5
2N/2E-33ADB (H)	5/16/91	-9 6	-70
4N/1E-21DBC (K)	5/16/91	-9 6	-70
	Surface water		
Columbia River at Warrendale, Oregon	1/12/85	-16 7	-127 0
Columbia River at Warrendale, Oregon	4/17/85	-16 6	-124 0
Columbia River at Warrendale, Oregon	7/25/85	-16 4	-120 5
Columbia River at Warrendale, Oregon	11/05/85	-16 4	-124 5
Columbia River at Warrendale, Oregon	3/26/86	-16 2	-122 0
Columbia River at Warrendale, Oregon	9/04/86	-16 5	-126 5
Columbia River at Warrendale, Oregon	11/19/86	-16 6	-126 0
Columbia River at Warrendale, Oregon	3/18/87	-16 7	-125 5
Columbia River at Warrendale, Oregon	5/12/87	-16 4	-123 5
Columbia River at Warrendale, Oregon	9/09/87	-16 6	-125 5

Columbia River water samples collected at the Warrendale site represent the other end member The 10 Columbia River samples cover a range of seasons, in order to describe the seasonal variability in the stable-water isotopes of the Columbia River A plot of the isotopic values is shown graphically in figure 9, along with the meteoric water line (Craig, 1961a)

Well 2N/1E-27CBC1, an industrial well located 0 2 miles from the Columbia River, is pumped continuously throughout the year and the isotopic composition of its water should represent steady-state mixing The isotope results indicate that approximately 60 percent of the water pumped from this well comes from the Columbia River

The isotopic results from well 1N/3E-12CAB2 (a public-supply well located about 0 4 miles from the Columbia River) show that this well was not, at the time of sampling, drawing significant water from the Columbia River Under periods of long pumping, it is possible that this well could draw water from the Columbia River It is also possible that the well draws water from the nearby Washougal River.

The results from the particle-tracking simulations indicate that well 2N/1F-27CBC1 may draw water from the Columbia River, and that well 1N/3E-12CAB2 does not draw water from the Columbia River. The results from the isotopic analyses are

consistent with the results from the particle-tracking simulations and further demonstrate the utility of stable isotopes of water in determining the contribution of water from the Columbia River to pumping wells in the Portland Basin
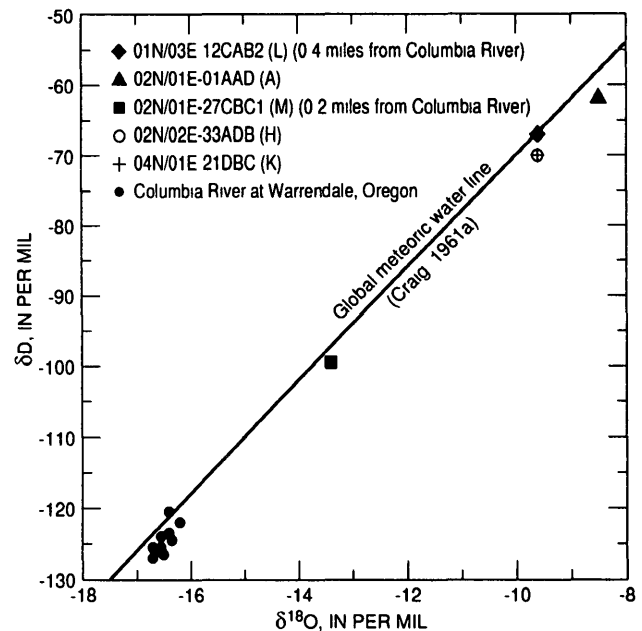
Figure 9. Stable isotopes of water from ground- and surface-water sites in the Portland Basin

COMPARISON OF CHLOROFLUOROCARBON-MODEL AGES WITH PARTICLE-TRACKER-MODEL AGES

For each group of particles backtracked from a given well with the particle-tracking simulations, there was usually a wide range in the calculated particle-recharge ages Because wells usually produce water from multiple zones with multiple water ages, a CFC-model age does not, as previously discussed, represent a weighted mean age of the water Similarly, a discharge-weighted mean, particle-tracker-model age from backward-tracked particles cannot be determined because detailed information regarding the contribution to well discharge from every possible flow path is not available due to large grid size and the parameter-averaging procedures used in the model Although it is not feasible to compare CFC-model ages with discharge-weighted mean, particle-tracker-model ages, there is one valid method of comparing results from the two models

The presence of CFCs in water samples indicates the presence of at least a component of modern water Because this is equivalent to having at least one particle of modern water contributing to a water sample, the youngest particle-tracker-model age (least time of travel from recharge point to well) for each well was chosen to represent that well for comparison to CFC-age dating The CFC-model ages, and the youngest particle-tracker-model ages, are presented as model recharge dates for comparison in table 5

Table 5 Maximum particle-tracker-model recharge dates and chlorofluorocarbon-model recharge dates for ground water from the Portland Basin

[CFC (chlorofluorocarbon) Particle-tracker maximum model date is date associated with youngest particle of water produced by the well according to backward particle tracking " <1944 " or " <1948 " indicates recharge before 1944 or 1948, respectively—these waters cannot be age-dated with CFCs "Cont" indicates that sample contains levels of CFCs greater than would be in water in equilibrium with 1991 global air]

Site-location number	Number of particles in backward particle tracking	Maximum particle-tracker-model recharge date, in years A.D.	CFC-model-recharge date, in years A.D.
1N/2E-13CDCC1(P)	486	1513	<1944
1N/2E-15DAAA1(J)	486	1671	<1944
1N/2E-34ABD1(B)	486	1982	Cont
1N/3E-8ABC(B)	972	1991	<1944
1N/3E-12CAB2(L)	2,430	1991	Cont
1N/3E-27CBB2(M)	486	1979	1953
1N/3E-35ACAD1(G)	486	1778	<1944
1N/3E-35BDB(F)	972	1888	1985
1N/4E-2AAA(A)	972	1991	1978
1N/4E-2DDD(R)	486	1973	<1944
1N/4E-10ABD(B)	1,944	1986	1949
1N/4E-11DCB(Q)	1,944	1984	<1944
1N/4E-24BAA(C)	2,916	1991	<1944
2N/1E-1AAD(A)	486	1991	<1948
2N/1E-4BAD1(C)	486	1847	Cont
2N/1E-11AAB1(A)	486	1956	1956
2N/1E-11BAC1(C)	486	1968	1967
2N/1E-27CBC1(M)	486	1991	Cont
2N/2E-7AAB1(A)	486	1982	Cont
2N/2E-7CAA(L)	486	1981	Cont
2N/2E-14DDC1(R)	972	1991	Cont
2N/2E-20AAA(A)	972	1991	1955
2N/2E-27BBC1(D)	486	1982	Cont
2N/2E-33ADB(H)	486	1983	1978
2N/3E-21DDB(R)	972	1991	1968
2N/3E-25ABB(B)	486	1991	1963

Table 5. Maximum particle-tracker-model recharge dates and chlorofluorocarbon-model recharge dates for ground water from the Portland Basin—Continued

Site-location number	Number of particles in backward particle tracking	Maximum particle-tracker-model recharge date, in years A.D	CFC-model-recharge date, in years A D
2N/3E-31DBA(K)	486	1982	1949
2N/4E-33CAC(L)	972	1991	1973
2N/4E-36CCA2(N)	972	1991	Cont
3N/1E-8DCB1(Q)	972	1991	1957
3N/1E-20BAD(C)	486	1906	<1944
3N/1E-27CDA1(P)	486	1991	1985
3N/1E-35ABA1(B)	972	1991	1976
3N/2E-1BAB(C)	486	1808	1964
3N/2E-3ABA1(B)	972	1991	Cont
3N/2E-23CBC(M)	486	1921	<1944
3N/3E-18ABC(B)	972	1991	1957
4N/1E-7CBC(M)	972	1991	Cont
4N/1E-14BDC(F)	2,430	1736	<1944
4N/1E-17ACC(G)	2,430	1958	<1944
4N/1E-19BDA2(F)	2,430	1948	<1944
4N/1E-21DBC(K)	2,430	1906	<1944
4N/1W-17CAA1(L)	486	-1780	<1944
4N/2E-9CAC(L)	2,430	1985	<1944
4N/2E-10CCB(N)	2,430	1980	1975
4N/2E-23DBA(K)	2,430	1957	1970
4N/2W-24ABB1(B)	486	401	<1944
5N/1E-8DCA(Q)	486	1991	<1944
5N/1E-34ACD3(G)	2,430	1987	1965
5N/2E-8ABA(B)	2,916	1991	1965
5N/2E-19ABA(B)	3,888	1991	1948

The two models for delineation of old and new ground water, the CFC-age-dating model and the particle-tracking model, were comparable at 39 of the 51 sites, or 76 percent of the sites Using the CFC model, 33 of the 51 sites yield modern ages, and 18 yield old ages. Using the particle-tracker model, 39 sites appear to receive modern water, and 12 do not

It is not surprising that results from the particle-tracker model and the CFC-age-dating technique were not always in agreement The Portland Basin ground-water flow model was designed to evaluate regional ground-water flow, rather than local or small-scale ground-water movement Local ground-water flow induced by well pumping, or annular leakage or inter-aquifer flow through existing wells, is not accounted for by the flow model The CFC-age-dating technique

is sensitive to local and small-scale ground-water influences, but may be subject to the effects of sorption, biodegradation, or incidental CFC contributions

Another difference between the two models is that the particle-tracking routine tracks particles backward from the faces of the model cells in which a given well is open, whereas the CFC-age-dating method measures actual contributions of CFCs to well water The result is that the particle-tracker model does not account for particle travel times to wells from the faces of the cells housing the open intervals of those wells The results of the two models may not agree if these travel times are significant Under such conditions, the particle-tracker model would be expected to yield conservative dates when being used to evaluate the presence or absence of modern water in water wells

This may explain the observation that, at 9 of the 12 sites at which the two models did not agree, the particle-tracker model calculated a modern age for water that contained no CFCs It is possible that modern ground water had crossed some model-cell faces, but had not yet reached all wells within those model cells Because determining locations of old (less likely to contain anthropogenic contamination) ground-water resources could be an important use of the particle-tracker model, errors biased in the direction of identification of water as modern water are probably preferable to errors biased in the direction of identification of water as old water The particle-tracker model may, therefore, be even more valuable than indicated by the 76 percent agreement with the CFC data

SUMMARY AND CONCLUSIONS

To determine the occurrence of modern ground water in aquifers in the Portland Basin, a particle-tracker model that uses the results of a regional ground-water flow model, along with an estimate of the distribution of porosity, was used to ascertain ground-water flow paths and to calculate ground-water ages The value of such a capability is that locations of vulnerable ground-water resources can be identified. An independent method of tracing modern ground water, CFC-age dating, was implemented and the results were compared to the results of the particle-tracking simulations when evaluating contributions of modern water to individual wells in the Portland Basin. The presence of CFCs in ground water indicates the presence of modern water (water recharged since 1944) CFC samples were collected from 54 ground-water wells in the Portland Basin for the purpose of determining the presence or absence of modern water In addition to providing information on the presence or absence of modern water, CFC concentrations can yield CFC-model recharge dates for ground water when combined with data on ground-water recharge temperature A mean-recharge temperature of 8°C was calculated from dissolved-nitrogen and -argon gas concentrations at 9 of the 54 sites This mean recharge temperature was combined with CFC concentrations from 54 ground-water wells to age-date ground water produced from those 54 wells

In order to provide a check on the CFC method, samples for tritium analysis were collected at 6 of the

54 sites sampled for CFCs The tritium results matched the CFC results Three of the six samples contained bomb tritium, indicating modern water Those same three samples also had modern CFC-model ages The other three samples, which did not contain bomb tritium, had old CFC-model ages

A sensitivity analysis was conducted to determine the number of particles per cell to use in the particle-tracking analysis. The results of the sensitivity analysis indicated that 486 particles per model grid cell provides a better estimate of the minimum ground-water travel times to individual wells than 6, 24, 54, 96, or 150 particles per cell, and that particle densities greater than 486 particles per cell would only provide a slightly better estimate of minimum travel times

The particle-tracking simulations were used to calculate residence times for water produced by 51 of the 54 wells sampled for CFCs Particle paths were calculated by using backward tracking of the particles upgradient to their recharge points The results of the particle-tracking simulations indicate that flow takes place on local, intermediate, and regional scales Ground water moves from higher altitudes towards discharge areas along rivers and streams, and to discharge points such as water wells Stable isotopes of ground water, collected at two wells located near the Columbia River, show that one of the wells produced water recharged primarily from the Columbia River The other well produced no measurable component of Columbia River water These results are consistent with the particle-tracker results

The results of the particle-tracking simulations and the CFC sampling were compared Limitations of the particle-tracker model and the CFC model will inevitably lead to discrepancies between the two models The particle-tracker model is based on a steady-state, three-dimensional, ground-water, numerical-flow model with no-flow boundaries, a regional model that cannot account for all local flow anomalies For instance, local vertical ground-water flow induced by well pumping, annular flow, or inter-aquifer flow through existing wells, is not accounted for by the flow model or particle-tracker model Additionally, the particle-tracker model is subject to errors associated with model cells that contain a weak sink (a sink that is not sufficiently strong to cause flow into the cell from all directions) Finally, the particle-tracking routine does not allow particles to be back-tracked from individual wells (particles for individual

wells were tracked from the cell faces of the cells in which the wells were open), and backtracking all the way to particle recharge points was not performed on particles that reached model cells adjacent to the flow-model boundary. CFCs may be subject to sorption and biodegradation, and the presence of CFCs in water samples does not guarantee the presence of CFCs in the aquifer. Water cascading into a well bore can pick up CFCs from the well-bore atmosphere or CFCs could conceivably enter water in the well delivery system Furthermore, the CFC method is sensitive to local flow effects. While this can be of value when attempting to determine the potential for contributions of modern water to a well, it can interfere with the determination of regional flow patterns

In spite of their limitations, results of the CFC model and the particle-tracker model were comparable at 39 (76 percent) of the 51 wells, when water with particle-tracker-model particles recharged since 1944 is considered modern. Furthermore, although the particle-tracker-model and the CFC-model results were not comparable at 12 sites, the particle-tracker model appeared to err on the conservative side when compared to the CFC model If the CFC model is accurate, the particle-tracker model behaved conservatively at 9 of the 12 sites At those nine sites, the particle-tracker model identified the presence of modern water, but the CFC-model ages were old At the other three sites, the particle-tracker model failed to identify the apparent presence of modern water

The results of both the CFC model and the particle-tracking model indicate that many Portland Basin wells produce at least a component of modern water Although wells with deep open intervals generally yield old water more often than wells with shallow open intervals, many wells with deep open intervals (open intervals hundreds of feet below land surface) do produce modern water Because many wells with deep open intervals in the Portland Basin produce modern water, aquifer depth alone is not a reliable method of estimating ground-water vulnerability Other factors, such as contaminant loadings and contaminant transport and fate, need to be considered when determining ground-water vulnerability The results obtained by comparing the two models indicate the particle-tracking simulations can be used to determine what parts of the Portland Basin are likely to produce modern water, and the CFC-age dating can provide a useful check on the reliability of particle-tracker results

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SUPPLEMENTAL DATA TABLES

Table 6. Site data, well data (for ground-water sites), and field parameters for sites in the Portland Basin sampled for chlorofluorocarbons

Site-identification number is a unique number assigned to each site for data-base purposes Data for well altitude, well depth, depth to top and bottom of open interval, and depth to water taken from McCarthy and Anderson (1990) A negative value for depth to water indicates artesian pressure converted to equivalent head above land surface An asterisk (*) next to the depth to water indicates a measurement reported by the well driller Date refers to date of water-level measurement Well use IN, industrial, D, domestic, I, irrigation, P, public supply, O, other, hydrogeologic unit US, unconsolidated sedimentary aquifer, TG, Troutdale gravel aquifer, TS, Troutdale sandstone aquifer, SC, sand and gravel aquifer—upper coarse subunit, UF, undifferentiated fine-grained unit, and OR, older rocks Field parameters are from spring 1991 Dissolved oxygen, in milligrams per liter Specific conductance, in microsiemens per centimeter at 25 degrees Celsius Temperature, in degrees Celsius " < " indicates less than " -- " indicates no analysis for this constituent

Site data		Well data								Field parameters			
Site-location number	Site-identification number	Altitude (feet)	Well depth (feet)	Depth to top of open interval (feet)	Depth to bottom of open interval (feet)	Depth to water (feet)	Date	Well use	Hydro-geologic unit	Dissolved oxygen	pH	Specific conductance	Temperature
					Ground-water sites								
1N/2E-13CDCC1(P)	453346122303401	20	569	484	559	-11 6*	11/6/80	O	SC	<1 0	8 4	163	13 2
1N/2E-15DAAA1(J)	453409122321001	23	415	138	415	14 0*	8/13/84	O	US,TS	<1 0	8 5	151	12 1
1N/2E-34ABD1(B)	453149122323101	291	490	415	490	248 9	4/04/89	P	TG	3 2	7 6	194	11 7
1N/3E-8ABC(B)	453522122274601	435	420	420	420	275 0*	4/15/68	D	TG	10 7	7 1	167	11 4
1N/3E-12CAB2(L)	453503122231101	34	87	44	79	26 7	3/29/89	P	US	6 3	6 7	100	11 8
1N/3E-27CBB2(M)	453224122255801	120	1,060	320	340	104 2	3/27/89	P	TS	<1 0	8 3	209	13 6
1N/3E-35ACAD1(G)	453143122235301	312	550	510	545	292 1	3/28/89	P	SC	<1 0	8 2	204	14 4
1N/3E-35BDB(F)	453141122242301	340	458	439	449	329 9	4/04/89	P	TS	2 2	8 7	217	12 3
1N/4E-2AAA(A)	453624122161001	1,077	160	150	160	85 8	3/05/87	D	TG	10 8	6 5	30	9 8
1N/4E-2DDD(R)	453536122161601	807	270	252	270	253 7	4/07/88	D	SC	9 0	6 8	79	10 5
1N/4E-10ABD(B)	453522122174601	597	496	495	496	407 0*	3/09/81	D	SC	<1 0	7 8	159	13 0
1N/4E-11DCB(Q)	453451122164001	523	340	300	340	242 1	4/07/89	D	SC	8 8	7 5	124	11 9
1N/4E-24BAA(C)	453348122153201	517	597	570	595	432 0	4/12/89	D	SC	<1 0	7 9	278	14 3
2N/1E-1AAD(A)	454124122371601	270	65	54	59	35 7	3/29/89	I	US	1 8	7 2	177	12 0
2N/1E-4BAD1(C)	454123122413701	215	303	227	295	149 3	3/30/89	P	TG	7 6	6 7	284	11 5
2N/1E-11AAB1(A)	454037122383301	23	228	172	205	146 0	3/30/89	P	TG	2 3	7 4	240	11 0
2N/1E-11BAC1(C)	454034122391301	230	293	233	293	150 1	3/30/89	P	TG	2 6	7 5	238	11 0
2N/1E-27CBC1(M)	453734122404701	42	128	55	125	33 0*	5/10/57	IN	US	5 0	7 0	243	12 9
2N/2E-7AAB1(A)	454040122360601	270	194	157	188	121 5	3/31/89	P	TG	4 4	6 7	312	10 9
2N/2E-7CAA(L)	454016122363401	300	237	236	237	150 5	3/30/88	D	TG	6 5	7 0	214	10 6
2N/2E-14DDC1(R)	453904122311201	239	146	130	146	88 4	4/01/88	P	TG	8 2	6 9	196	11 1
2N/2E-20AAA(A)	453855122344601	210	221	65	216	58 6	3/30/88	I	TG	<1 0	6 7	217	11 6
2N/2E-27BBC1(D)	453800122331501	314	327	270	305	171 7	3/31/89	P	TG	5 1	7 2	177	11 0
2N/2E-33ADB(H)	453702122333901	304	277	267	277	163 9	3/03/87	I	TG	7 2	7 1	236	11 2
2N/3E-3BBA(D)	454134122254201	465	516	516	516	126 0*	3/30/88	O	OR	3 4	8 8	139	13 7
2N/3E-21DDB(R)	453821122261401	286	101	-91	101	27 5	3/31/88	D	TG	7 4	7 7	139	11 2
2N/3E-24DBC(K)	453825122224901	665	560	512	559	424 6	4/12/89	D	OR	5 4	8 3	177	14 1

Table 6. Site data, well data (for ground-water sites), and field parameters for sites in the Portland Basin sampled for chlorofluorocarbons--Continued

Site data		Well data								Field parameters			
Site-location number	Site-identification number	Altitude (feet)	Well depth (feet)	Depth to top of open interval (feet)	Depth to bottom of open interval (feet)	Depth to water (feet)	Date	Well use	Hydro-geologic unit	Dissolved oxygen	pH	Specific conductance	Temperature
					Ground-water sites—Continued								
2N/3E-25ABB(B)	453807122225101	430	315	265	295	189 3	4/12/89	D	OR	5 4	7 8	236	13 4
2N/3E-31DBA(K)	453646122285201	277	378	344	374	175 8	3/31/88	I	TG	5 6	8 2	177	12 0
2N/4E-33CAC(L)	453640122193001	550	110	108	110	18 7	3/06/87	D	TG	9 8	6 5	58	12 0
2N/4E-36CCA2(N)	453634122155301	1,050	65	55	65	49 2	3/05/87	D	TG	11 8	5 7	14	9 8
3N/1E-8DCB1(Q)	454513122423601	172	157	156	157	126 1	3/28/89	D	TG	4 7	6 8	214	11 4
3N/1E-20BAD(C)	454359122424401	173	183	183	183	143 0*	10/01/51	D	TG	<1 0	7 5	376	11 6
3N/1E-27CDA1(P)	454237122402001	25	65	33	63	9 3	3/29/88	P	US	4 3	7 4	251	11 9
3N/1E-35ABA1(B)	454221122384501	110	172	80	165	75 2	3/30/89	P	TG	5 4	7 1	187	11 9
3N/2E-1BAB(C)	454647122303201	345	112	92	112	9 4	3/29/89	D	OR	<1 0	9 1	126	11 5
3N/2E-3ABA1(B)	454650122323001	290	144	94	136	113 0	3/27/89	P	TG	6 1	7 0	246	12 2
3N/2E-23CBC(M)	454341122320201	298	238	238	238	117 9	3/31/89	I	TS	<1 0	7 4	256	11 6
3N/3E-18ABC(B)	454458122285901	353	130	120	130	-1 1	3/29/89	D	TG	11 0	6 6	93	12 1
4N/1E-7CBC(M)	455029122442501	175	58	43	48	26 0*	9/18/78	D	TG	9 6	6 7	138	11 4
4N/1E-14BDC(F)	454952122391701	298	320	315	320	277 0	4/05/89	I	UF	<1 0	7 3	148	12 1
4N/1E-17ACC(G)	454951122424301	261	290	279	284	236 4	11/20/87	D	UF	4 0	7 0	214	11 8
4N/1E-19BDA2(F)	454902122440301	40	208	162	200	22 4	3/29/89	P	UF	2 0	7 2	236	11 4
4N/1E-21DBC(K)	454850122412201	260	458	326	443	212 7*	7/09/85	IN	UF	<1 0	7 2	209	12 2
4N/1W-17CAA1(L)	454944122501501	25	327	327	327	27 9	4/04/89	P	OR	<1 0	7 9	820	12 0
4N/2E-9CAC(L)	455032122342001	423	373	365	370	328 3	3/31/89	D	UF	<1 0	6 9	157	12 2
4N/2E-10CCB(N)	455031122332001	525	89	79	89	50 8	3/31/89	D	UF	8 2	6 3	119	10 6
4N/2E-11ACC(G)	455051122313101	385	238	190	194	166 1	3/31/89	D	UF	<1 0	7 3	1,520	12 5
4N/2E-23DBA(K)	454902122311801	442	370	323	370	264 8	3/20/85	P	UF	6 9	6 7	76	10 6
4N/2W-24ABB1(B)	454917122523401	135	300	227	300	47 8	4/04/89	P	OR	2 6	7 3	255	12 5
5N/1E-8DCA(Q)	455540122422001	45	102	98	102	21 8	3/28/89	D	US	<1 0	7 2	767	11 5
5N/1E-34ACD3(G)	455224122395001	410	257	220	-257	188 7	3/28/89	P	UF	9 3	6 3	165	11 4
5N/2E-8ABA(B)	455616122345401	183	210	22	189	8 0*	3 /29/82	D	OR	6 7	7 1	153	11 5
5N/2E-19ABA(B)	455433122361001	821	200	158	200	-1 0*	3/31/81	D	OR	<1 0	8 6	214	11 0
					Surface-water sites								
1N/3E-11DAD(J)	453513122234100									--	7 3	28	10 7
1N/3E-13ABA(B)	453440122233900									--	7 0	155	9 7
2N/1E-28DDA(R)	453728122405400									--	8 7	158	11 6
5N/2E-9ADD(H)	455554122332000									13 6	6 0	45	13 0

Table 7. Chlorofluorocarbon concentrations in water samples from the Portland Basin and corresponding chlorofluorocarbon-model recharge dates

[Site-location number see figure 2, CFC (chlorofluorocarbon), CFC concentrations given in picograms of CFC per kilogram of sample, CFC-model recharge dates for ground-water samples calculated based on estimated recharge temperature of 8 degrees Celsius—for surface-water samples, the measured water temperature rounded to the nearest whole number was used, samples containing CFC concentrations greater than that expected for waters in equilibrium with 1991 atmosphere cannot be age dated—these samples are designated "cont", " < " indicates less than, " -- " indicates no data]

Site-location number	First sampling (spring 1991)						Second sampling (fall 1991)					
	Sample date	Time	CCl_3F	CCl_2F_2	CCl_3F model date	CCl_2F_2 model date	Sample date	Time	CCl_3F	CCl_2F_2	CCl_3F model date	CCl_2F_2 model date
Ground-water samples												
1N/2E-13CDCC1(P)	5/30/91	1650	8	<1	1953	<1944	--	--	--	--	--	--
		1708	2	<1	1950	<1944	--	--	--	--	--	--
		1727	2	<1	1950	<1944	--	--	--	--	--	--
1N/2E-15DAAA1(J)	5/16/91	0851	8	<1	1953	<1944	--	--	--	--	--	--
		0903	8	<1	1953	<1944	--	--	--	--	--	--
		0920	7	<1	1953	<1944	--	--	--	--	--	--
1N/2E-34ABD1(B)	5/14/91	1213	7,005	2,918	cont	cont	--	--	--	--	--	--
		1222	6,423	2,609	cont	cont	--	--	--	--	--	--
		1232	6,361	2,703	cont	cont	--	--	--	--	--	--
1N/3E-8ABC(B)	4/15/91	1033	13	<1	1955	<1944	--	--	--	--	--	--
		1135	12	5	1955	1949	--	--	--	--	--	--
		1140	12	<1	1955	<1944	--	--	--	--	--	--
1N/3E-12CAB2(L)	4/24/91	1017	1,585	14,332	cont	cont	--	--	--	--	--	--
		1024	1,284	12,599	cont	cont	--	--	--	--	--	--
		1028	3,324	12,664	cont	cont	--	--	--	--	--	--
1N/3E-27CBB2(M)	5/14/91	1030	14	32	1955	1962	--	--	--	--	--	--
		1042	7	14	1953	1956	--	--	--	--	--	--
		1058	6	14	1953	1956	--	--	--	--	--	--
1N/3E-35ACAD1(G)	5/13/91	1140	9	<1	1953	<1944	--	--	--	--	--	--
		1156	6	<1	1953	<1944	--	--	--	--	--	--
		1207	7	<1	1953	<1944	--	--	--	--	--	--
1N/3E-35BDB(F)	5/13/91	1339	1,262	422	cont	cont	--	--	--	--	--	--
		1350	1,058	281	cont	1985	--	--	--	--	--	--
		1404	1,055	294	cont	1985	--	--	--	--	--	--
1N/4E-2AAA(A)	4/22/91	1427	739	236	1984	1980	10/15/91	0923	662	272	1984	1985
		1442	699	220	1983	1978	--	0940	674	267	1984	1985
		1452	970	226	1990	1979	--	0953	671	270	1984	1985
1N/4E-2DDD(R)	5/03/91	1530	42¹	7	1961	1951	--	--	--	--	--	--
		1541	15	<1	1955	<1944	--	--	--	--	--	--
		1550	7	<1	1953	<1944	--	--	--	--	--	--
1N/4E-10ABD(B)	4/22/91	1721	49	6	1961	1951	10/15/91	1134	12	8	1955	1953
		1747	17	4	1956	1949	--	1149	14	7	1955	1952
		1811	10	7	1954	1952	--	1217	8	5	1953	1950

Table 7. Chlorofluorocarbon concentrations in water samples from the Portland Basin and corresponding chlorofluorocarbon-model recharge dates—Continued

Site-location number	First sampling (spring 1991)						Second sampling (fall 1991)					
	Sample date	Time	CCl_3F	CCl_2F_2	CCl_3F model date	CCl_2F_2 model date	Sample date	Time	CCl_3F	CCl_2F_2	CCl_3F model date	CCl_2F_2 model date
						Ground-water samples—Continued						
1N/4E-11DCB(Q)	5/03/91	1337	26	<1	1958	<1944	--	--	--	--	--	--
		1342	28	<1	1958	<1944	--	--	--	--	--	--
		1348	26	<1	1958	<1944	--	--	--	--	--	--
1N/4E-24BAA(C)	4/30/91	1719	13	<1	1955	<1944	--	--	--	--	--	--
		1740	12	<1	1954	<1944	--	--	--	--	--	--
		1756	2	<1	1950	<1944	--	--	--	--	--	--
2N/1E-1AAD(A)	5/15/91	1415	<1	68	<1948	1967	--	--	--	--	--	--
		1435	79	71	1964	1968	--	--	--	--	--	--
		1445	175	75	1969	1968	--	--	--	--	--	--
2N/1E-4BAD1(C)	5/08/91	1050	3,233	1,529	cont	cont	--	--	--	--	--	--
		1101	2,616	1,548	cont	cont	--	--	--	--	--	--
		1108	3,115	1,672	cont	cont	--	--	--	--	--	--
2N/1E-11AAB1(A)	5/08/91	0900	42	57	1961	1966	10/10/91	1354	21	60	1957	1967
		0915	29	28	1958	1961	--	1412	20	57	1957	1966
		0927	37	29	1960	1961	--	1427	20	57	1956	1966
2N/1E-11BAC1(C)	5/09/91	1029	151	177	1968	1976	10/10/91	1529	190	302	1969	1987
		1034	140	104	1967	1971	--	1549	194	321	1970	1988
		1041	133	101	1967	1971	--	1607	196	306	1970	1987
2N/1E-27CBC1(M)	5/07/91	1426	18,243	811	cont	cont	--	--	--	--	--	--
		1433	16,601	755	cont	cont	--	--	--	--	--	--
		1439	17,562	752	cont	cont	--	--	--	--	--	--
2N/2E-7AAB1(A)	5/09/91	1354	64,401	33,357	cont	cont	--	--	--	--	--	--
		1400	66,063	30,714	cont	cont	--	--	--	--	--	--
		1410	64,843	31,039	cont	cont	--	--	--	--	--	--
2N/2E-7CAA(L)	5/07/91	1059	34,406	14,817	cont	cont	--	--	--	--	--	--
		1119	32,580	12,821	cont	cont	--	--	--	--	--	--
		1127	32,029	12,693	cont	cont	--	--	--	--	--	--
2N/2E-14DDC1(R)	5/09/91	1231	12,167	6,143	cont	cont	--	--	--	--	--	--
		1241	11,813	4,861	cont	cont	--	--	--	--	--	--
		1248	12,039	4,745	cont	cont	--	--	--	--	--	--
2N/2E-20AAA(A)	5/15/91	0746	21	101	1957	1971	--	--	--	--	--	--
		0755	18	53	1956	1966	--	--	--	--	--	--
		0808	12	47	1955	1965	--	--	--	--	--	--
2N/2E-27BBC1(D)	5/08/91	1526	4,503	881	cont	cont	--	--	--	--	--	--
		1548	3,728	729	cont	cont	--	--	--	--	--	--
		1600	3,385	702	cont	cont	--	--	--	--	--	--

Site-location number	First sampling (spring 1991)						Second sampling (fall 1991)					
	Sample date	Time	CCl_3F	CCl_2F_2	CCl_3F model date	CCl_2F_2 model date	Sample date	Time	CCl_3F	CCl_2F_2	CCl_3F model date	CCl_2F_2 model date
					Ground-water samples—Continued							
2N/2E-33ADB(H)	5/16/91	1118	605	208	1980	1978	--	--	--	--	--	--
		1128	601	208	1980	1978	--	--	--	--	--	--
		1139	679	274	1983	1984	--	--	--	--	--	--
2N/3E-3BBA(D)	5/15/91	1133	11	<1	1954	<1944	--	--	--	--	--	--
		1144	6	<1	1952	<1944	--	--	--	--	--	--
		1159	6	<1	1952	<1944	--	--	--	--	--	--
2N/3E-21DDB(R)	4/16/91	1815	254	176	1971	1976	10/10/91	1741	225	136	1971	1974
		1836	217	192	1970	1977	--	1806	151	107	1968	1971
		1841	185	167	1969	1976	--	--	--	--	--	--
2N/3E-24DBC(K)	4/26/91	1139	72	40	1963	1963	10/15/91	1625	70	55	1963	1966
		1144	70	43	1963	1964	--	1645	68	55	1963	1966
		1150	76	49	1964	1965	--	1704	66	54	1963	1966
2N/3E-25ABB(B)	4/26/91	1435	106	37	1966	1963	10/17/91	1046	87	48	1965	1965
		1445	89	39	1965	1963	--	1125	92	52	1965	1966
		1450	84	42	1964	1964	--	1137	91	50	1965	1965
2N/3E-31DBA(K)	4/23/91	1128	46	5	1961	1949	10/17/91	1405	14	6	1955	1951
		1133	43	5	1961	1949	--	1411	13	7	1955	1952
		1148	14	6	1955	1950	--	1417	11	10	1954	1954
2N/4E-33CAC(L)	4/22/91	1129	443	135	1976	1973	10/15/91	1358	459	204	1977	1978
		1134	430	129	1975	1973	--	1410	491	214	1977	1979
		1139	437	129	1976	1973	--	1423	510	224	1978	1980
2N/4E -36CCA2(N)	4/24/91	1442	2,089	33,056	cont	cont						
		1454	1,534	27,297	cont	cont						
		1506	1,658	32,373	cont	cont						
3N/1E-8DCB1(Q)	4/25/91	1848	69	19	1963	1958	10/16/91	1519	65	24	1963	1960
		1859	63	20	1963	1959	--	1532	63	23	1963	1960
		1908	58	16	1962	1957	--	1611	64	23	1963	1960
3N/1E-20BAD(C)	4/29/91	1643	17	12	1956	1955	--	--	--	--	--	--
		1654	17	<1	1956	<1944	--	--	--	--	--	--
		1705	4	6	1951	1951	--	--	--	--	--	--
3N/1E-27CDA1(P)	4/09/91	1145	1,958	281	cont	1985	--	--	--	--	--	--
		1230	2,146	340	cont	1989	--	--	--	--	--	--
		1245	1,958	305	cont	1986	--	--	--	--	--	--
3N/1E-35ABA1(B)	5/08/91	1328	2,967	270	cont	1984	--	--	--	--	--	--
		1344	2,813	166	cont	1976	--	--	--	--	--	--
		1358	2,163	212	cont	1978	--	--	--	--	--	--

Table 7. Chlorofluorocarbon concentrations in water samples from the Portland Basin and corresponding chlorofluorocarbon-model recharge dates—Continued

Site-location number	First sampling (spring 1991)						Second sampling (fall 1991)					
	Sample date	Time	CCl₃F	CCl₂F₂	CCl₃F model date	CCl₂F₂ model date	Sample date	Time	CCl₃F	CCl₂F₂	CCl₃F model date	CCl₂F₂ model date

<p align="center">Ground-water samples—Continued</p>

Site-location number	Sample date	Time	CCl₃F	CCl₂F₂	CCl₃F model date	CCl₂F₂ model date	Sample date	Time	CCl₃F	CCl₂F₂	CCl₃F model date	CCl₂F₂ model date
3N/2E-1BAB(C)	4/18/91	1159	218	15,573	1970	cont	--	--	--	--	--	--
		1210	91	16,777	1965	cont	--	--	--	--	--	--
		1222	76	15,180	1964	cont	--	--	--	--	--	--
3N/2E-3ABA1(B)	4/08/91	1738	5,742	3,218	cont	cont	--	--	--	--	--	--
		1816	5,975	3,343	cont	cont	--	--	--	--	--	--
		1908	1,541	559	cont	cont	--	--	--	--	--	--
3N/2E-23CBC(M)	4/29/91	1353	63	10	1963	1954	10/18/91	1048	<1	<1	<1948	<1944
		1412	19	8	1956	1953	--	1054	<1	<1	<1948	<1944
		1422	10	6	1954	1951	--	1059	5	4	1952	1949
3N/3E-18ABC(B)	4/19/91	1109	72	17	1963	1957	10/09/91	1728	98	59	1965	1967
		1134	61	18	1963	1958	--	1732	94	60	1965	1967
		1144	58	17	1962	1957	--	1738	146	138	1968	1974
4N/1E-7CBC(M)	4/30/91	1000	2,335	1,000	cont	cont	--	--	--	--	--	--
		1010	2,007	960	cont	cont	--	--	--	--	--	--
		1024	1,995	958	cont	cont	--	--	--	--	--	--
4N/1E-14BDC(F)	4/30/91	1356	123	<1	1967	<1944	--	--	--	--	--	--
		1408	77	<1	1964	<1944	--	--	--	--	--	--
		1418	16	<1	1956	<1944	--	--	--	--	--	--
4N/1E-17ACC(G)	5/15/91	1502	27	<1	1958	<1944	--	--	--	--	--	--
		1507	4	<1	1951	<1944	--	--	--	--	--	--
		1514	3	<1	1950	<1944	--	--	--	--	--	--
4N/1E-19BDA2(F)	4/08/91	1244	6	<1	1953	<1944	--	--	--	--	--	--
		1258	<1	<1	<1948	<1944	--	--	--	--	--	--
		1321	<1	<1	<1948	<1944	--	--	--	--	--	--
4N/1E-21DBC(K)	5/16/91	1419	3	<1	1951	<1944	--	--	--	--	--	--
		1437	<1	<1	<1948	<1944	--	--	--	--	--	--
		1446	<1	<1	<1948	<1944	--	--	--	--	--	--
4N/1W-17CAA1(L)	5/30/91	1332	7	<1	1953	<1944	--	--	--	--	--	--
		1352	<1	<1	<1948	<1944	--	--	--	--	--	--
		1415	<1	<1	<1948	<1944	--	--	--	--	--	--
4N/2E-9CAC(L)	4/11/91	1257	12	<1	1955	<1944	--	--	--	--	--	--
		1310	8	<1	1953	<1944	--	--	--	--	--	--
		1326	62	6	1963	1951	--	--	--	--	--	--
4N/2E-10CCB(N)	4/18/91	1614	473	509	1976	cont	10/16/91	1315	471	248	1977	1982
		1623	487	160	1977	1975	--	1346	477	244	1977	1982
		1634	494	159	1977	1975	--	1409	457	237	1976	1981

Table 7. Chlorofluorocarbon concentrations in water samples from the Portland Basin and corresponding chlorofluorocarbon-model recharge dates—Continued

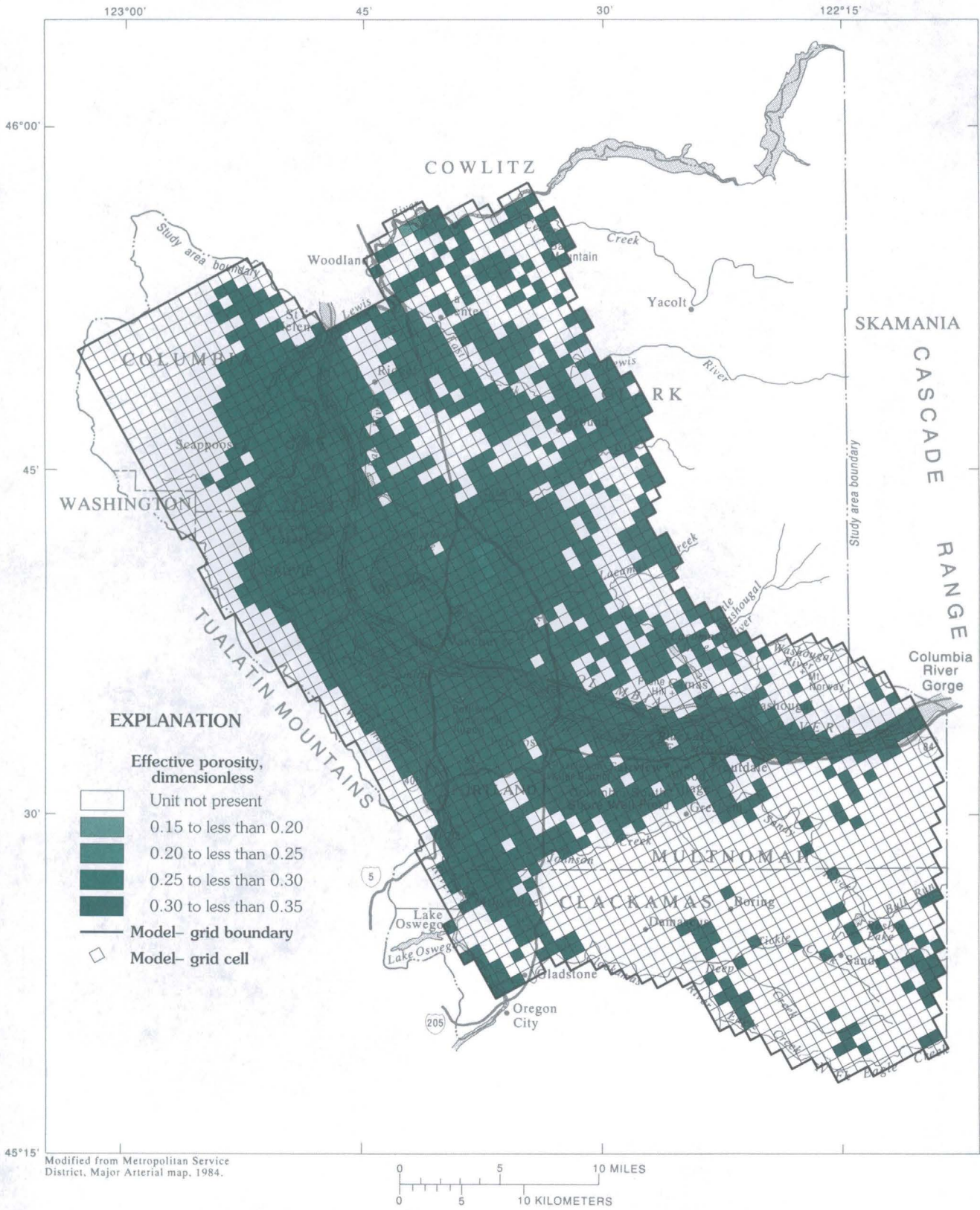| Site-location number	First sampling (spring 1991)						Second sampling (fall 1991)					
	Sample date	Time	CCl$_3$F	CCl$_2$F$_2$	CCl$_3$F model date	CCl$_2$F$_2$ model date	Sample date	Time	CCl$_3$F	CCl$_2$F$_2$	CCl$_3$F model date	CCl$_2$F$_2$ model date
					Ground-water samples—Continued							
4N/2E-11ACC(G)	4/18/91	1419	52	19	1962	1958	--	--	--	--	--	--
		1439	35	18	1959	1958	--	--	--	--	--	--
		1449	60	941	1962	cont	--	--	--	--	--	--
4N/2E-23DBA(K)	4/09/91	1523	323	92	1973	1970	10/09/91	1014	341	144	1974	1974
		1547	298	112	1972	1972	--	1046	337	142	1974	1974
		1639	318	117	1973	1972	--	1105	332	140	1973	1974
4N/2W-24ABB1(B)	5/30/91	1036	12	<1	1955	<1944	--	--	--	--	--	--
		1059	<1	<1	<1948	<1944	--	--	--	--	--	--
		1110	<1	<1	<1948	<1944	--	--	--	--	--	--
5N/1E-8DCA(Q)	4/16/91	1259	15	<1	1955	<1944	--	--	--	--	--	--
		1329	<1	<1	<1948	<1944	--	--	--	--	--	--
		1336	<1	<1	<1948	<1944	--	--	--	--	--	--
5N/1E-34ACD3(G)	4/10/91	0958	110	55	1966	1966	10/09/91	1400	138	67	1967	1968
		1018	104	72	1966	1968	--	1430	95	46	1965	1965
		1031	108	81	1966	1969	--	1451	91	45	1965	1965
5N/2E-8ABA(B)	4/12/91	1211	112	47	1966	1965	10/16/91	0945	117	84	1966	1969
		1218	107	61	1966	1967	--	1013	117	79	1966	1969
		1229	111	62	1966	1967	--	1045	120	83	1966	1969
5N/2E-19ABA(B)	4/19/91	1645	52	5	1962	1949	10/10/91	1051	213	10	1970	1954
		1656	33	5	1959	1949	--	1059	236	13	1971	1956
		1706	23	4	1957	1948	--	--	--	--	--	--
					Surface-water grab samples							
1N/3E-11DAD(J) (Washougal River)	4/24/91	1150	2,031	301	cont	1990	--	--	--	--	--	--
		1150	1,592	302	cont	1990	--	--	--	--	--	--
		1150	1,647	292	cont	1989	--	--	--	--	--	--
1N/3E-13ABA(B) (Columbia River)	4/24/91	1218	3,118	328	cont	1991	--	--	--	--	--	--
		1219	2,242	479	cont	cont	--	--	--	--	--	--
		1220	3,293	317	cont	1990	--	--	--	--	--	--
2N/1E-28DDA(R) (Columbia River)	5/07/91	1541	3,537	346	cont	cont	--	--	--	--	--	--
		1543	3,627	248	cont	1986	--	--	--	--	--	--
		1545	2,772	269	cont	1988	--	--	--	--	--	--
5N/2E-9ADD(H) (ephemeral pond)	4/10/91	1612	1,461	250	cont	1987	--	--	--	--	--	--
		1613	1,430	277	cont	1990	--	--	--	--	--	--
		1614	1,688	371	cont	cont	--	--	--	--	--	--

APPENDIX

Figure A1. Simulated distribution of effective porosity of the unconsolidated sedimentary aquifer in the ground-water model of the Portland Basin.

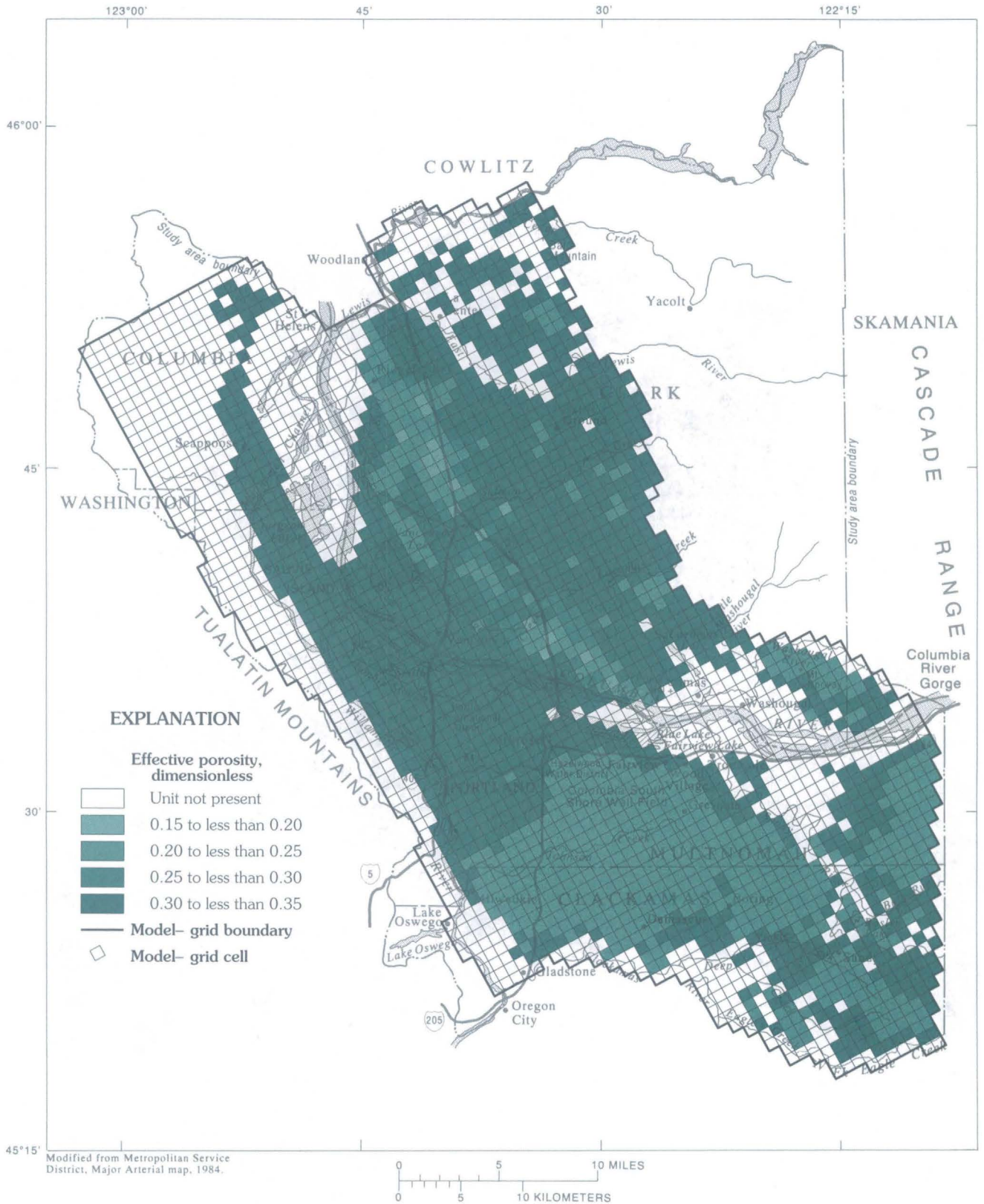**Figure A2.** Simulated distribution of effective porosity of the Troutdale gravel aquifer in the ground-water model of the Portland Basin.
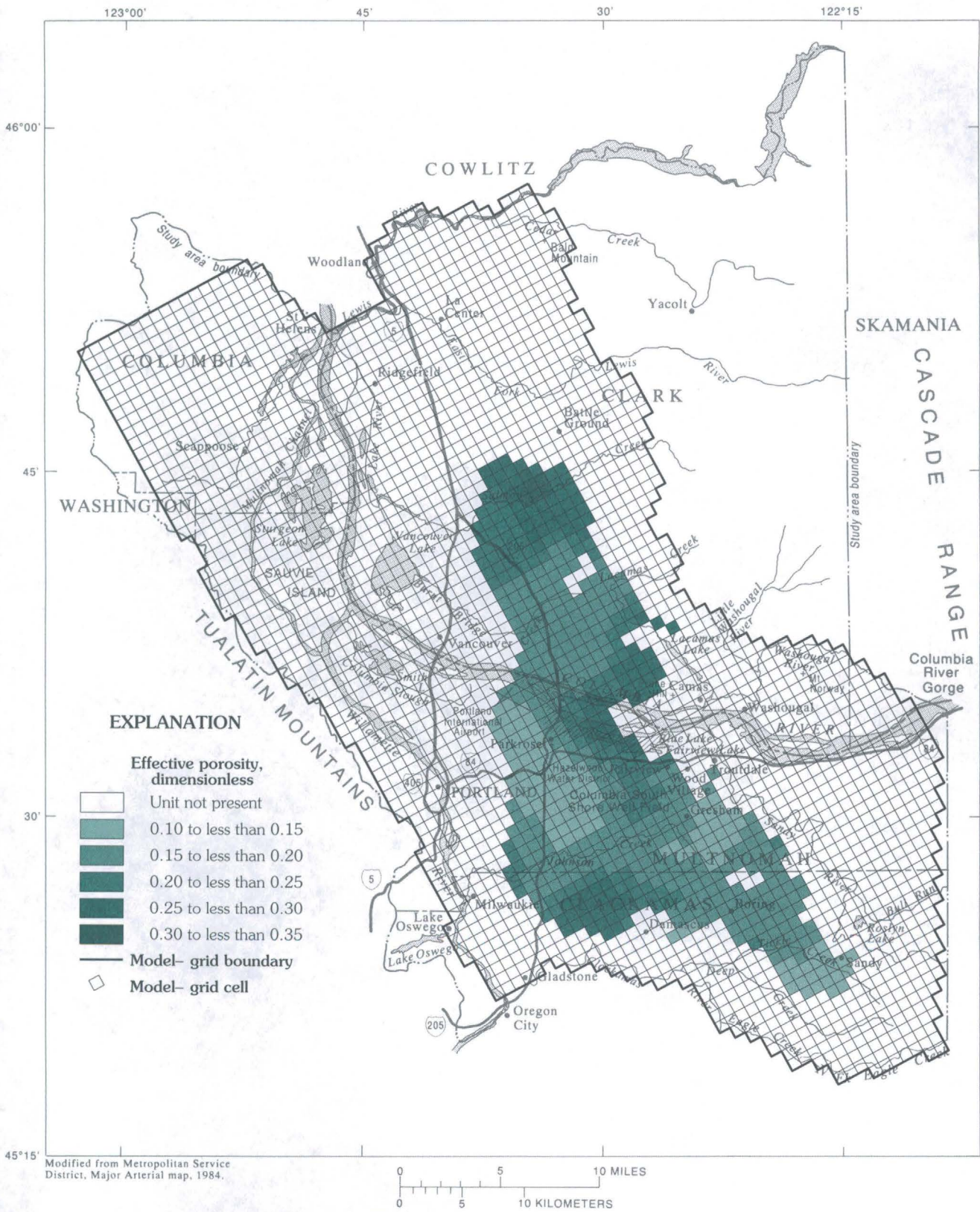
Figure A3. Simulated distribution of effective porosity of confining unit 1 in the ground-water model of the Portland Basin.
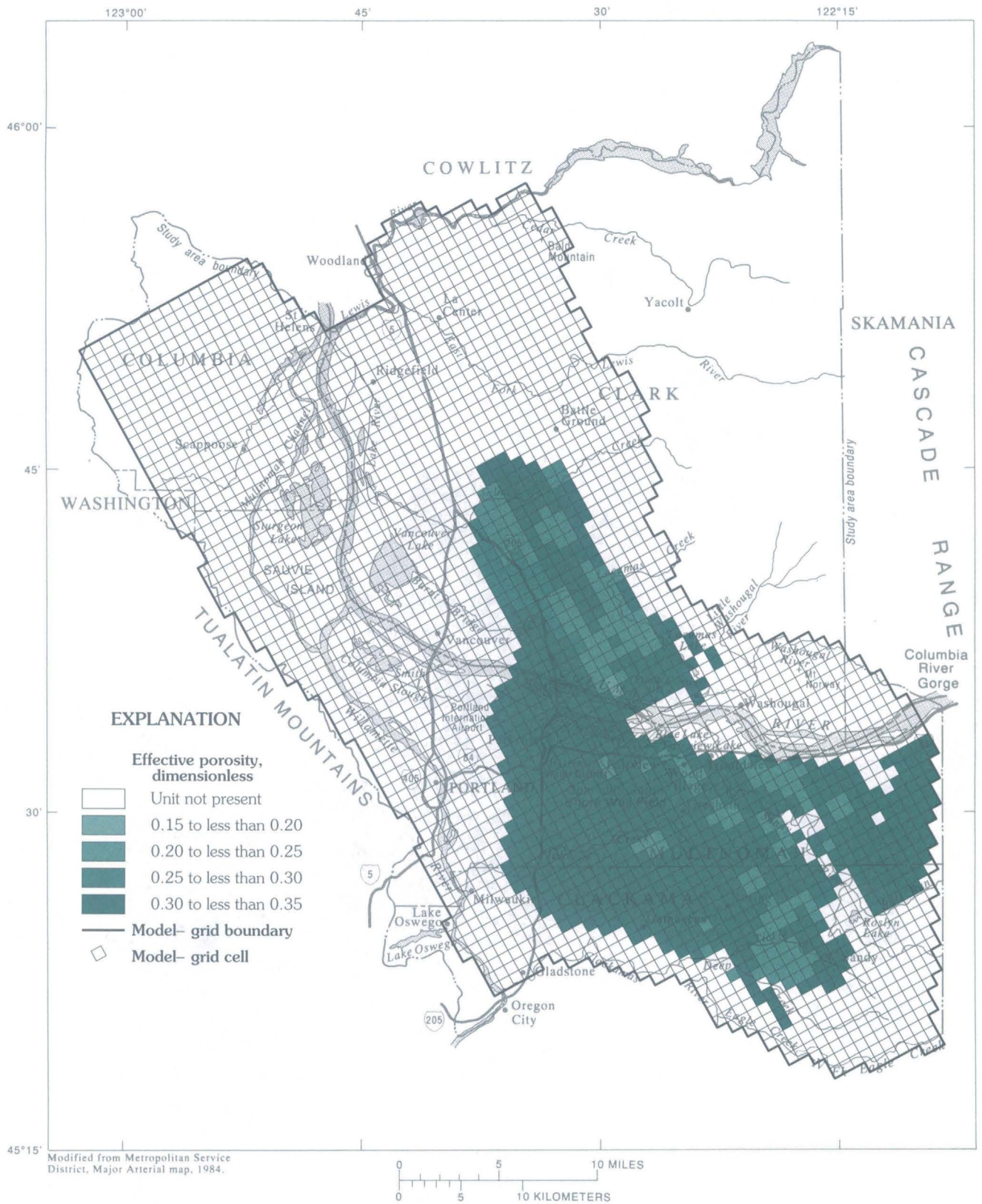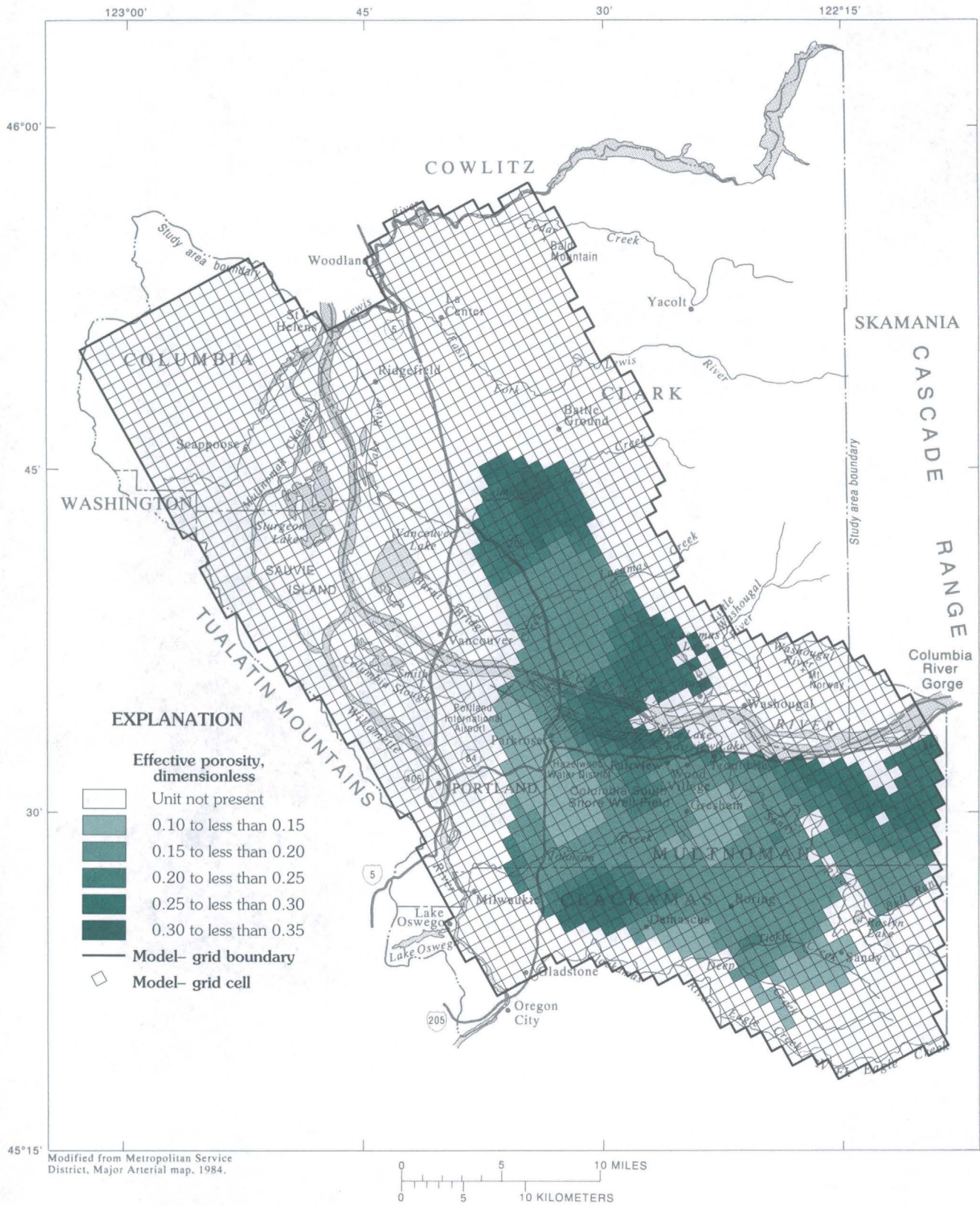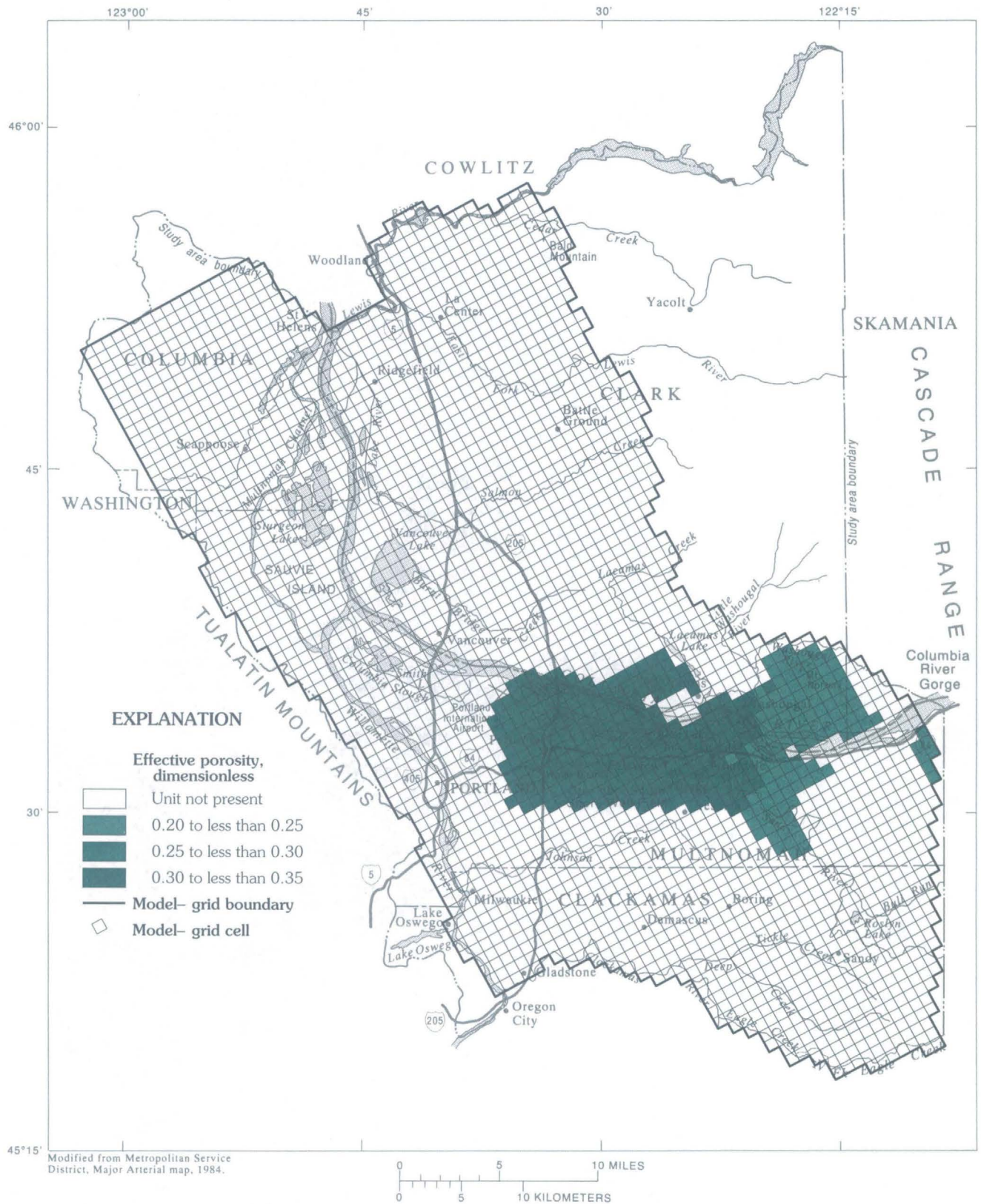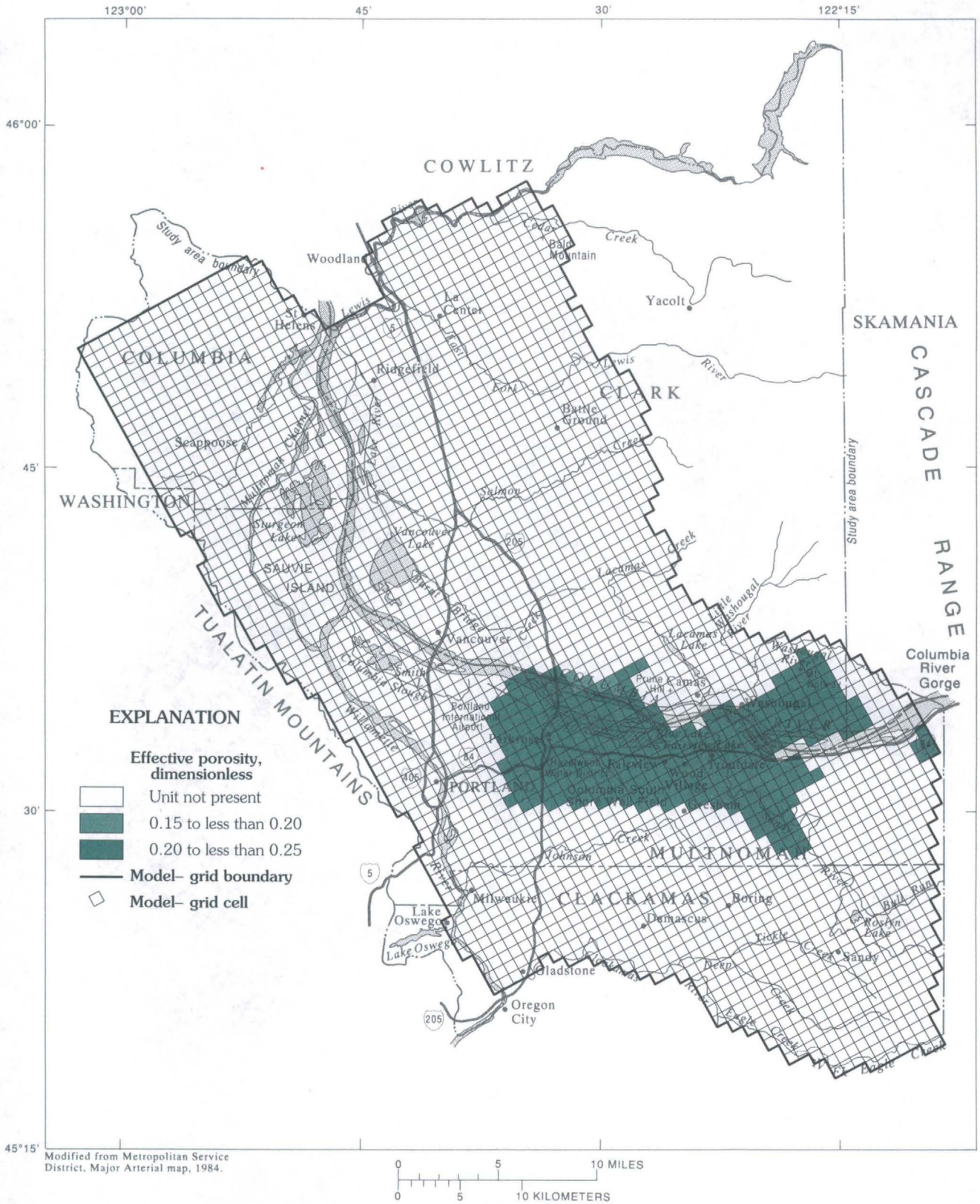
Figure A4. Simulated distribution of effective porosity of the Troutdale sandstone aquifer in the ground-water model of the Portland Basin.

Figure A5. Simulated distribution of effective porosity of confining unit 2 in the ground-water model of the Portland Basin.

Figure A6. Simulated distribution of effective porosity of the sand and gravel aquifer—upper subunit in the ground-water model of the Portland Basin.

Figure A7. Simulated distribution of effective porosity of the sand and gravel aquifer—lower subunit in the ground-water model of the Portland Basin.
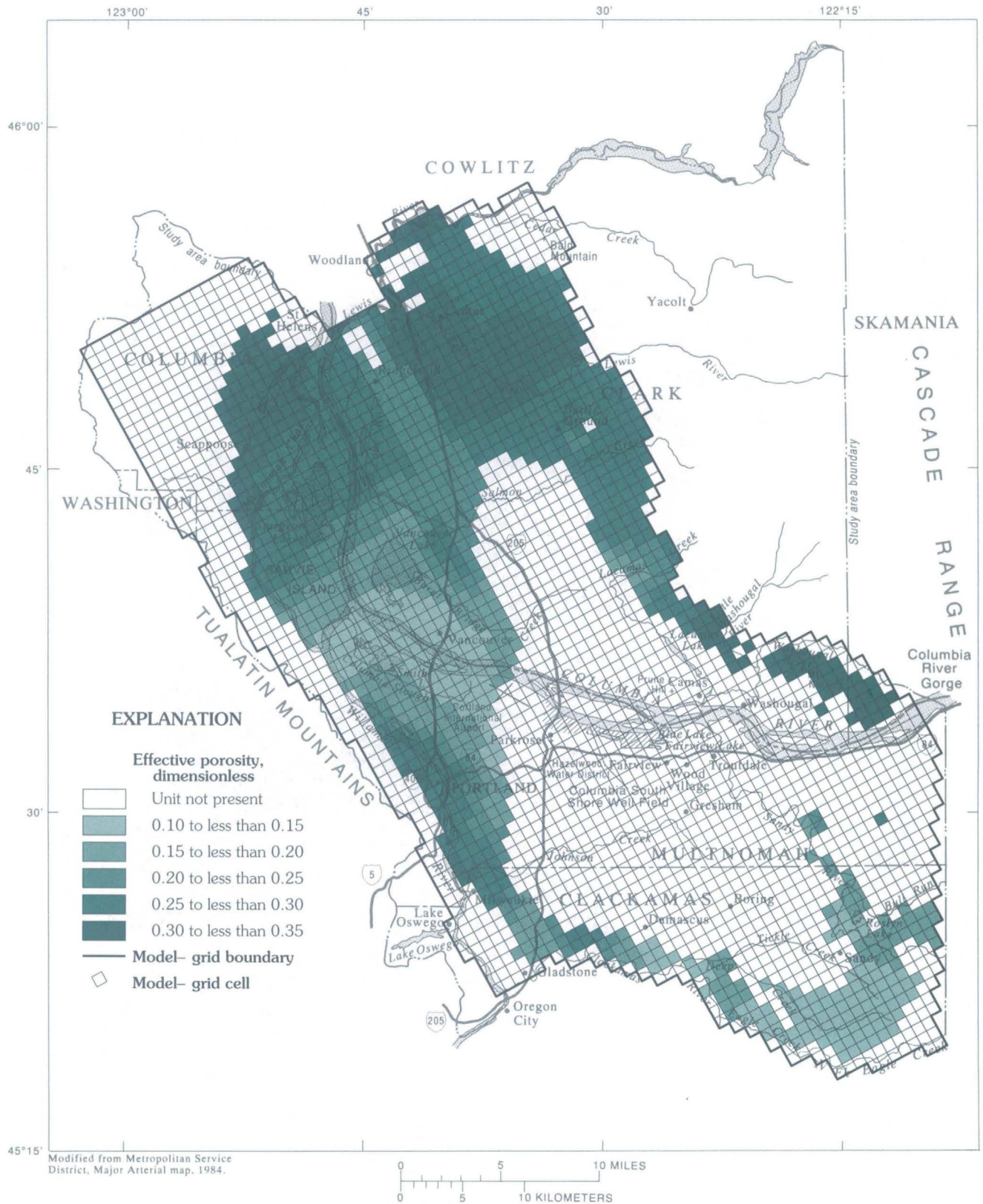
Figure A8. Simulated distribution of effective porosity of the undifferentiated fine-grained unit in the ground-water model of the Portland Basin.
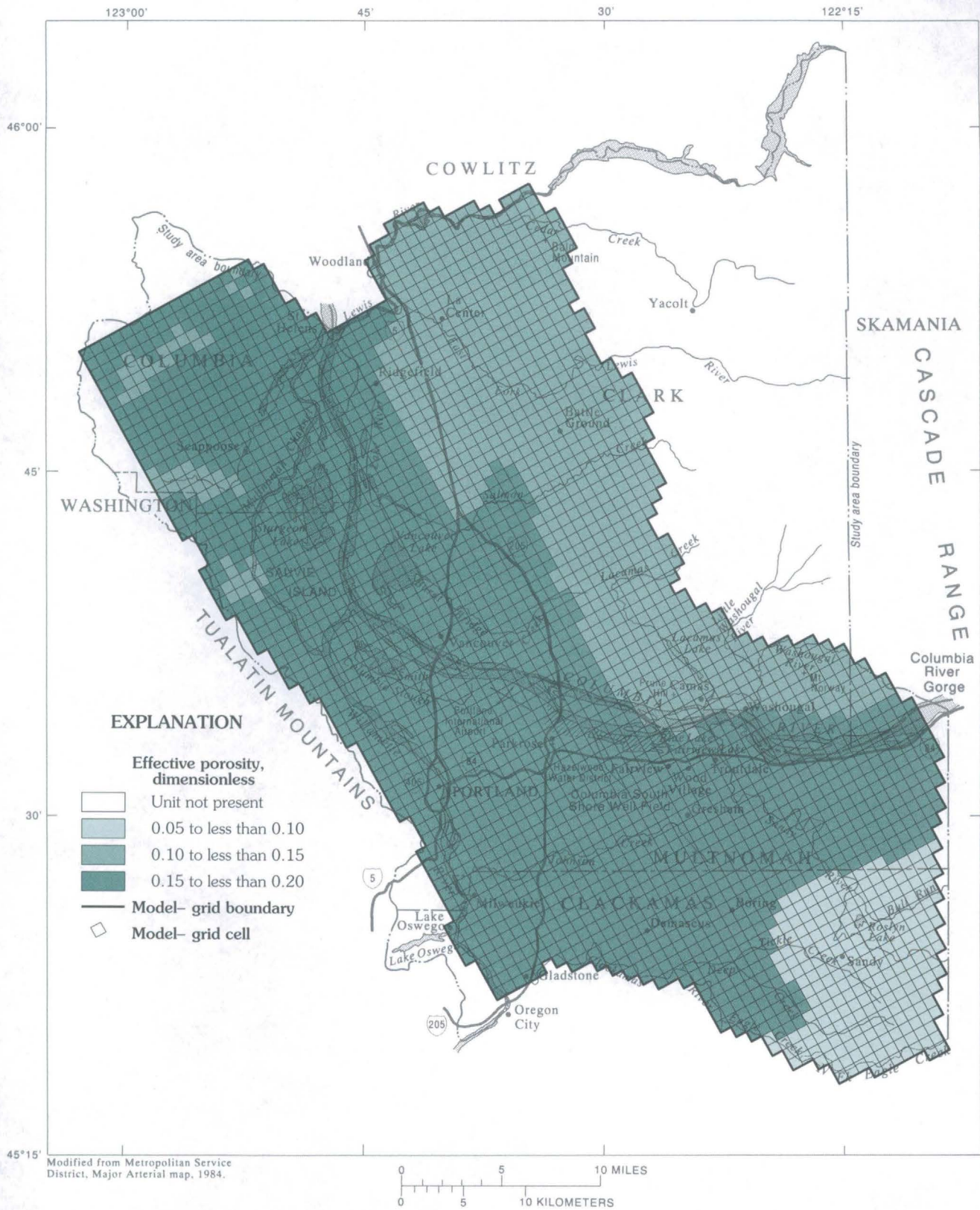
Figure A9. Simulated distribution of effective porosity of the older rock unit in the ground-water model of the Portland Basin.