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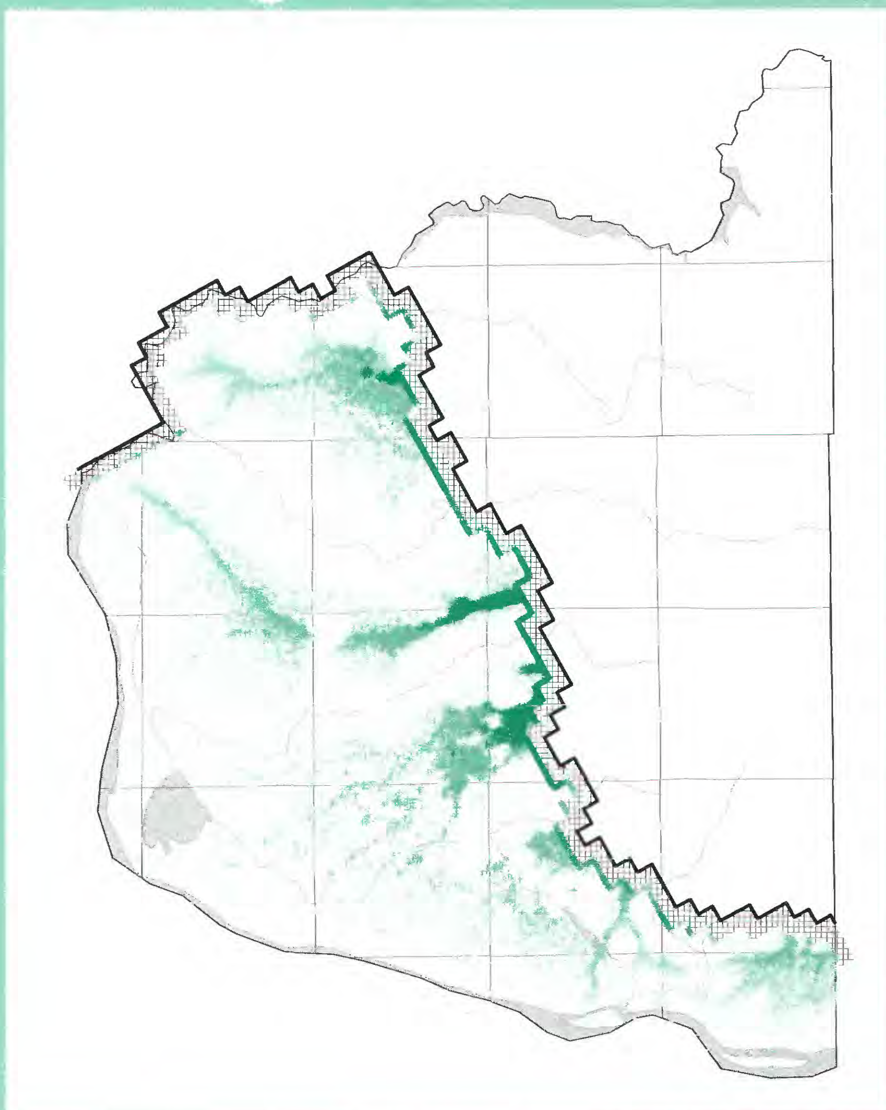

Water-Supply Paper 2488

Prepared in cooperation with
Intergovernmental Resource Center
Clark County, Washington

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Use of a Ground-Water Flow Model with Particle Tracking to Evaluate Ground-Water Vulnerability, Clark County, Washington

Cover illustration. Recharge points for simulated particles of water within the ground-water flow system of Clark County, Washington, based on a particle-tracking analysis using MODPATH. The ground-water flow system was represented as part of a three-dimensional ground-water flow model of the Portland Basin, Oregon and Washington, simulated with MODFLOW, using a grid of 90 columns, 50 rows, and 8 layers. The particles were generated by placing a regularly spaced array of 6 particles per cell, 1 on each cell face within the ground-water flow model that represents Clark County, for a total of about 60,000 particles, and tracking the particles backwards in time through the simulated flow system. The recharge points are shaded on the basis of the distance traversed by the particles, with darker shades representing longer distances. Recharge areas for intermediate- and regional-scale flow systems are indicated by a high density of dark recharge points. The results of the particle-tracking simulation were used to evaluate ground-water vulnerability by identifying recharge areas and their characteristics, determining the downgradient impact of land use at recharge areas, and estimating the age of ground water. A description of the methods used and the results of the evaluation of ground-water vulnerability are presented in this report.

Frontispiece. View of Vancouver, Washington (center left) and southwestern Clark County looking north across the Columbia River from Oregon.

U.S. Department of Interior
U.S. Geological Survey

Use of a Ground-Water Flow Model with Particle Tracking to Evaluate Ground-Water Vulnerability, Clark County, Washington

By DANIEL T. SNYDER, JAMES M. WILKINSON, and LEONARD L. ORZOL

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2488

Prepared in cooperation with
INTERGOVERNMENTAL RESOURCE CENTER,
CLARK COUNTY, WASHINGTON

U.S. Department of the Interior
Bruce Babbitt, Secretary

U.S. Geological Survey
Charles G. Groat, Director

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1998

For sale by the
U.S. Geological Survey
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Denver, CO 80225

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Library of Congress Cataloging in Publication Data

Snyder, Daniel T.
Use of a ground-water flow model with particle tracking to evaluate ground-water vulnerability, Clark County, Washington / by Daniel T. Snyder, James M. Wilkinson, and Leonard L. Orzol.
p. cm. — (U.S. Geological Survey water-supply paper : 2488)
"Prepared in cooperation with Intergovernmental Resource Center, Clark County, Washington."
Includes bibliographical references.
ISBN 0-607-89534-9 (alk. paper)
1. Groundwater flow—Washington (State)—Clark County—Mathematical models. I. Wilkinson, James M. II. Orzol, L. L. III. Title. IV. Series.
GB1197.7.S63 1998
551.49'09797'86—dc21 98-40877
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FIGURES

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DEFINITION OF TERMS

Advection. The process whereby solutes are transported by the bulk mass of flowing fluid.

Anthropogenic. Resulting from or relating to activities of humans.

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquifer sensitivity. The relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest; aquifer sensitivity is a function of the intrinsic characteristics of the hydrogeologic setting and is not dependent on land-use practices and contaminant characteristics.

Boundary, no-flow. No-flow or inactive model cells are those for which no flow into or out of the cell is permitted in any time step of the simulation; no-flow boundaries are used in models to represent conditions along hydrologic boundaries such as ground-water divides or low-permeability rock contacts.

Contaminant. An undesirable substance not normally present, or an unusually large concentration of a naturally occurring substance, in water, soil, or other environmental medium.

Contamination. The addition to water of any substance or property that prevents the use or reduces the usability of the water.

Diffusion. The process whereby particles of liquids, gases, or solids intermingle as the result of their spontaneous movement caused by thermal agitation and, in dissolved substances, move from a region of larger to one of smaller concentration.

Discharge. The process of removal of water from the saturated zone; also the water removed.

Discharge area. An area in which ground water is discharged to the land surface, surface water, or atmosphere.

Dispersion, mechanical. See Mechanical dispersion.

Flow path. The subsurface course a water molecule or solute follows in a given ground-water velocity field.

Ground-water vulnerability. The relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest; vulnerability is a function of land-use practices, contaminant characteristics, and aquifer-sensitivity conditions.

Hydrodynamic dispersion. The spreading and mixing of chemical constituents in water caused by diffusion and mechanical dispersion.

Hydrogeologic unit. Any soil, rock unit, or zone that, by virtue of its hydraulic properties, has a distinct influence on the storage or movement of ground water.

Internal sink. See Sink, internal

Internal source. See Source, internal

Mechanical dispersion. The mixing that occurs as a consequence of local variations in velocity around some mean velocity of flow that arise from heterogeneities at different scales.

No-flow boundary. See Boundary, no-flow.

Porosity, effective. The amount of interconnected pore space available for fluid transmission. It is expressed as a percentage of the total volume occupied by the interconnecting interstices.

Recharge. The process of addition of water to the saturated zone; also the water added.

Recharge area. An area in which ground water is recharged from the land surface or surface water.

Retardation. The extent to which something is held back or slowed down.

Sink, internal. Hydrologic features such as discharging wells, gaining rivers, or vegetation that are represented in a ground-water model to simulate the consumption or outflow of water.

Sink, weak. See Weak sink cells.

Source, internal. Hydrologic features such as recharging wells, losing rivers, or precipitation that are represented in a ground-water model to simulate the generation or inflow of water.

Steady state. Conditions remain constant through time.

Traveltime. The time required for ground water to travel between two locations.

Transient flow. The condition in which, at any point in the ground-water system, the magnitude or direction of flow changes with time.

Velocity, average interstitial. The average rate of ground-water flow in interstices expressed as the product of hydraulic conductivity and hydraulic gradient divided by the effective porosity.

Weak sink cells. Model-grid cells that contain one or more internal sinks that do not 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 the cell across other cell faces and through the sink(s).

Use of a Ground-Water Flow Model with Particle Tracking to Evaluate Ground-Water Vulnerability, Clark County, Washington

By Daniel T. Snyder, James M. Wilkinson, *and* Leonard L. Orzol

Abstract

A ground-water flow model was used in conjunction with particle tracking to evaluate ground-water vulnerability in Clark County, Washington. Using the particle-tracking program, particles were placed in every cell of the flow model (about 60,000 particles) and tracked backwards in time and space upgradient along flow paths to their recharge points. A new computer program was developed that interfaces the results from a particle-tracking program with a geographic information system (GIS). The GIS was used to display and analyze the particle-tracking results. Ground-water vulnerability was evaluated by selecting parts of the ground-water flow system and combining the results with ancillary information stored in the GIS to determine recharge areas, characteristics of recharge areas, downgradient impact of land use at recharge areas, and age of ground water.

Maps of the recharge areas for each hydrogeologic unit illustrate the presence of local, intermediate, or regional ground-water flow systems and emphasize the three-dimensional nature of the ground-water flow system in Clark County. Maps of the recharge points for each hydrogeologic unit were overlaid with maps depicting aquifer sensitivity as determined by DRASTIC (a measure of the pollution potential of ground water, based on the intrinsic characteristics of the near-surface unsaturated and saturated zones) and recharge from on-site waste-disposal systems. A large number of recharge areas were identified, particularly in southern Clark County, that have a high aquifer sensitivity, coincide with areas of recharge from on-site waste-disposal systems, or both.

Using the GIS, the characteristics of the recharge areas were related to the downgradient parts of the ground-water system that will eventually receive flow that has recharged through these areas. The aquifer sensitivity, as indicated by DRASTIC, of the recharge areas for downgradient parts of the flow system was mapped for each hydrogeologic unit. A number of public-supply wells in Clark County may be receiving a component of water that recharged in areas that are more conducive to contaminant entry. The aquifer sensitivity maps illustrate a critical deficiency in the DRASTIC methodology: the failure to account for the dynamics of the ground-water flow system. DRASTIC indices calculated for a particular location thus do not necessarily reflect the conditions of the ground-water resources at the recharge areas to that particular location. Each hydrogeologic unit was also mapped to highlight those areas that will eventually receive flow from recharge areas with on-site waste-disposal systems. Most public-supply wells in southern Clark County may eventually receive a component of water that was recharged from on-site waste-disposal systems.

Traveltimes from particle tracking were used to estimate the minimum and maximum age of ground water within each model-grid cell. Chlorofluorocarbon (CFC)-age dating of ground water from 51 wells was used to calibrate effective porosity values used for the particle-tracking program by comparison of ground-water ages determined through the use of the CFC-age dating with those calculated by the particle-tracking program. There was a 76 percent agreement in predicting the presence of modern water in the 51 wells as determined using CFCs and calculated by the particle-tracking program. Maps showing the age of ground water were prepared for all the hydrogeologic units. Areas with the youngest ground-water ages are expected to be at greatest risk for contamination from anthropogenic sources. Comparison of these maps with maps of public-supply wells in Clark County indicates that most of these wells may withdraw ground water that is, in part, less than 100 years old, and in many instances less than 10 years old.

Results of the analysis showed that a single particle-tracking analysis simulating advective transport can be used to evaluate ground-water vulnerability for any part of a ground-water flow system. The particle-tracking method can be applied to evaluate current water resources, such as public-supply wells, or to aid in the identification of sites

for future development. This method can be used at any scale or discretization and is directly transferable to other studies that use the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model of McDonald and Harbaugh (1988) (known as MODFLOW) to simulate ground-water flow systems. The work presented here differs from previous work in that, instead of analysis of a specific area or group of areas within the modeled flow system, this analysis was done on the entire flow system simultaneously, and the GIS was then used to select and evaluate areas of interest within the ground-water flow system. In addition, the coupling of the results of the numerical modeling and particle-tracking analysis with a GIS provides an improved capability to analyze and use the results.

INTRODUCTION

In Clark County, Washington, water for municipal, domestic, industrial, and agricultural uses is derived almost entirely from ground-water resources. Because of this dependency on ground water and concern that the quantity and quality of this resource be preserved, the Intergovernmental Resource Center, Clark and Skamania Counties, Washington (IRC), successfully petitioned the State of Washington to designate Clark County as a "ground-water management area" in 1987. This designation made Clark County eligible for funding from the Washington Department of Ecology to study the ground-water resources of the county and to develop a ground-water management plan for this resource. IRC began a cooperative study with the U.S. Geological Survey (USGS) in 1987 to describe the ground-water flow system in the Portland Basin of Oregon and Washington, which includes most of Clark County and to develop a ground-water flow model. In 1990, a new cooperative study was begun to develop a method of using the ground-water flow model to evaluate ground-water vulnerability in Clark County.

Clark County is situated in what will be referred to in this report as the "Portland Basin," which is defined by geologic, hydrologic, and political boundaries that identify an area of about 1,310 mi^2 (square miles) of northwestern Oregon and southwestern Washington (fig. 1). The terms "aquifer sensitivity" and "ground-water vulnerability" are used throughout this report. Aquifer sensitivity describes the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest; it is a function of the intrinsic characteristics of the hydrogeologic setting and is not dependent on land-use practices and contaminant characteristics. Ground-water vulnerability also describes the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest; however, it is also a function of land-use management practices, contaminant characteristics, and aquifer-sensitivity conditions. The usage of these terms is consistent with the definitions established for the context of pesticide management by the U.S. Environmental Protection Agency (1993).

Land- and water-use planners and managers in Clark County, as well as those in other areas, need to be able to evaluate the likely effects of past, present, and future land-use decisions on ground-water quality. With this information, planners and managers could then (1) assess the vulnerability of current ground-water resources to contamination from existing land uses, (2) evaluate the vulnerability of areas for future development of ground-water resources, or (3) determine the effect of planned land-use activities on ground-water vulnerability.

This study developed, as demonstrated in this report, an approach that uses information available in ground-water flow models to evaluate ground-water vulnerability through the use of particle tracking. Although particle tracking as a modeling tool has been available for some time, a new computer program was developed for this study that has the advantage of being able to store the results of the particle-tracking simulations in a GIS (geographic information system). The data stored in GIS format contain spatial and descriptive information about particle paths and particle starting and ending points. The GIS then was used to display and analyze the results, which, when combined with information such as locations of public-supply wells, springs, gaining stream reaches, aquifer sensitivity, and recharge from on-site waste-disposal systems, provide new ways to evaluate ground-water vulnerability.

Purpose and Scope

The purpose of this study was to develop and demonstrate a method of using a ground-water flow model to evaluate ground-water vulnerability. The study involved four phases of activity: (1) use of a ground-water flow model to describe the dynamics of the ground-water flow system, (2) particle-tracking analysis and development of an interface to input the results of the particle-tracking analysis to a GIS, (3) sampling and analysis of ground water for environmental tracers (chlorofluorocarbons [CFCs] and tritium) to determine the presence of modern water for comparison with the particle-tracking results, and (4) use of a GIS to analyze the results of the particle-tracking analysis to evaluate ground-water vulnerability. The purpose of this report is to describe the methods used and to evaluate ground-water vulnerability in Clark County as an example of the method's application.

Approach

This study used a calibrated ground-water flow model and particle-tracking software to (1) estimate recharge areas for any part of the ground-water flow system, (2) relate characteristics such as aquifer sensitivity of the recharge area to downgradient parts of the ground-water flow system, (3) identify those parts of the flow system that might become affected by effluent from on-site waste-disposal systems at recharge areas, and (4) estimate the age of the ground water for any part of the ground-water flow system. The methods used for this demonstration project in Clark County are directly applicable to other ground-water systems that have been evaluated using the USGS modular three-dimensional finite-difference ground-water flow model of McDonald and Harbaugh (1988) (hereafter referred to as MODFLOW).

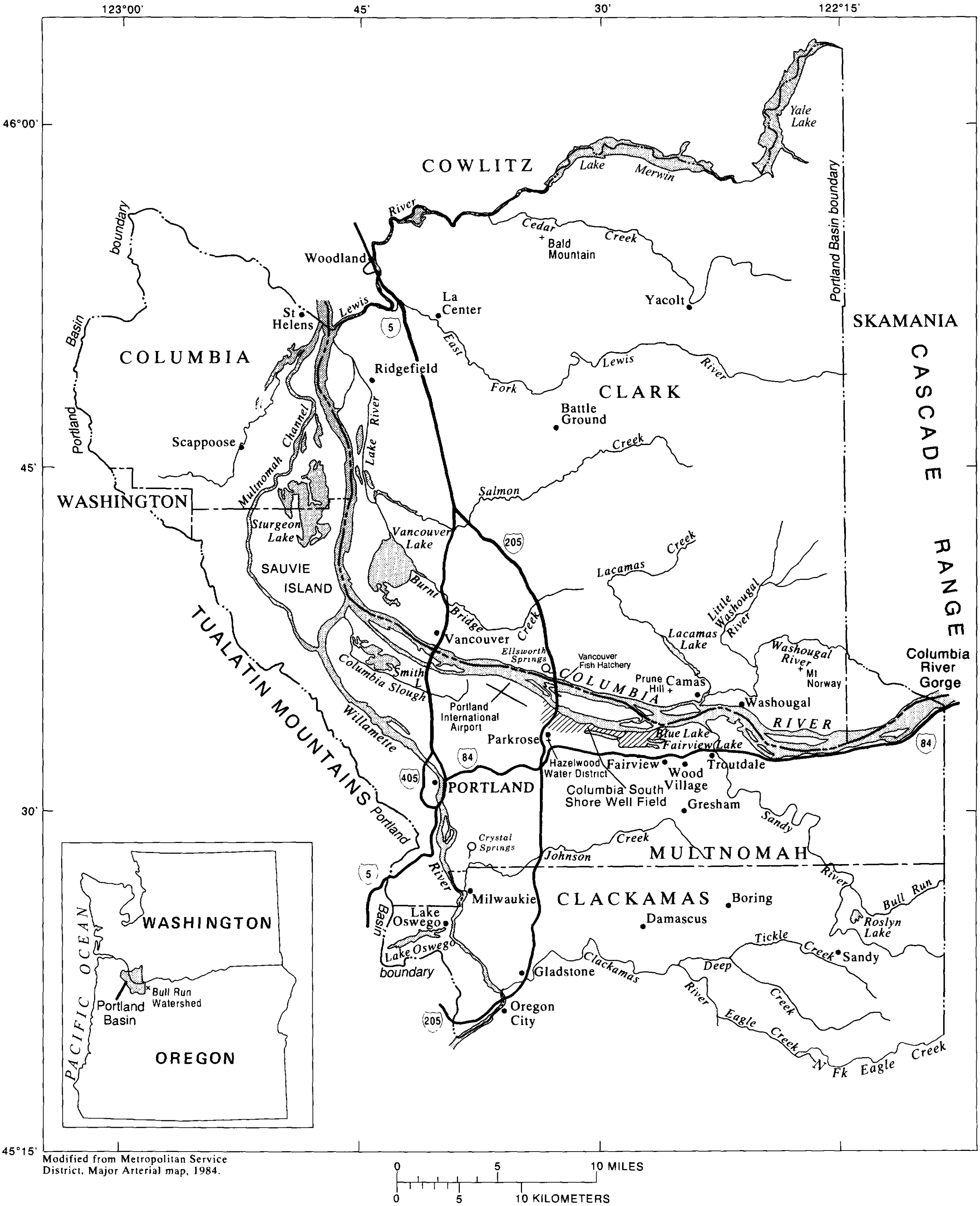


Figure 1. Location and general features of the Portland Basin, including the Clark County, Washington, study area.

Particle tracking is a method of calculating the advective movement of hypothetical water particles through a simulated ground-water flow system. The particle-tracking program computes the position of a particle in the saturated zone after some period of time by using the ground-water velocity distribution, as determined by a ground-water flow model, and estimates of effective porosity. A particle can be started and followed forward in time from any point as it moves downgradient towards a discharge area, or it can be tracked backwards in time from any point upgradient towards a recharge area, as was done in this study. The paths of the imaginary particles of water moving through the simulated ground-water system are referred to as "pathlines." This study used the USGS three-dimensional particle-tracking program developed by Pollock (1989), which is referred to as MODPATH.

The ground-water flow model developed for the Portland Basin (Morgan and McFarland, 1996) by using the steady-state conditions for the stresses existing during the period from 1987–88 was used to provide input to the particle-tracking program. The results of the particle-tracking program were then processed by a new software program that stores information in a GIS database. This database contains all the information calculated by the particle-tracking program, including spatial information such as the path traversed by the particles and starting and ending positions of the particles. Information such as hydrogeologic unit traversed, traveltime from one location to another, and particle velocity is also stored. Within Clark County, particles were placed in every cell of the ground-water flow model. Flow paths to each cell were determined by tracking the particles backwards to their recharge points. A recharge point is defined as the point at which water enters the saturated part of the ground-water flow system. Two independent methods of age-dating ground water using CFCs and tritium were compared with the ability of the ground-water flow model and the particle-tracking program to predict the presence of modern water in selected wells in the Portland Basin. The results of the CFC-age dating also were used to calibrate effective porosity values for use in the particle-tracking program.

As an example of the utility of ground-water flow modeling and particle tracking, the results of the particle-tracking analysis were used in combination with information already available in a GIS database to evaluate ground-water vulnerability in Clark County. In this analysis, only the advective component of contaminant transport was considered, and potential contaminants were assumed to be conservative; that is, contaminant movement was assumed to be equivalent to that of a particle of water. The locations of recharge areas were compared with a DRASTIC analysis (a commonly used method of calculating aquifer sensitivity or the pollution potential of ground water) (Aller and others, 1987) prepared by the Intergovernmental Resource Center (Swanson, 1991) to identify recharge areas where hydrogeologic conditions are most conducive to entry of a contaminant into the ground-water flow system. Areas that may potentially be contaminated by on-site waste-disposal systems also were compared with recharge areas to distinguish recharge areas that currently may be threatened. Ground-water vulnerability also was evaluated by creating maps that depict the characteristics of recharge areas to selected areas of the ground-water flow system. The flow paths and discharge areas for ground water that is recharged in areas of high aquifer sensitivity or areas of potential contamination from on-site waste-disposal systems were delineated for each aquifer. These maps were used to illustrate a critical deficiency in DRASTIC— the failure to account for the dynamics of the ground-water flow system. DRASTIC analysis alone does not incorporate information about the direction and velocity of ground-water flow; DRASTIC indices calculated for a particular location thus do not necessarily reflect the conditions of the ground-water resources at the recharge areas to that particular location. The particle-tracking results also were used to create maps of the minimum and maximum traveltimes from recharge points to any cell in the Clark County part of the model. These maps provide a method of estimating the potential for a contaminant introduced at the recharge area to reach a particular part of the ground-water flow system within a specified period of time.

Previous Studies

The movement of contaminants in ground water can be evaluated by using analytical methods as well as by using models that simulate either advective or advective-dispersive transport. The basic concepts of solute transport are presented by Reilly and others (1987). Although advection models cannot be used to compute solute concentrations in ground water, they represent a valuable intermediate step between ground-water flow models and more costly and complex advective-dispersive solute-transport models. Examples of previous work to evaluate the impact of land-use activities on ground-water flow systems using only the advective component of solute transport are abundant in the literature. Methods range from analytical flow models to three-dimensional numerical modeling. Bair and others (1991) used particle tracking in combination with analytical flow modeling to delineate traveltime capture areas of wells. A good illustration of the use of two-dimensional numerical modeling in the analysis of patterns and rates of ground-water flow is provided by Buxton and Modica (1992). Shafer (1987) used two-dimensional numerical modeling in combination with particle tracking to calculate time-related capture zones. Morrissey (1989) compared the results of three-dimensional numerical modeling of the recharge area contributing water to a pumped well with other methods. An excellent example of the use of a three-dimensional numerical model in conjunction with particle tracking to evaluate recharge areas is provided in a study by Buxton and others (1991). Other studies that used three-dimensional numerical modeling and particle tracking include Bair and others (1990), Delin and Almendinger (1991), Bair and Roadcap (1992), Springer and Bair (1992), and Barlow (1994a and 1994b).

The work presented here differs from previous work in that instead of analysis of a specific area or group of areas within the modeled flow system, this analysis was done on the entire flow system simultaneously, and the GIS was then used to select and evaluate areas of interest within the ground-water flow system. In addition, the coupling of the results of the numerical modeling and particle-tracking analysis with a GIS provides an improved capability to analyze and use the results.

Description of the Study Area

Clark County encompasses 628 mi^2 in southwestern Washington and is bounded by the Lewis River to the north, the Columbia River to the south and west, and the foothills of the west side of the Cascade Range to the east (fig. 1). Clark County lies within a sediment-filled structural basin known as the Portland Basin. The hydrogeology of the Portland Basin has been the focus of several recent investigations by the U.S. Geological Survey (McCarthy and Anderson, 1990; Swanson and others, 1993; Collins and Broad, 1993; Snyder and others, 1994; Morgan and McFarland, 1996; McFarland and Morgan, 1996) that form the foundation for much of the work presented here.

The topography of Clark County is characterized by flat-lying, alluvial lands along the Columbia River and its tributaries that are broken by low rolling hills or buttes with benches and hilly areas that rise to meet the foothills of the Cascade Range to the east and northeast. Altitude of the land surface ranges from about 10 feet along the Columbia River to about 3,000 feet in the foothills of the Cascade Range. The Columbia River flows westward out of the Columbia River Gorge until it passes the city of Vancouver, where it flows northward. The tributaries to the Columbia River that drain Clark County include the Lewis, East Fork Lewis, Lake, Little Washougal, and Washougal Rivers and Cedar, Salmon, Burnt Bridge, and Lacamas Creeks.

The city of Vancouver, the major urban area of Clark County, had a population of about 128,000 in 1997. Other cities and towns include Camas, Washougal, Battle Ground, Ridgefield, La Center, and Yacolt. The total population of Clark County in 1997 was about 317,000.

The climate of Clark County is temperate with dry, moderately warm summers and wet, mild winters, although the topography of the area produces considerable variations in the local climate. The average temperature for Vancouver is about 52°F (degrees Fahrenheit) and ranges from about 38°F in January to about 66°F in July. Precipitation in Clark County ranges from about 41 in/yr (inches per year) near Vancouver to over 100 in/yr in the western Cascade Range. About 58 percent of Clark County is forested, about 21 percent consists of urban lands, about 15 percent consists of agricultural lands, and about 6 percent is classified as other land-use types.

Geologic Setting

The overviews of the geology and hydrology of the Portland Basin presented in the following sections summarize more detailed descriptions in reports by (1) Swanson and others (1993), who discuss the thickness, extent, and lithology of hydrogeologic units in the basin, (2) McFarland and Morgan (1996), who describe the ground-water flow system of the basin, including its boundaries, hydraulic characteristics, and components of recharge and discharge, and (3) Morgan and McFarland (1996), who discuss the geology and hydrology as it relates to simulation of the ground-water flow system using numerical modeling.

The northwest-trending Portland Basin was formed by structural deformation of the underlying Eocene and Miocene volcanic and marine sedimentary rocks. Late Miocene and younger fluvial and lacustrine sediments are overlain by unconsolidated Pleistocene catastrophic flood deposits and Holocene Columbia River alluvium (McFarland and Morgan, 1996; Swanson and others, 1993). The consolidated and unconsolidated basin-fill sediments are thickest adjacent to the Columbia and Willamette Rivers, where they may be as much as 1,800 feet thick.

Hydrogeologic Units

Hydrogeologic units in the Portland Basin, as defined by Morgan and McFarland (1996) and used in their model of the ground-water flow system, may comprise one or more geologic units. From youngest to oldest the eight hydrogeologic units they delineated within the basin include the:

(1) unconsolidated sedimentary aquifer (US);

(2) Troutdale gravel aquifer (TG);

(3) confining unit 1 (C1);

(4) Troutdale sandstone aquifer (TS);

(5) confining unit 2 (C2);

(6) sand and gravel aquifer, upper coarse-grained subunit (SC);

(7) sand and gravel aquifer, lower fine-grained subunit (SF); and

(8) older rocks (OR).

A ninth unit, the undifferentiated fine-grained sediments (UF), is mapped where the Troutdale sandstone aquifer is missing and confining units 1 and 2 cannot be differentiated. The undifferentiated fine-grained sediments may be as young as confining unit 1. The two-letter abbreviations listed after each unit name are used throughout this report to facilitate discussion and may appear in place of, or in addition to, the unit name.

For the purpose of simplifying discussion and display of the particle-tracking analyses, the results from several hydrogeologic units were combined. References to the undifferentiated fine-grained sediments in the remainder of the report will include confining units 1 and 2; the sand and gravel aquifer upper coarse-grained and lower fine-grained subunits will be collectively referred to as the sand and gravel aquifer (SG) (fig. 2).

Morgan and McFarland (1996)		THIS REPORT	
US		US	
TG		TG	
UF	C1	UF	
	TS	TS	
	C2		
SC		SG	
SF			
OR		OR	

Figure 2. Comparison of hydrogeologic unit terminology for the Portland Basin.

Ground-Water Occurrence and Movement

Recharge to the Portland Basin is primarily through the infiltration of precipitation. However, runoff into drywells, and on-site waste-disposal systems are locally important sources of recharge. Estimated recharge over the modeled area of the Portland Basin from these three sources ranges from 0 to 49 in/yr with a mean of 22 in/yr (Snyder and others, 1994). Irrigation return flow and losing streams may constitute locally important sources of seasonal recharge, but are insignificant on a regional scale. Large capacity wells located near the Columbia River also can induce recharge from the river to the shallow alluvial aquifers (McCarthy and others, 1992; Morgan and McFarland, 1996).

Movement and discharge of ground water is primarily controlled by the topography of the basin, which creates regional, intermediate, and local ground-water flow systems. The Columbia River represents the regional discharge area for the ground-water flow system in Clark County. Much of the ground water discharging to the river from Clark County enters the system in upland recharge areas along the western Cascade Range, moves downward and horizontally towards the river, and finally moves upward to discharge to the river. The Lewis River, East Fork Lewis River, and Salmon Creek are examples of discharge areas for intermediate ground-water flow systems. Local ground-water flow systems are much smaller with distances on the order of only hundreds of feet between recharge and discharge areas (Morgan and McFarland, 1996).

Ground-water discharge in the Portland Basin is primarily to streams, rivers, wells, and springs (McFarland and Morgan, 1996). The largest component of ground-water discharge in the Portland Basin is to streams and rivers. Ground-water withdrawals from wells in Clark County are primarily used for industry and public supply, with smaller amounts used for irrigation and domestic purposes (Collins and Broad, 1993). The major springs in southwestern Clark County are located along the north side of the Columbia River between Vancouver and Prune Hill.

Acknowledgments

The authors would like to thank Rodney D. Swanson, formerly with the Intergovernmental Resource Center and currently with Clark County Department of Community Development, for his many suggestions during the study. In particular, the idea of mapping ground-water systems by the age of the ground water was developed jointly during conversations with him.

GROUND-WATER FLOW MODEL

Description

A three-dimensional, regional ground-water flow model of the Portland Basin (including most of Clark County), constructed and calibrated to steady-state time-averaged conditions for the period 1987–88 during a previous USGS study (Morgan and McFarland, 1996), was used in this investigation. Morgan and McFarland (1996) used the USGS modular three-dimensional finite-difference ground-water flow model by McDonald and Harbaugh (1988) with enhancements by Orzol and McGrath (1992) to simulate ground-water flow and to test and refine the conceptual understanding of the flow system in the Portland Basin. The active cells of the model grid cover 981 mi^2 of the Portland Basin and include most of Multnomah County, Oregon, and about one-half of Clark County, Washington, as well as parts of Clackamas, Washington, and Columbia Counties in Oregon and Skamania County in Washington (fig. 3). The y-axis of the model is oriented 28.8 degrees west of north to align it with the predominant direction of ground-water flow. The finite-difference model of the basin was constructed by dividing the nine hydrogeologic units delineated by Morgan and McFarland (1996) into eight model layers. Each model layer is subdivided by a rectilinear grid, which consists of 3,040 active cells that have a uniform grid-cell spacing of 3,000 feet (a cell area of 0.32 mi^2) and a variable thickness. Hydrogeologic units are not restricted to a single model layer, but may span multiple model layers. The map and section of the saturated hydrogeologic units used in the ground-water flow model are shown in figure 3.

The hydraulic characteristics of the rocks and sediments that form aquifers and confining beds of the ground-water system control the direction and velocity of ground-water movement within the system. Estimates of horizontal hydraulic conductivity were made by McFarland and Morgan (1996) from multiple-well aquifer tests, single-well tests, and published data. These distributions were used as initial values that were subsequently modified during calibration of the numerical model to achieve a best fit between simulated and observed data. The median values of hydraulic conductivity range from about 0.1 ft/d (feet per day) for the older rocks to about 100 ft/d for the unconsolidated sedimentary aquifer. Vertical anisotropy ratios of hydraulic conductivities (horizontal to vertical) were estimated for each hydrogeologic unit from published values for similar classes of rock materials and then were modified during calibration of the numerical model. The vertical anisotropy ratios determined from calibration were 1,000:1 for the older rocks and all fine-grained units (C1, C2, UF, and SF) and 100:1 for the primary aquifer units (US, TG, TS, and SC) (Morgan and McFarland, 1996).

The water budget determined by use of the ground-water flow model indicates that recharge to the ground-water flow system from the infiltration of precipitation accounts for 86 percent of the 1,670 ft^3/s (cubic feet per second) inflow to the basin. Runoff into drywells contributes 4 percent, on-site waste-disposal systems contribute 2 percent, seepage from smaller rivers and streams contributes 5 percent, and seepage from the Columbia and Willamette Rivers and other sources (inflows) contribute 3 percent (Morgan and McFarland, 1996). Of the 1,670 ft^3/s of ground-water discharge in the basin, 58 percent is discharged to smaller rivers and streams, 27 percent is discharged to the Columbia and Willamette Rivers, 10 percent is discharged to wells, and less than 5 percent is discharged to springs and other sinks (outflows).

Limitations

Many assumptions are necessary to simplify a real hydrogeologic system to the extent that it can be represented by a mathematical model. Some of these assumptions limit the scope of application of the model and the hydrologic questions that can reasonably be addressed. The major simplifying assumptions and the limitations they impose are summarized below from Morgan and McFarland (1996).

The model uses a steady-state simulation of time-averaged conditions for the period 1987–88, including climate, land use, and water use. Because the model has not been calibrated to transient conditions, the model cannot be used to predict the transient response of the system. The limitation imposed by this is that intermediate heads and fluxes in the system, between the time a new stress is applied and the time the system reaches a new steady state, cannot be predicted using the model. The model can, however, be used to simulate steady-state conditions for various stress conditions, and the steady-state water levels and fluxes under various ground-water management conditions can be compared and evaluated on the basis of the eventual effect they would have on the system.

A second limitation on the use of the model is that, as constructed, transmissivities of hydrogeologic units do not change when the saturated thickness of the units change. This is not a serious limitation unless new stresses on the system are great enough to cause significant change to the saturated thickness of any unit. Model results should be examined critically if large water-level changes are simulated in the uppermost hydrogeologic units.

Finally, boundary conditions involve considerable simplification of the hydrologic system and can have substantial effects on model results; thus, boundary conditions must be clearly understood to avoid serious errors in model application. The lateral boundary of the Portland Basin model was specified as a "no-flow" boundary on the basis of assumptions that it coincided with either ground-water flow divides or low-permeability rocks. These assumptions were considered valid for the stress conditions in the basin during the 1987–88 simulation period; however, they should be evaluated carefully when simulating other stress conditions.

For many purposes, these assumptions do not impose serious limitations on the use of the model. However, care must be used when interpreting the results, as changes in any of these conditions can influence the location of recharge areas, pathlines, and the age of ground water.

PARTICLE-TRACKING ANALYSIS

The particle-tracker software used to calculate pathlines is MODPATH, the USGS three-dimensional particle-tracking program developed by Pollock (1989). MODPATH was chosen for the study because it (1) simulates particle pathlines within three-dimensional flow models, (2) is widely applied to ground-water investigations, (3) is designed to use input data and results from MODFLOW, and (4) has a FORTRAN source code that is available and well documented and that facilitates modification and enhancement. The plotting part of MODPATH, called MODPATH-PLOT, was modified to output the basic numerical data on particle coordinates and other attributes (such as velocity, distance, and traveltime) in the form of ARC/INFO digital maps and data files (Orzol, 1997). ARC/INFO is a GIS that is capable of displaying and performing operations on spatial features and their associated characteristics. The modified version of MODPATH-PLOT, known as MODTOOLS, does not change the method used to calculate particle pathlines, but enhances the ability to display and analyze the results of the particle-tracking program. This significant improvement enables the use of the database, statistical, and display capabilities of ARC/INFO and facilitates comparison with other types of spatial information.

MODPATH uses a semianalytical particle-tracking scheme and is based on the assumption that each directional velocity component for a particle of water varies linearly within a grid cell in its own coordinate direction (Pollock, 1989). This assumption allows an analytical expression to be derived that describes the flow path of water within a grid cell. Given the initial position of a particle anywhere in a cell, the pathline and traveltime within the cell can be computed directly. Steady-state ground-water heads and intercell flow rates are first determined using MODFLOW. This information is then input to MODPATH along with effective porosity values and user-specified starting particle locations. MODPATH then calculates three-dimensional pathlines and time-of- travel information as particles are tracked individually through the simulated flow system using the calculated distribution of velocity throughout the flow system. MODTOOLS is used to create digital maps of the starting points, ending points, points at intermediate time steps, and particle pathlines. These digital maps have associated digital attribute files which contain information such as starting, ending, and intermediate particle positions (model cell, intracell location, altitude, hydrogeologic unit), traveltime, distance, and velocity.

The Portland Basin model by Morgan and McFarland (1996) uses the Streamflow-Routing package for MODFLOW (Prudic, 1989) to account for stream losses or gains to model cells. The latest release (1994) of MODPATH, version 3.0 (Pollock, 1994) can incorporate data output from this module; however, version 1.2 of MODPATH, which was used in this study, does not incorporate budget data output from this module. To compensate for the losses from or gains to streams from model cells, data output from the Well and Streamflow-Routing modules of MODFLOW were combined and used as the Well input to MODPATH.

Distribution and Calibration of Effective Porosity

Calculation of Effective Porosity

Effective porosity for each grid cell is used with the results of the flow model by MODPATH to calculate the velocity distribution of the simulated ground-water flow system. The velocity distribution then can be used to determine ground-water flow paths and traveltimes. The effective porosity values do not have any effect on the location of particle pathlines or the points of particle recharge; however, ground-water velocity (or more precisely, the average interstitial velocity) is inversely proportional to the effective porosity.

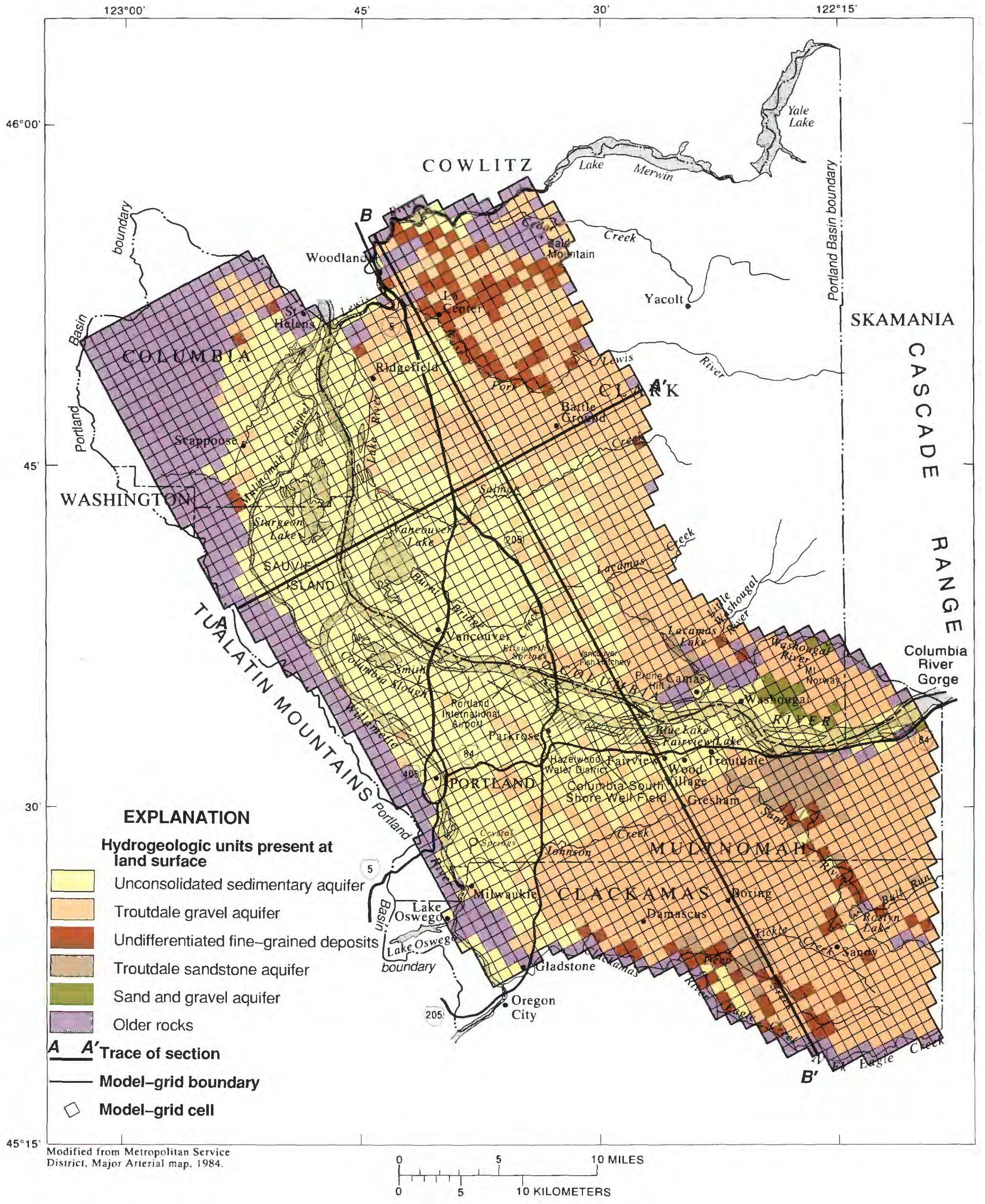
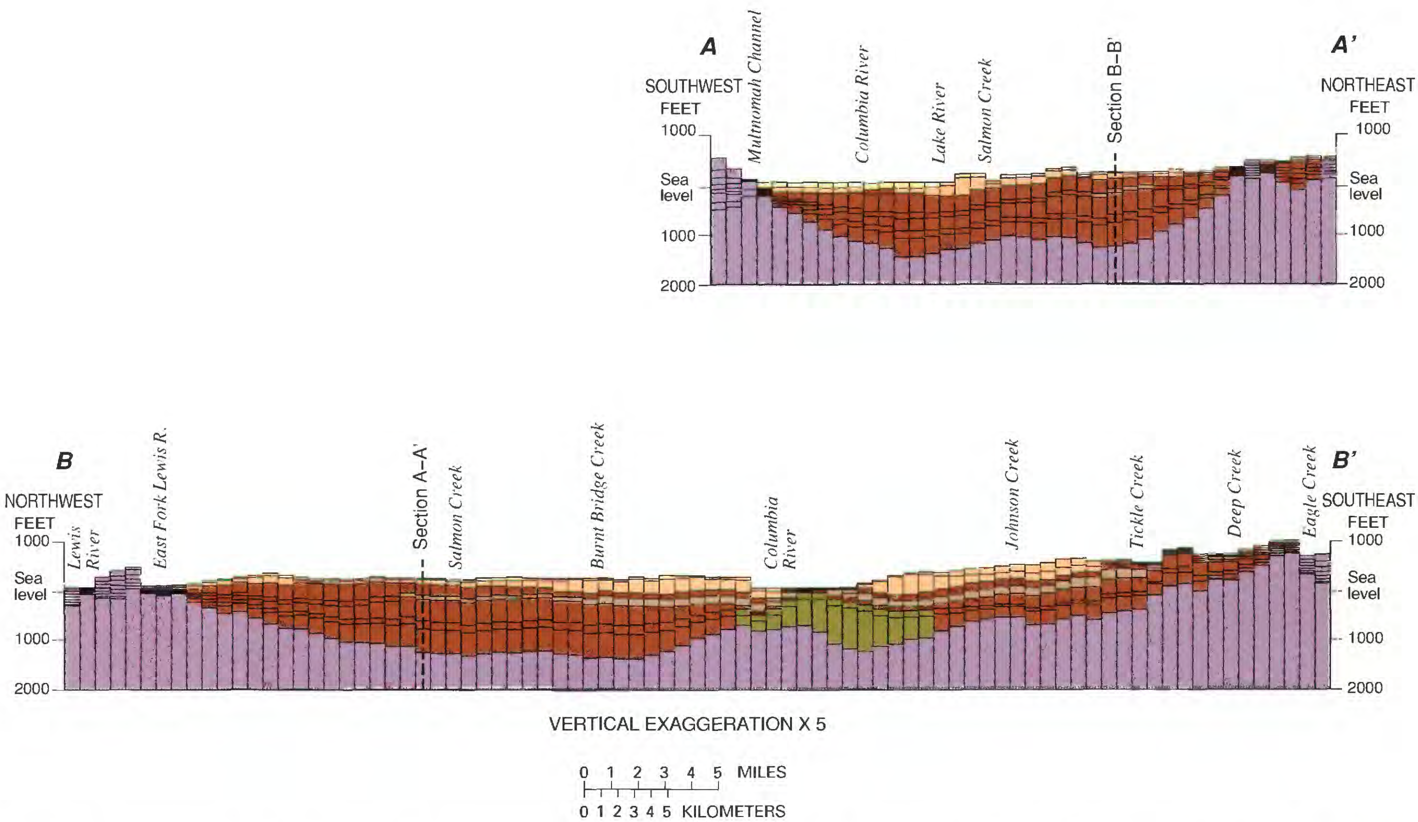


Figure 3. Ground-water flow model grid and modeled hydrogeology.



The three-dimensional distribution of effective porosity for the model was estimated in this study by using an empirical relation between hydraulic conductivity and effective porosity developed by Ahuja and others (1989) and modified using information from Morris and Johnson (1967). The method of estimating the effective porosity for the hydrogeologic units modeled in the Portland Basin and the resulting distributions of effective porosity are presented in Hinkle and Snyder (1997). A summary of the effective porosities used in the particle-tracking program is presented in table 1.

Chlorofluorocarbon-Age Dating and Comparison

Chlorofluorocarbon-age dating was used to determine the presence or absence of modern water (water containing CFCs) in samples from 54 ground-water wells in the Portland Basin. Results of the CFC-age dating were compared with minimum traveltimes calculated by the particle-tracking program as a means of verifying the traveltimes estimated using the particle-tracking program. The CFC-age dates also were used to help calibrate effective porosity values used in the particle-tracking program (see section "Calibration of Effective Porosity").

Fifty-four existing wells were sampled for CFCs during the spring of 1991, in order to determine the presence or absence of modern water (Hinkle and Snyder, 1997). CFCs are stable, gaseous, synthetic compounds that have been produced since the 1930s. Once released to the atmosphere, part of the CFCs becomes dissolved in water that is in contact with the atmosphere. Atmospheric concentrations of trichlorofluoromethane (CCl_3F) and dichlorodifluoromethane (CCl_2F_2), as a function of time, have been reconstructed (Busenberg and Plummer, 1992).

Table 1. Effective porosities of hydrogeologic units used in the simulation by the particle-tracking program

Hydrogeologic unit	Minimum	Maximum	Mean	Standard deviation
Unconsolidated sedimentary aquifer	0.19	0.31	0.31	0.005
Troutdale gravel aquifer	.18	.31	.28	.042
Confining unit 1	.13	.30	.19	.042
Troutdale sandstone aquifer	.18	.31	.29	.033
Confining unit 2	.13	.30	.20	.043
Sand and gravel aquifer upper coarse-grained subunit	.22	.31	.28	.043
Sand and gravel aquifer lower fine-grained subunit	.20	.24	.24	.006
Undifferentiated fine-grained sediments	.13	.31	.23	.060
Older rocks	.07	.18	.15	.033

By measuring CFC concentrations in a ground-water sample and estimating the recharge temperature of the ground water, an age of the ground water since recharge can be assigned to the sample (Busenberg and Plummer, 1992). A detection limit of less than 1 picogram/kilogram (less than 1 part in 10^{15}) for CFCs provides a measure with which to "date" water back to approximately 1948 with CCl_3F and 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 would be water with a recharge date no earlier than 1948 or 1944 for CCl_3F or CCl_2F_2, respectively. For a more detailed discussion of the theory and application of CFC-age dating, see Busenberg and Plummer (1992).

Samples from 6 of the 54 wells sampled for CFCs were analyzed for tritium to provide an independent check on the CFC results. The presence of high concentrations of tritium also can be 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. Samples containing bomb tritium indicate that at least a part of the water was recharged since 1953 (Drever, 1988, p. 379). The presence or absence of tritium was consistent with the recharge dates determined using CFCs at the six wells (Hinkle and Snyder, 1997).

The particle-tracking program was used to calculate traveltimes for water samples collected at 51 of the 54 wells sampled for CFCs. Pathlines and traveltimes for three wells adjacent to the model boundary could not be calculated reliably. The cells representing each well location were populated with 486 particles distributed on the faces of each cell, resulting in a range of 486 to 3,888 particles per well depending on the number of model layers used to represent the well. Particle paths were determined by using backward tracking of the particles upgradient to their recharge points. The particle-tracking program used the original (or baseline) effective porosity values in the calculation of traveltimes for comparison with CFC-model ages. Because the presence of CFCs in water samples indicates that at least part of the water in the sample is modern, for each well the pathline (from recharge point to well) with the minimum traveltime was chosen to represent the age of water from the well for comparison with CFC-age dating.

When comparing the ground-water ages determined using CFC-age dating and particle tracking, a number of factors must be considered. First, the particle-tracking program uses a regional-scale ground-water flow model that cannot account for small-scale flow effects or anomalies. For instance, local vertical ground-water flow, induced by well pumping or resulting from annular flow or interaquifer flow through existing wells, is not accounted for by the flow model or particle-tracking program. Conversely, because CFCs can be detected at picogram-per-kilogram concentration levels, the CFC method is sensitive to these local flow effects. These differences in scale can result in the presence of CFCs even when the particle-tracking program estimates that no modern water should be present. Furthermore, CFCs may undergo sorption or biodegradation, which can result in the absence of CFCs in some samples for which the particle-tracking program estimates a modern age. In spite of these limitations, CFC-age dating and particle-tracking results agreed at 39 (76 percent) of the 51 wells compared (Hinkle and Snyder, 1997). The recharge dates determined using the particle-tracking program also were entirely consistent with the presence or absence of tritium at the six wells sampled for tritium. The agreement between the use of CFCs and tritium and the particle-tracking program indicates that particle-tracking techniques can be used to identify parts of the Portland Basin likely to yield modern water to wells. The accurate delineation of modern ground water is an important factor in the identification of areas with a higher probability of containing anthropogenic contaminants.

Calibration of Effective Porosity

The age of ground water, or traveltime, is inversely related to the velocity of ground water, which itself is inversely related to effective porosity. As effective porosity decreases, velocity increases, and the estimated age of ground water decreases. The effective porosity values used for the particle-tracking program were calibrated by comparing ground-water ages determined through the use of CFC-model age dating with ground-water ages calculated by the particle-tracking program using different values of effective porosity. Data from the 51 wells that were sampled and analyzed for CFCs (including the 6 wells sampled and analyzed for tritium) were the basis for comparison with the minimum ground-water ages determined by the particle-tracking program.

Effective porosity values were evaluated by uniformly scaling the entire three-dimensional array of effective porosity using multiplication factors ranging from 0.50 to 1.50 times the baseline estimates of effective porosity in 100 increments. It was not necessary to rerun the particle-tracking analysis for each increment of effective porosity tested, because changes in effective porosity influence only the average interstitial velocities and not the trajectories of the pathlines. Because ground-water velocity is inversely proportional to effective porosity, ground-water ages were calculated directly by dividing the baseline ground-water ages, calculated for each well by using the particle tracker, by the multiplication factor of baseline effective porosity being evaluated.

The presence of modern ground water (ground water that has recharged since 1944) as determined by the particle-tracking program (using each value of effective porosity) was compared with the presence of modern ground water as determined by using CFC-age dating. Percent agreement for each value of effective porosity was calculated as 100 multiplied by the number of comparisons where the two methods indicated the presence or absence of modern water, divided by the total number of comparisons. The values of percent agreement ranged from a minimum of 71 percent for effective porosities between 0.50 and 0.55 times the baseline values and a maximum of 78 percent for effective porosities between 1.09 and 1.33 times the baseline values (fig. 4). Percent agreement equaled 76 percent for the baseline values (1.00 times the baseline effective porosity).

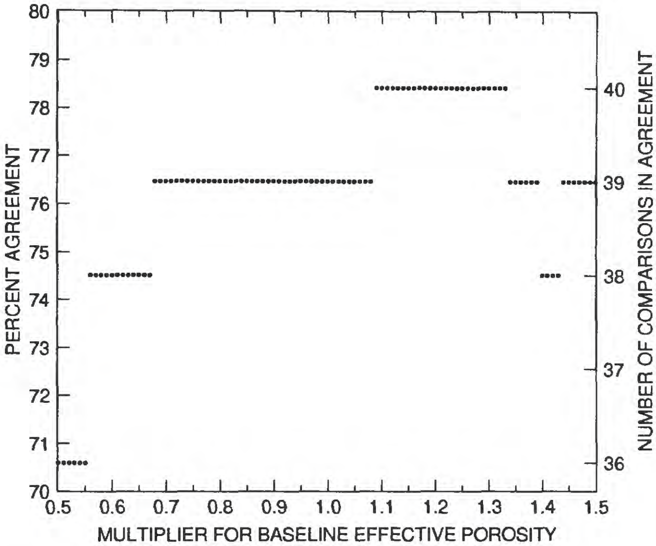


Figure 4. Relation between effective porosity and percent agreement of particle-tracking program ages with chlorofluorocarbon-model ages.

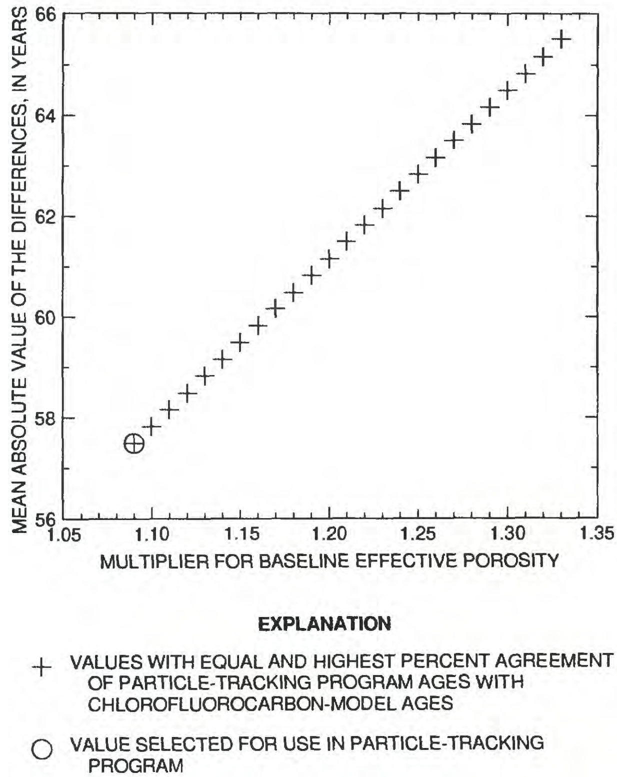


Figure 5. Relation between effective porosity and mean absolute value of the differences (MAVD) between particle-tracking program ages and chlorofluorocarbon-model ages.

To help determine an optimum value of effective porosity between 1.09 to 1.33 times the baseline values, a method was sought that would minimize the differences between the ages determined using the particle-tracking program and the CFC model for those wells where the presence or absence of modern water, as determined by the two methods, was not in agreement. The mean of the absolute value of the differences (MAVD) between the ground-water ages determined by the particle-tracking program and the CFC model for the 11 wells where the particle-tracking program and CFC-age-dating methods were not in agreement was used. Smaller values of the MAVD indicate a better agreement between ground-water ages calculated by the particle-tracking program and those calculated by the CFC model. The MAVD was found to vary linearly with effective porosity and had a minimum of 57 years at 1.09 times the baseline values and a maximum of 66 years at 1.33 times the baseline values (fig. 5). On the basis of the results of these analyses, values of effective porosity of 1.09 times the baseline values provided the best agreement between the ground-water ages determined by the particle-tracking program and the CFC model. The 1.09 multiplier of the baseline values of effective porosity was used throughout the rest of the study.

Identification of Recharge Areas

The ground-water flow model and the particle-tracking program were used to map recharge areas of the ground-water flow system and for each hydrogeologic unit in Clark County. The identification of recharge areas is an important step in the process of determining ground-water vulnerability. Each model-grid cell in the ground-water flow model was populated with particles that were tracked backwards along their flow paths to recharge points. The GIS can be used to select the subset of recharge points for any particles tracked backwards from any part of the ground-water model, such as from cells representing the open interval (perforated or screened interval) of an individual well to cells representing an entire hydrogeologic unit. As an example of this application, the GIS was used to select the subset of recharge points for particles that were tracked backwards from the model cells in each hydrogeologic unit. The resulting maps of the distribution of recharge points can be used to delineate recharge areas for each hydrogeologic unit in Clark County.

There are an infinite number of possible starting positions for particles on the faces of the model-grid cells. Ideally, as many particles as possible should be started in each cell to increase the probability of adequately describing the characteristics of the population of all possible pathlines for that cell. However, hardware, software, and the logistics of handling large data sets limit the number of particles that can be used practically in a particle-tracking run. For the purposes of this study, six particles per cell were used. Each model cell was populated with 1 particle in the center of each of the 6 cell faces. Each of the 10,299 active model-grid cells within Clark County that are not adjacent to the model boundary were populated with particles. This resulted in a total of 61,794 particles; the distribution of particles in each layer is shown in figure 6. Because particles that encountered a model cell adjacent to a no-flow boundary were stopped, points indicating recharge along the cells adjacent to a no-flow boundary may have been stopped while still below the water table and may have entered the system at some other point in the flow system. These particles likely have a longer actual traveltime, which may result in shorter or more conservative estimates of minimum traveltime.

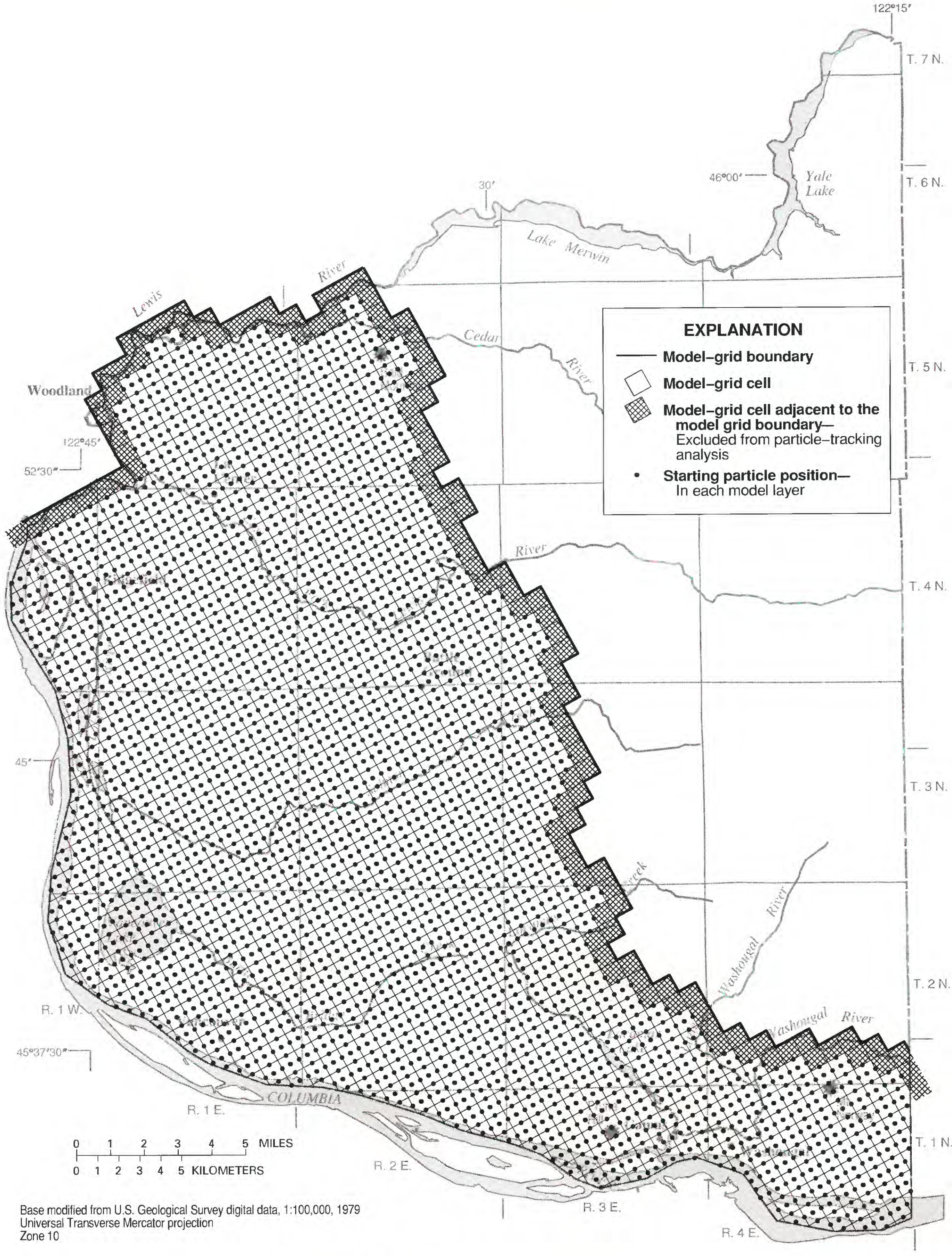


Figure 6. Particle positions prior to backward particle tracking.

The location and density of recharge points can be used with distance along pathlines between starting particle positions and recharge points to identify recharge areas for local, intermediate, and regional flow systems. For the purposes of this report, the characterization of local, intermediate, and regional flow systems as described by Fetter (1988, p. 221–225) will be applied. Fetter (1988) characterizes a local ground-water flow system as having its recharge area at a local topographic high 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 at the basin divide and the discharge area at the valley bottom. Local flow systems are usually shallower, with shorter flow paths and more rapid circulation of ground water compared to regional flow systems. Intermediate flow systems have properties falling between those of local and regional flow systems.

Recharge areas for local flow systems occur throughout the basin. Recharge areas for intermediate flow systems generally are in the interior of the basin at topographically high areas or along the drainage divides for rivers and streams. The recharge areas for regional flow systems generally are within cells adjacent to model boundaries or in cells that are along topographically high areas that form ground-water divides.

The density of recharge points also can be used to help identify recharge areas for local, intermediate, or regional flow systems (fig. 7). The density of recharge points in an area is proportional to the number of model cells that receive ground-water flow originating in that area. Recharge areas for local systems may have recharge particles that, having traveled only a short distance, are nearly uniformly distributed at the water table, similar to the distribution of the starting positions of the particles on cell faces prior to being tracked backwards to their recharge points. Recharge areas for intermediate and regional systems would be expected to have a greater density of recharge points than for local systems, as more particles are accumulated along longer pathlines. It must be emphasized that the density of recharge points is not related to the rate or volume of recharge occurring at the surface. The relative number of particles for any flow system (local, intermediate, or regional) is not a function of the quantity of recharge to that system, but rather is proportional to the number of model cells that receive ground-water flow originating in that area. Finally, distances between starting particle positions and recharge points can help to identify the scale of the flow system. Short distances indicate local recharge to the immediate area, whereas longer distances indicate recharge to intermediate or regional flow systems.

Maps of the recharge points for all the hydrogeologic units within the modeled part of the ground-water flow system in Clark County, with respect to the altitude of land surface and to the distance traveled by the particles, are presented in figures 8 and 9, respectively. The low-lying areas have a low density of recharge points that are evenly distributed and have relatively short pathlines (figs. 8 and 9), indicating recharge to local flow systems. Topographically higher areas between the drainages of the rivers and streams have a high density of recharge points with pathlines of moderate length, indicating recharge to intermediate flow systems. A high density of recharge points with the longest pathlines is found along the eastern boundary of the flow model at the contact between basin-fill sediments and older rocks. Recharge to the regional flow system would be expected to take place along this boundary, which represents the regional ground-water flow divide to the east for the hydrogeologic units simulated.

Because individual layers of the ground-water flow model do not necessarily correspond to hydrogeologic units, the results from the cells representing the model layers in each hydrogeologic unit were combined to develop composite maps of the recharge points for each unit (figs. 10A-F). These maps emphasize the three-dimensional nature of the ground-water flow system in the Portland Basin.

Much of the water in the unconsolidated sedimentary aquifer is recharged directly to the aquifer where it crops out (is exposed at land surface). As a result, ground-water flow in the aquifer is generally in local flow systems, as is shown in figure 10A by the uniform distribution of recharge points with short pathlines. Some recharge points for the aquifer, however, are located at distances of several miles or more from the nearest exposure of the unconsolidated sedimentary aquifer. These are recharge points for intermediate flow systems that have discharge areas where the unconsolidated sedimentary aquifer is exposed. Examples are the topographically high areas between Salmon Creek and the East Fork Lewis River and in the higher elevations north of Camas and Washougal.

Recharge points for the Troutdale gravel aquifer are evenly distributed across some parts of the unit that are exposed, indicating the presence of recharge to local flow systems (fig. 10B). Several broad areas between river and stream drainages (Cedar Creek and East Fork Lewis River; East Fork Lewis River and Salmon Creek; Salmon Creek and Burnt Bridge Creek/Lacamas Creek) that are topographically higher show a greater density of recharge points that have longer pathlines, indicating that these areas may recharge intermediate flow systems. There are also a few areas along the eastern boundary of the model that have a high density of recharge points with the longest pathlines, suggesting that regional flow may pass through some parts of the Troutdale gravel aquifer as it moves vertically through recharge or discharge areas.

The undifferentiated fine-grained sediments (fig. 10C) show a strong correlation between topography and the location of recharge areas. The density of recharge points with intermediate to long pathlines is greatest in discrete areas and along narrow bands corresponding to topographically higher areas between river and stream drainages, indicating intermediate flow. There is some correlation between the occurrence of recharge points and the presence of the unit at land surface. The unit has been exposed by downcutting streams that are usually discharge areas for local and intermediate flow systems. There is a high density of recharge points with long pathlines along the eastern boundary of the ground-water flow model, indicating recharge to the regional flow system. The paucity of recharge points in the southwestern part of the unit, which is downgradient, indicates that upward flow in this area prevents recharge on the overlying surface from reaching the undifferentiated fine-grained unit. As the ground water continues downgradient through the undifferentiated fine-grained unit, the direction of flow becomes upward as it approaches the discharge area near the Columbia River.

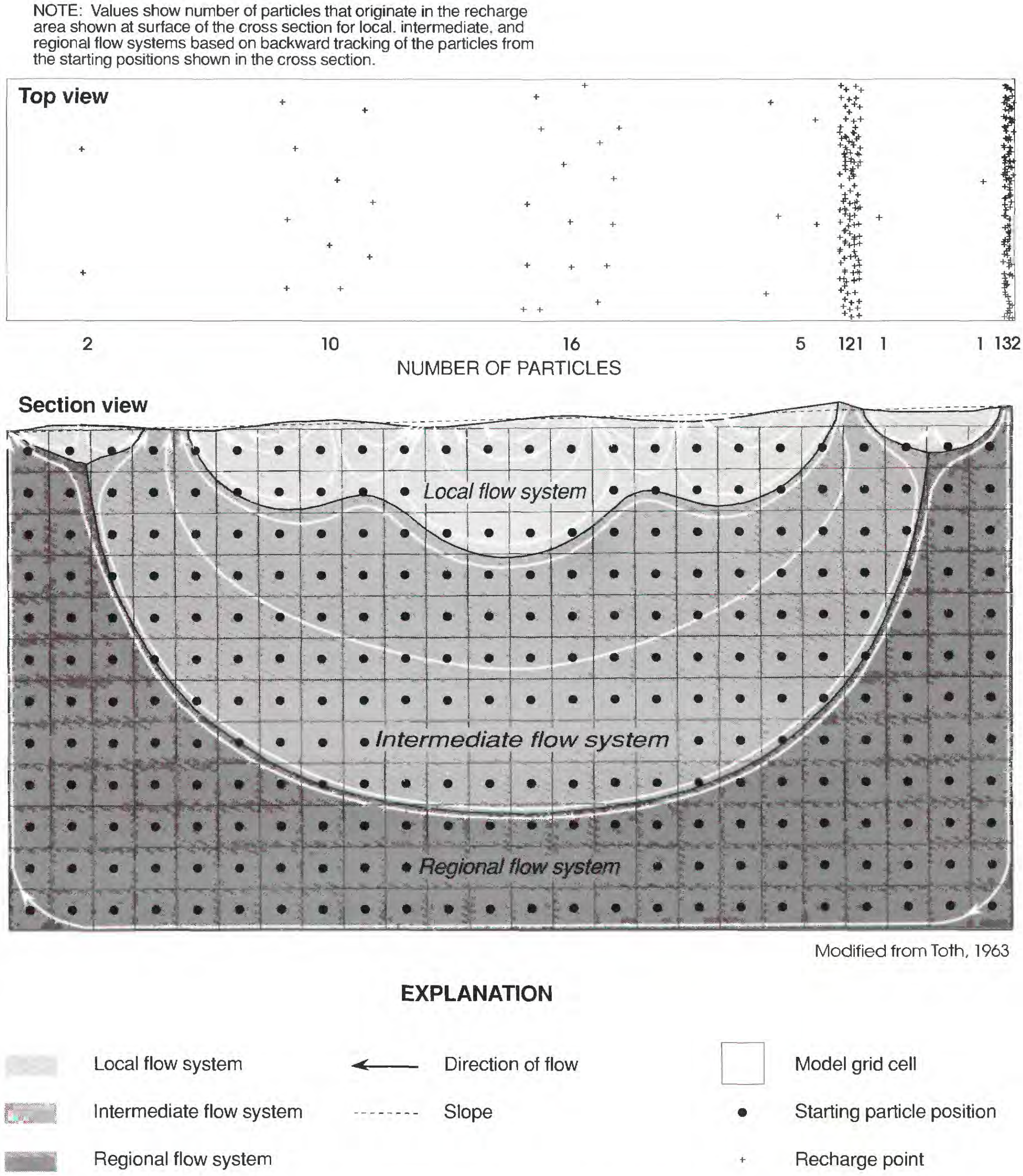


Figure 7. Hypothetical example of relation between density of recharge points derived from backward particle tracking and location of recharge areas for local, intermediate, and regional flow systems.

The Troutdale sandstone aquifer covers part of south-central Clark County (fig. 10D). The recharge points for particles tracked backwards from the cells representing this unit are distributed along and outside the eastern edge of the unit's extent. The high density clusters of recharge points at topographically higher areas are due to the occurrence of intermediate recharge or recharge at outcrops of the aquifer. In addition, the Troutdale sandstone aquifer receives some recharge from the regional flow system that originates along the model boundary east of the unit's extent.

The sand and gravel aquifer in Clark County is limited in extent and occurs in southeastern Clark County (fig. 10E). Most of the recharge in the area east of the city of Washougal occurs on or around Mount Norway and helps to replenish the local and intermediate flow systems. The lengths of the pathlines are longest for particles recharging at the top of Mount Norway and decrease for recharge occurring downslope, towards the Columbia River. The part of the sand and gravel aquifer west of the city of Camas is replenished by regional flow that recharges along the eastern boundary of the model north of Lacamas Lake, as indicated by recharge points with longer pathlines.

Recharge to the older rocks is primarily through regional flow as indicated by the predominance of recharge points with long pathlines originating along the eastern boundary of the flow model along the western flank of the Cascade Range (fig. 10F).

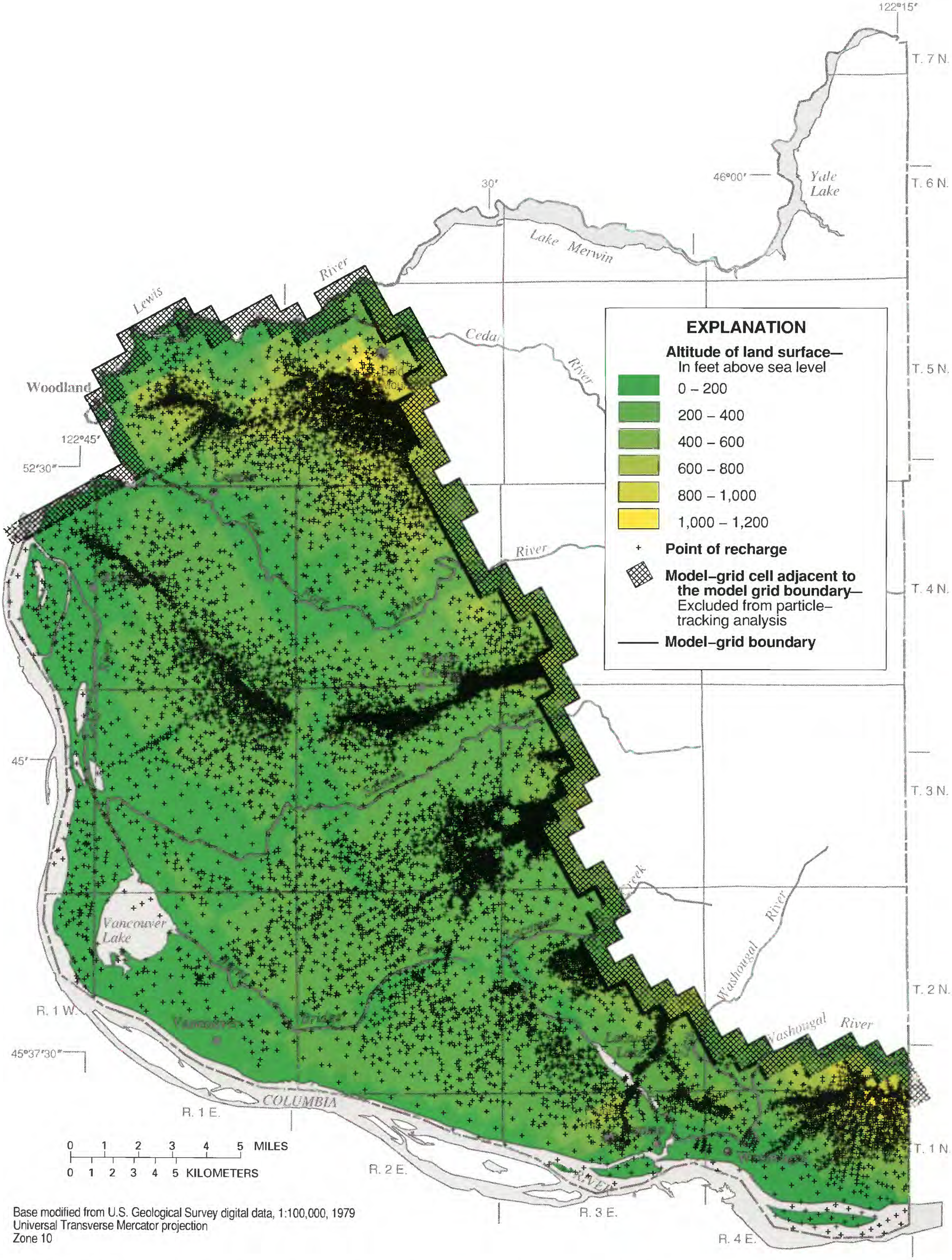


Figure 8. Altitude of land surface and relation to distribution of recharge points, based on particles that recharge all hydrogeologic units.

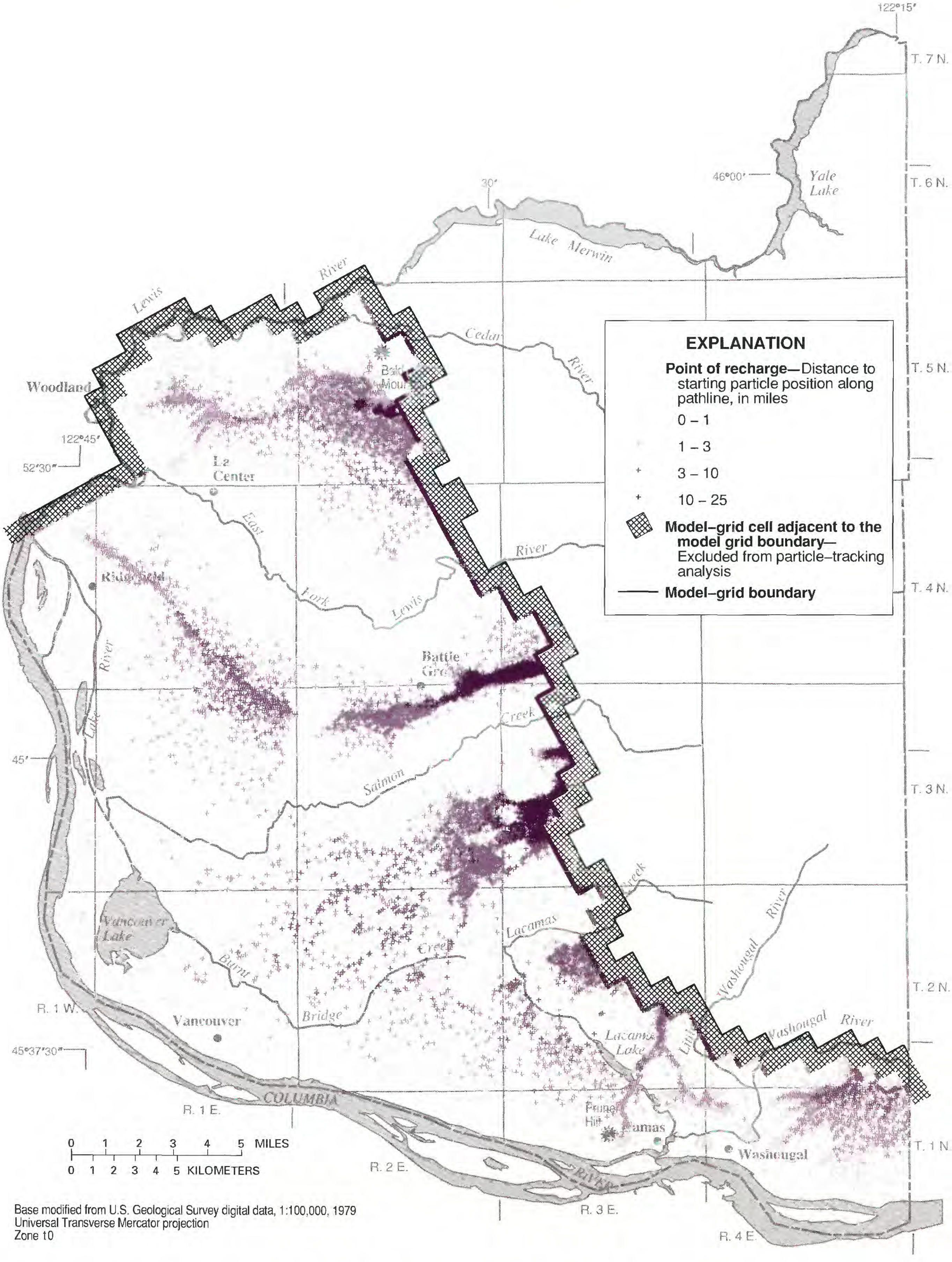


Figure 9. Distance traveled and distribution of recharge points, based on particles that recharge all hydrogeologic units.

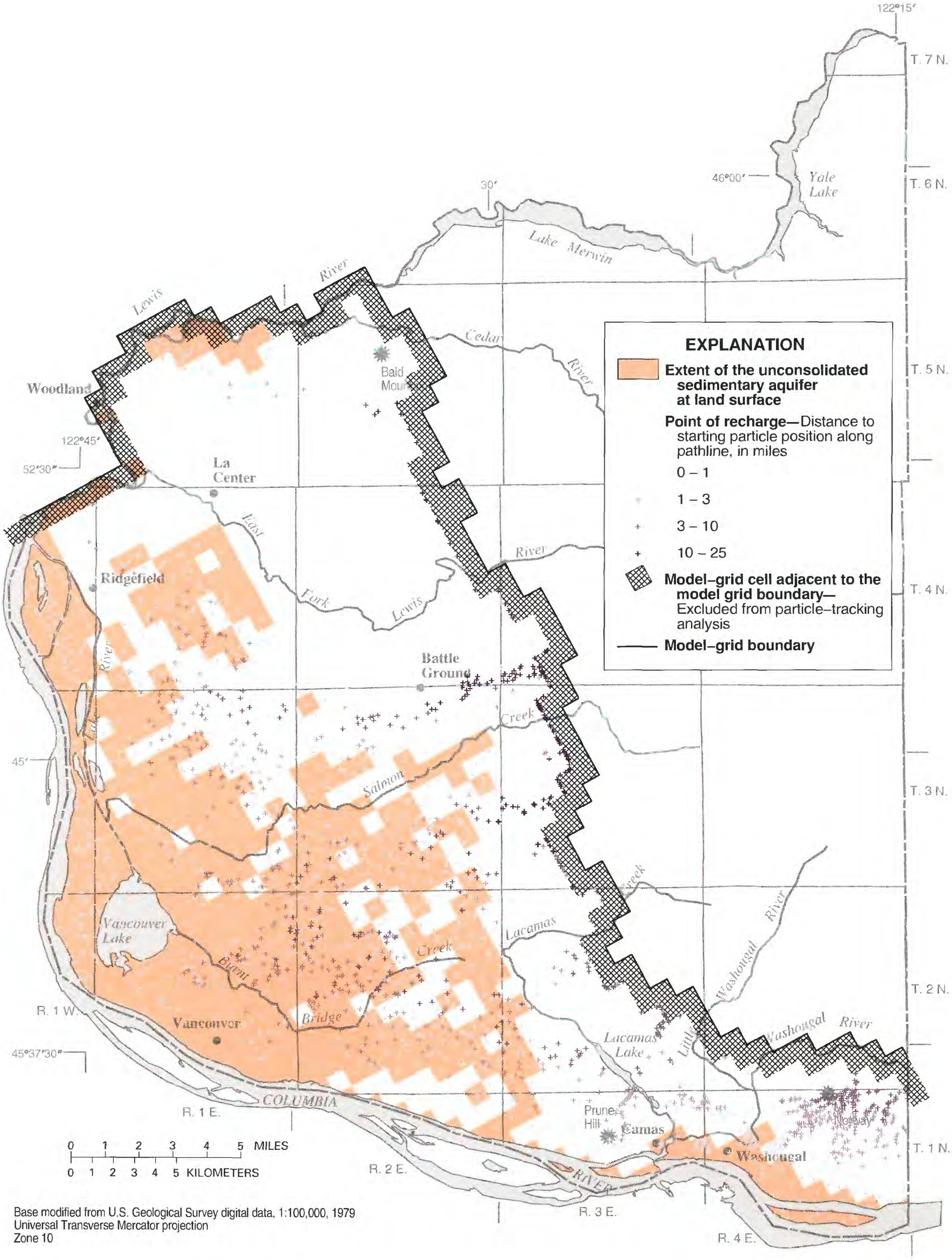


Figure 10A. Distance traveled and distribution of recharge points, based on particles that recharge the unconsolidated sedimentary aquifer.

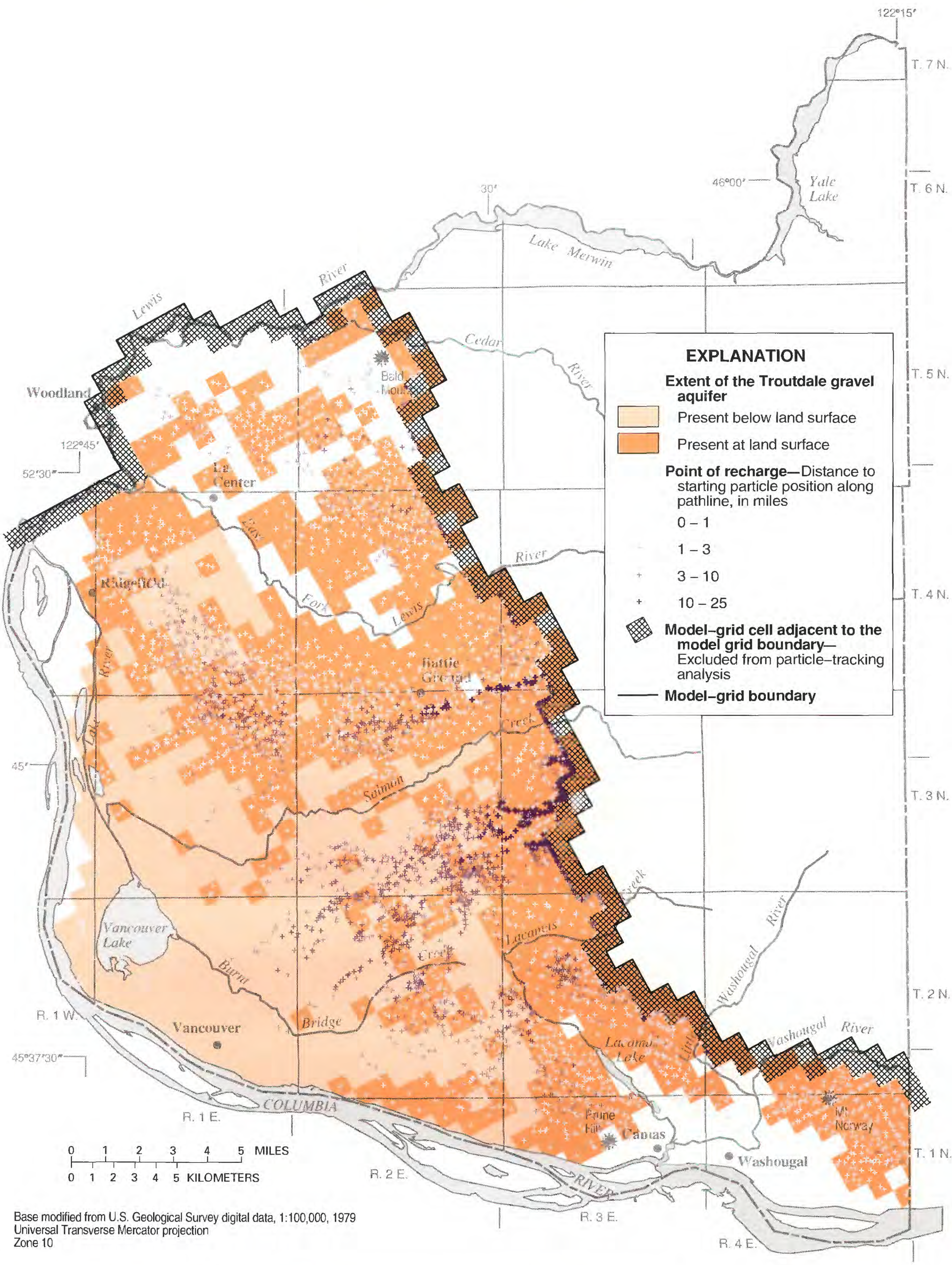


Figure 10B. Distance traveled and distribution of recharge points, based on particles that recharge the Troutdale gravel aquifer.

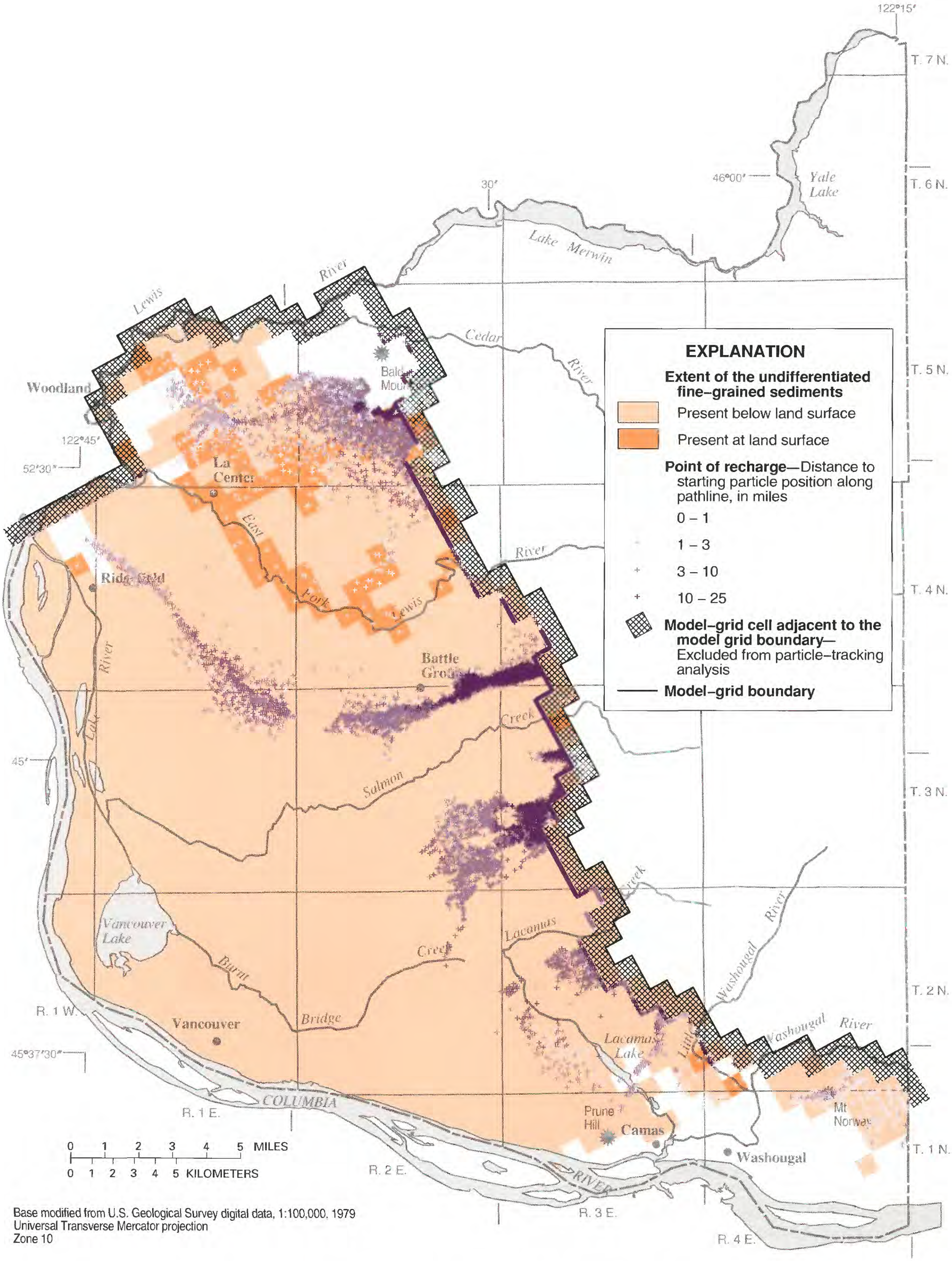


Figure 10C. Distance traveled and distribution of recharge points, based on particles that recharge the undifferentiated fine-grained sediments.

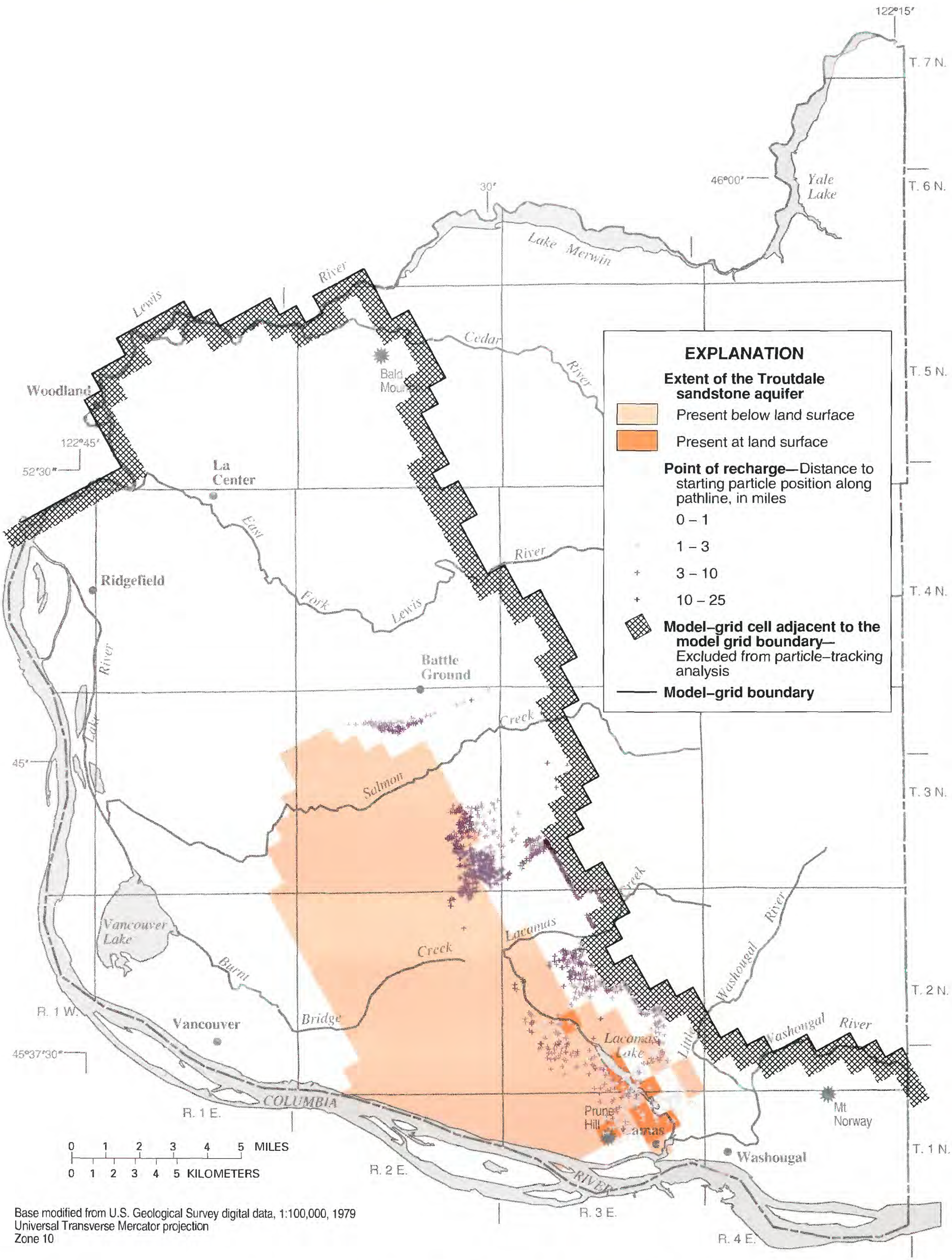


Figure 10D. Distance traveled and distribution of recharge points, based on particles that recharge the Troutdale sandstone aquifer.

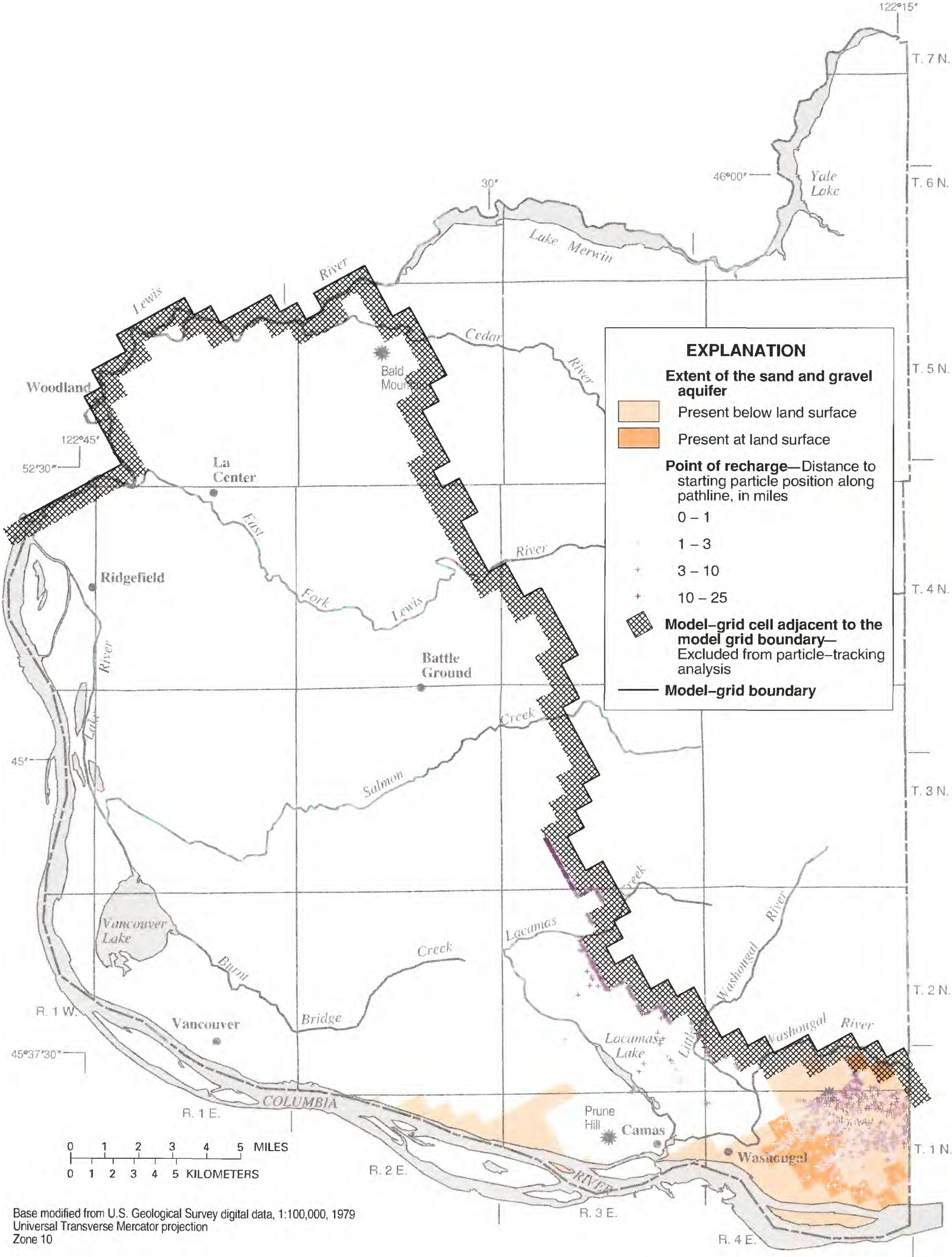


Figure 10E. Distance traveled and distribution of recharge points, based on particles that recharge the sand and gravel aquifer.

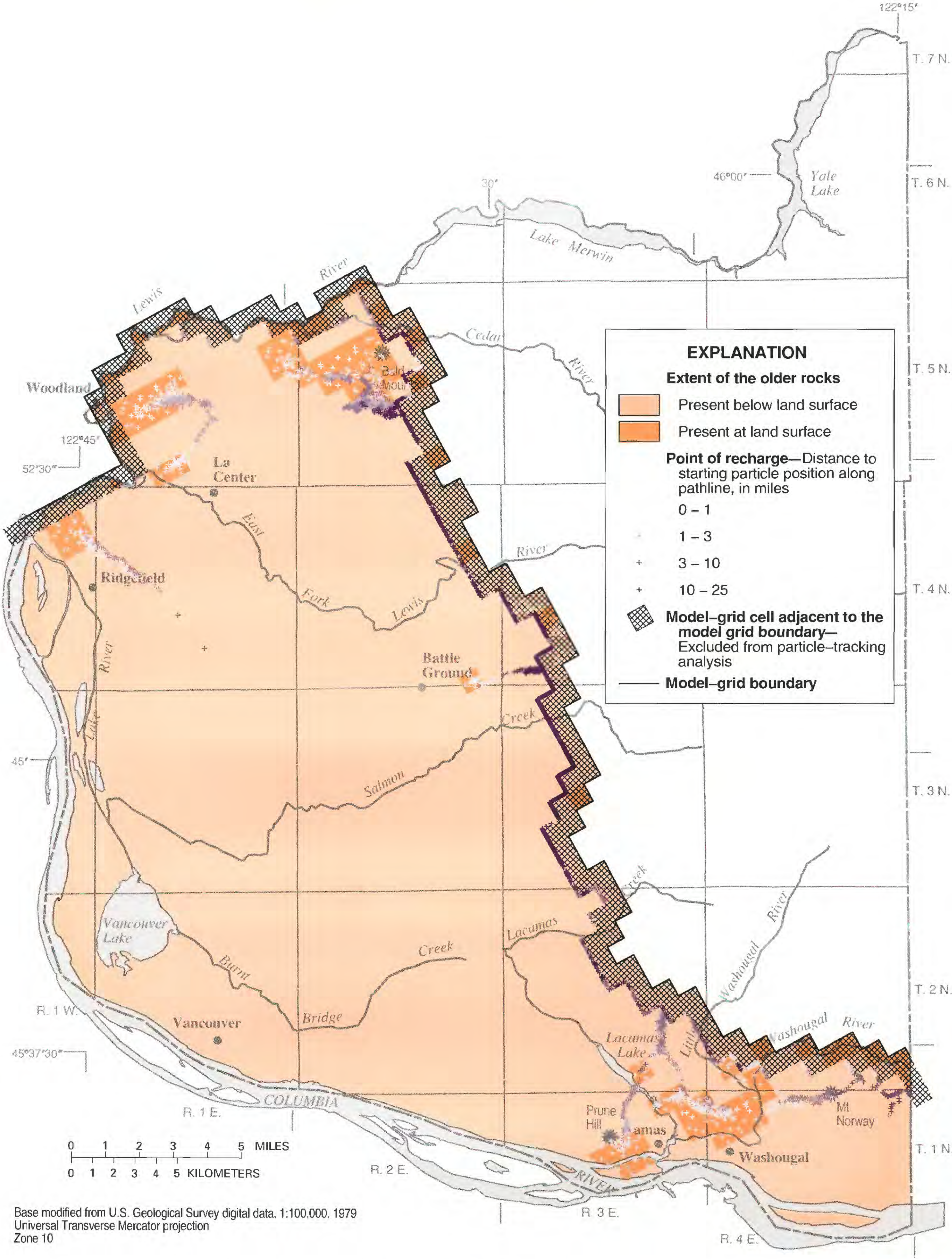


Figure 10F. Distance traveled and distribution of recharge points, based on particles that recharge the older rocks.

Water entering here at the edge of the basin flows through the older rocks and discharges at or near the Columbia River and adjacent water bodies. Recharge to intermediate flow systems is indicated by the occurrence of areas with a high density of recharge points and shorter pathlines at topographically higher areas, especially where the older rocks are present at the surface, such as north of Ridgefield, east of Woodland, near Bald Mountain, east of Battle Ground, and in the area between Prune Hill and Mount Norway.

Uncertainties and Limitations

The use of a particle-tracking program is subject to the same limitations previously discussed for the ground-water flow model, as well as additional limitations inherent to the particle-tracking methodology. The ground-water flow model was designed as a regional flow model. Data collection and ground-water flow simulations were made on the basis of a uniform grid-cell spacing of 3,000 feet. The most appropriate use of the results of the ground-water flow model or particle-tracking program is in a regional context. Care should be taken when attempting to use the results of this particular model for site-specific studies. These studies may require additional information on the hydraulic characteristics of the ground-water flow system at a resolution similar to that of the model discretization required in the area of interest.

The particle tracker only simulates the advective transport of water and does not consider hydrodynamic dispersion; neither does it consider retardation of possible contaminants as a result of adsorption or chemical interactions. It should also be noted that the particle-tracking program simulates movement in the saturated zone only. Movement and traveltime through the unsaturated zone (the area between land surface and the water table in which the pores may contain air, water, or both) is not accounted for and may result in an underestimate of the traveltime. Additional limitations of MODPATH are described by Pollock (1989, p. 19–21). Two limitations that require further discussion are the effects of boundaries and the relation between size of model cells and representation of internal sinks.

Caution is required when interpreting the results of a particle-tracking program 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 model-cell face. However, boundaries that are simulated as no flow may actually have small ground-water inflows entering from outside the model. This situation arises along the eastern boundary of the ground-water flow model in Clark County (Morgan and McFarland, 1996). The result of not modeling these small inflows is insignificant for most uses of the regional ground-water flow model; however, pathlines near these boundaries may be deflected or truncated. Particles that enter model cells adjacent to no-flow boundaries may move laterally until they reach the water table, resulting in particle paths and traveltimes 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.

Another limitation in particle tracking may occur when simulating cells with internal sinks, such as discharging wells, springs, gaining streams or rivers, or boundaries with variable inflow (general-head conditions) (Pollock, 1989; Zheng, 1994). Pollock (1989) describes this limitation as follows:

> 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. Pathlines 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 pathlines represent a fixed quantity of flow.
>
> 2. Pathlines 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, and particles that entered a weak-sink cell were allowed to pass through the cell.

EVALUATION OF GROUND-WATER VULNERABILITY

The results of the particle-tracking analysis can be used alone or in conjunction with other information to evaluate ground-water vulnerability. Three methods will be discussed: using characteristics of the recharge areas, relating recharge area characteristics to downgradient parts of the flow system, and determining the age of ground water in the system. Recharge areas, as defined by the location of recharge points for a part of the ground-water system, can be used to identify and prioritize areas for water-quality monitoring and land-use protection. Using the GIS, the characteristics of the recharge areas, such as aquifer sensitivity or the occurrence of contaminants, can be related to downgradient parts of the ground-water system that may eventually receive the recharge water through ground-water flow. This analysis makes it possible to estimate those parts of the flow system that may be most susceptible to the effects of land-use activities. Finally, the particle-tracking program is able to estimate the traveltime between the point of recharge and other parts of the ground-water flow system. This information can be used to identify areas of the flow system with the same age of ground water as the land-use activities that may have degraded recharge water.

Characteristics of Recharge Areas

An important aspect of ground-water protection is the identification of recharge areas, areas where water enters the ground-water flow system and replenishes an aquifer, and the compatibility of these recharge areas with specific land-use activities. Maps of the recharge areas determined for the aquifers in Clark County (figs. 10A-F) can be used by water-resource managers in combination with maps of aquifer sensitivity and the location of contaminant sources to assess ground-water vulnerability.

Ground-water recharge areas, as determined by the particle-tracking program, can be used with aquifer-sensitivity maps to identify recharge areas more conducive to contaminant entry. This study used a DRASTIC analysis for Clark County prepared by the Intergovernmental Resource Center (Swanson, 1991) as a means of comparing the aquifer sensitivity of different areas. DRASTIC is a methodology developed for the U.S. Environmental Protection Agency that measures the pollution potential of ground water on the basis of the intrinsic characteristics of the near-surface unsaturated and saturated zones (Aller and others, 1987). The term "DRASTIC" is an acronym for the seven features of the ground-water system at the recharge boundary on which the method is based. The features, with their relative importance or weight, are:

Acronym	Feature	Weight
D	Depth to water	5
R	Net recharge	4
A	Aquifer media	3
S	Soil media	2
T	Topography (slope)	1
I	Impact of the vadose zone	5
C	Hydraulic conductivity of the aquifer	3

An area is mapped for each feature and is assigned a rating using a predetermined scale established by Aller and others (1987). The maps are then overlaid and an overall DRASTIC index is determined for each resulting area by multiplying the feature ratings of each map layer by the corresponding weight and summing the results. Higher DRASTIC indices indicate a greater pollution potential or aquifer sensitivity. DRASTIC indices for Clark County are shown in figure 11 (Swanson, 1991).

The DRASTIC indices of the recharge areas for the ground-water flow system in Clark County can be determined by overlaying the DRASTIC map with the map of recharge points derived by particle tracking (fig. 11). Most areas that have a high density of recharge points are in areas of relatively low DRASTIC indices, such as north of the East Fork Lewis River, southeast of Ridgefield, north and east of Lacamas Lake, around Mount Norway, and along the eastern boundary of the ground-water flow model. Some areas with a high density of recharge points are in areas of relatively high DRASTIC indices, such as southwest of Battle Ground, south of Salmon Creek, and northwest of Lacamas Lake. This mapped association is an illustration of the type of analysis that can be used to assign priority to areas being considered for more restrictive land-use activities to prevent aquifer contamination. Further delineation to protect the recharge areas for specific parts of the ground-water flow system, such as an aquifer or a part of an aquifer, also is possible, but is not illustrated in this report.

Maps of actual or potential contaminant sources also can be used in conjunction with information on the location of recharge areas derived by particle tracking to assess possible contamination of recharge areas. With this intent, the Intergovernmental Resource Center and the USGS have compiled maps of Clark County depicting landfills and dumps, average annual recharge from on-site waste-disposal systems (septic and cesspool systems), average annual recharge from drywells and sumps, population density, transportation corridors, underground storage tanks, and land use.

An analysis of average annual recharge at the water table from on-site waste-disposal systems is used to demonstrate this approach. Snyder and others (1994) reported significant recharge from on-site waste-disposal systems in the vicinity of Burnt Bridge Creek in southern Clark County. A map of recharge from on-site waste-disposal systems, derived from that study, was overlaid with the map of the recharge points derived from particle tracking (fig. 12). Possible strategies for improved protection of the recharge areas would be to upgrade the on-site waste-disposal systems or install sewers in areas that have a higher density of recharge points and higher rates of recharge from on-site waste-disposal systems.

Potential Impacts Downgradient from Recharge Areas

By using the results of the particle-tracking analysis and a GIS, it is possible to relate the characteristics of a recharge area, such as aquifer sensitivity or the location of contaminant sources, to the downgradient part of the ground-water flow system that will eventually receive flow from that area (fig. 13). Using the GIS, each model cell easily can be assigned the minimum, mean, maximum, or sum of any characteristic describing the recharge areas for the particles that recharge the cells. This capability makes it possible to map the characteristics of the ground-water flow system according to the characteristics of the recharge area. These maps could facilitate the identification of recharge area characteristics, such as the aquifer sensitivity or the presence of contaminant sources, for ground-water resources, such as public-supply wells, springs, or gaining stream reaches.

The aquifer sensitivity at the point of recharge can be assigned to any part of the ground-water flow system by using the method described above. The maximum DRASTIC index at the recharge areas for ground water in the model-grid cells within the unconsolidated sedimentary aquifer and Troutdale gravel aquifer are shown in figures 14A and 14B, respectively. These hydrogeologic units are the most heavily used for public supply in Clark County. Similar maps for other hydrogeologic units are shown in Appendix A, figures A1–A4. Public-supply wells open to the unconsolidated sedimentary aquifer in the southern part of Clark County receive a component of ground water that recharged through areas that have high aquifer-sensitivity (DRASTIC) indices (fig. 14A). Wells open to the Troutdale gravel aquifer in southwestern Clark County also receive water from recharge areas with high DRASTIC indices, indicating a high aquifer sensitivity (fig. 14B).

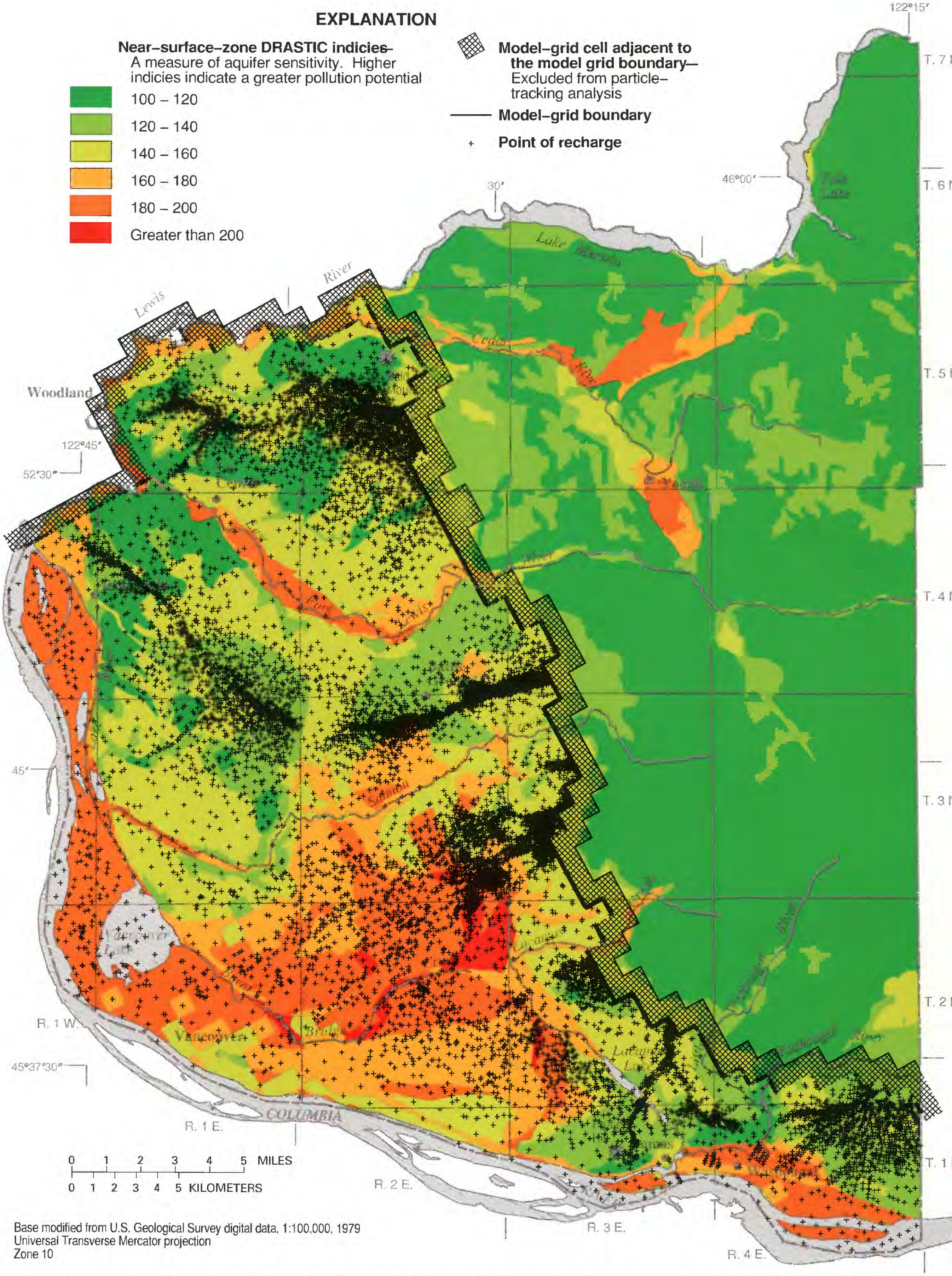


Figure 11. DRASTIC indices for the near-surface saturated and unsaturated zones, and distribution of recharge points for all particles that recharge all hydrogeologic units.

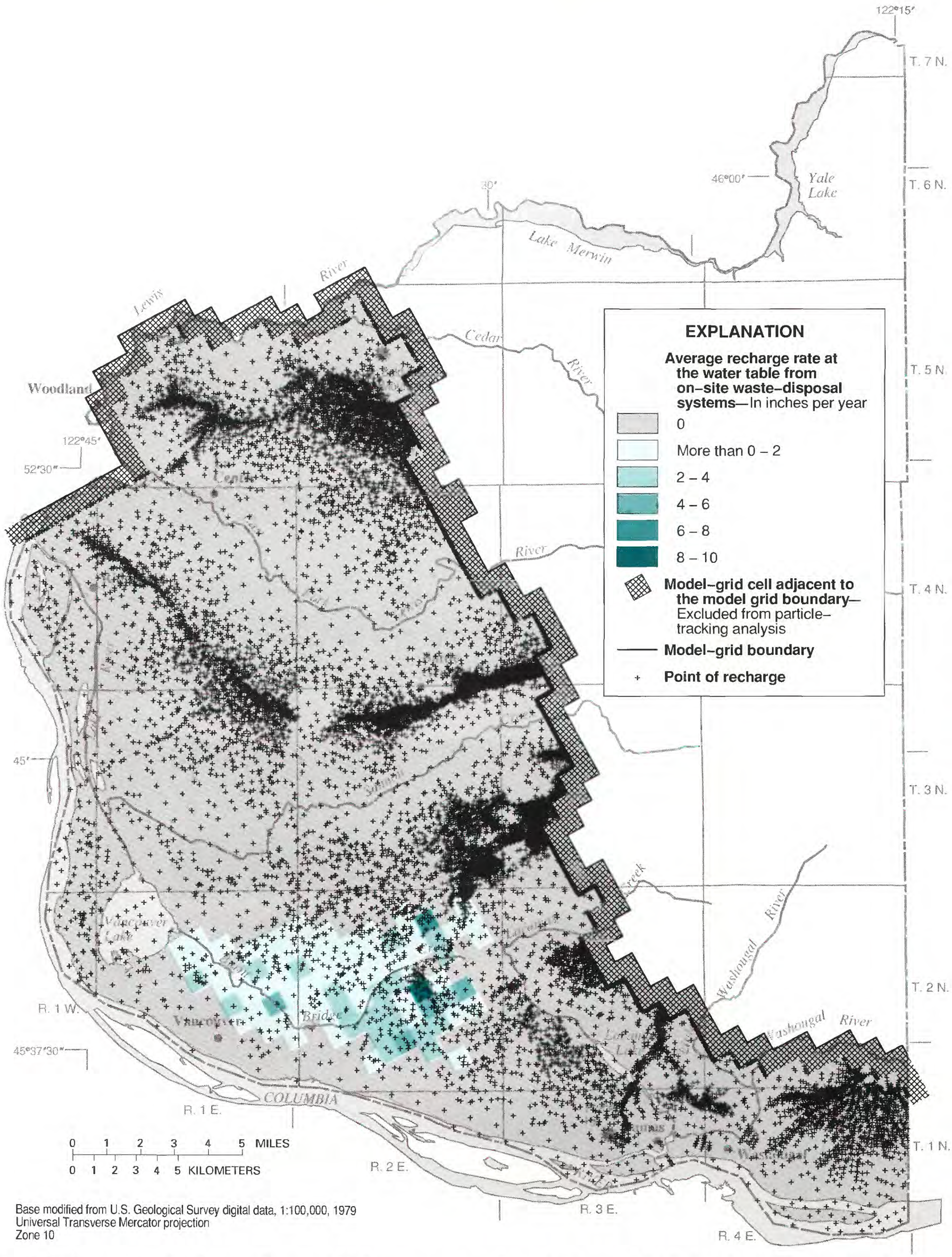
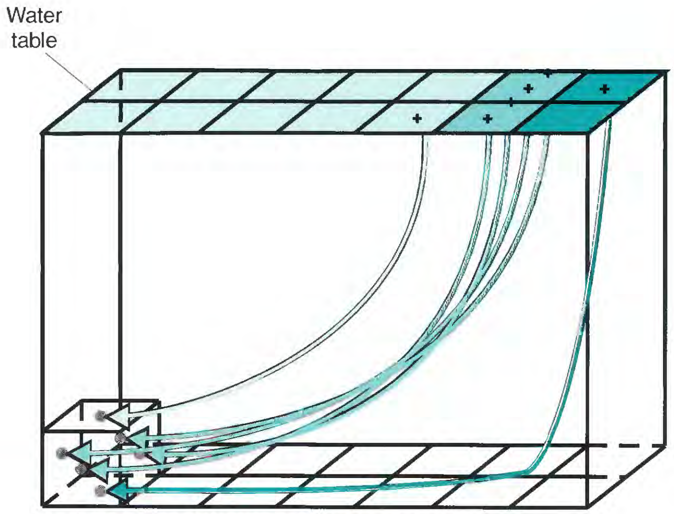


Figure 12. Average annual recharge at the water table from on-site waste-disposal systems and distribution of recharge points, based on particles that recharge all hydrogeologic units.



Recharge area characteristics for example cell:

Minimum = 100
Mean = 150
Maximum = 200
Sum = 900

As a demonstration, to create a maximum DRASTIC index map of the model layer containing the example cell, each cell in the layer would be shaded using the maximum DRASTIC index of any recharge area for particles entering the cell. In this case, the example cell would be set to the value of 200 representing the highest DRASTIC index.

EXPLANATION

Characteristics of recharge areas
For example: DRASTIC index, land use, or water quality

100 - Low value of characteristic to be mapped

150 - Medium value of characteristic to be mapped

200 - High value of characteristic to be mapped

Particle flow path from recharge area to model cell

+ **Point of recharge**

● **Particle**

Figure 13. Method of relating characteristics of the recharge area to a downgradient part of the ground-water flow system using particle tracking. (Each model cell can be assigned the minimum, mean, maximum, or sum of the characteristic describing the recharge areas for the particles that recharge the cell.)

These maps illustrate a critical deficiency in the DRASTIC methodology—the failure to account for the dynamics of the ground-water flow system. DRASTIC analysis alone does not incorporate information about the direction and velocity of ground-water flow; DRASTIC indices calculated for a particular location thus do not necessarily reflect the conditions of the ground-water resources at the recharge areas for that particular location. Comparison of the DRASTIC map (fig. 11) with the map of the DRASTIC indices derived from particle tracking for the Troutdale gravel aquifer (fig. 14B) shows some of these deficiencies. In the DRASTIC map, the 6 areas having DRASTIC indices greater than 200 in south-central Clark County are small and distinct. However, in the map of the DRASTIC indices for the Troutdale gravel aquifer, these areas are larger and elongated to the southwest, resulting from recharge in the area to the northeast and the subsequent flow of ground water from northeast to southwest towards the Columbia River. Water withdrawn from many of the wells located in southwestern Clark County that are open to the Troutdale gravel aquifer may include water that was recharged in areas with a higher DRASTIC index than is indicated by the DRASTIC map. This is because DRASTIC reflects conditions at only the surface and does not consider conditions upgradient at the location where the underlying ground water may have actually recharged.

The effect of the movement of ground water on the DRASTIC indices for downgradient parts of the flow system also is readily illustrated by the model sections across the flow system presented in figure 14C. Section A-A' is parallel to the principal direction of ground-water flow, which is from northeast to southwest. Section B-B' is normal to the principal direction of flow, which is to the southwest. In each section, model cells within each layer have been shaded to show the maximum DRASTIC index (derived from particle tracking) within the recharge area to the cell. Low DRASTIC indices dominate the lower part of the flow system (fig. 14C), because recharge is from the east from areas of relatively low DRASTIC indices. Higher DRASTIC indices are present in the middle parts of the flow system. These higher indices are the result of several intermediate flow systems that are recharged in areas of relatively higher DRASTIC indices south of Battle Ground and in the upper reaches of the Burnt Bridge Creek drainage. The effect of local flow systems can be seen in both sections as both higher and lower DRASTIC indices occur in the uppermost part of the flow system.

The ground-water flow model and particle-tracking program also can be used to assess the parts of the ground-water flow system that may receive contaminants through advective transport of contaminants from sources within their recharge areas. As an example, the maximum average recharge rate due to on-site waste-disposal systems in recharge areas for the unconsolidated sedimentary aquifer and Troutdale gravel aquifer are presented in figures 15A and 15B, respectively. Maps and model sections for the other hydrogeologic units are presented in Appendix B, figures B1–B3. All values of recharge from on-site waste-disposal systems derived from particle tracking are equal to zero for the sand and gravel aquifer and older rocks; no maps are presented for these units. It should be noted that the rate of recharge from on-site waste-disposal systems to the water table at the recharge area does not necessarily represent the rate of wastewater transported to downgradient parts of the ground-water flow system as a result of the discretization of weak sinks (see section titled "Uncertainties and Limitations").

Figure 15A shows the parts of the unconsolidated sedimentary aquifer that will eventually receive a component of water that entered the flow system in an area of recharge from on-site waste-disposal systems. Comparison with the distribution of recharge at the water table from on-site waste-disposal systems (fig. 12) shows the influence of the ground-water flow system.

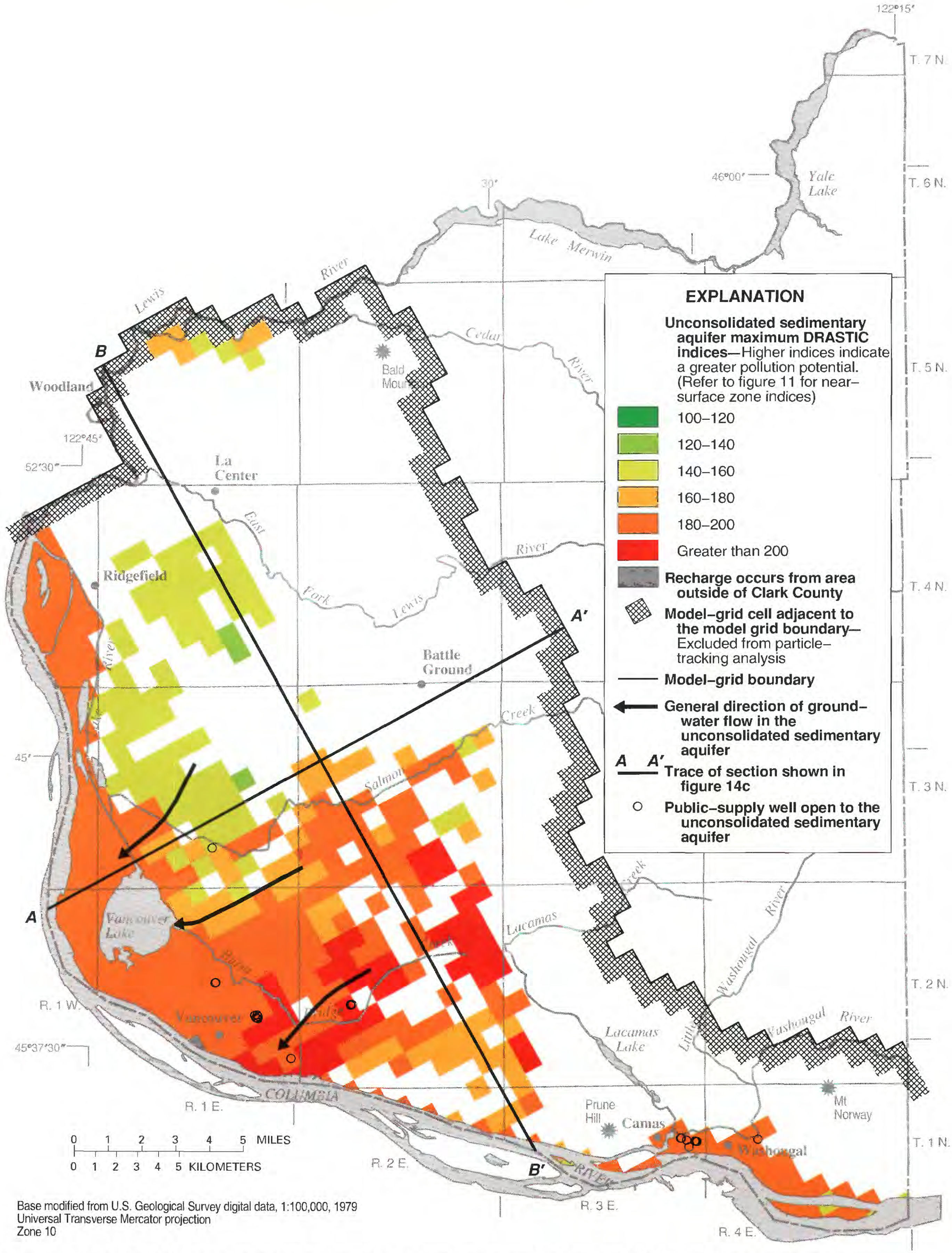


Figure 14A. Maximum DRASTIC indices for the unconsolidated sedimentary aquifer, based on DRASTIC indices where particles recharge the unconsolidated sedimentary aquifer.

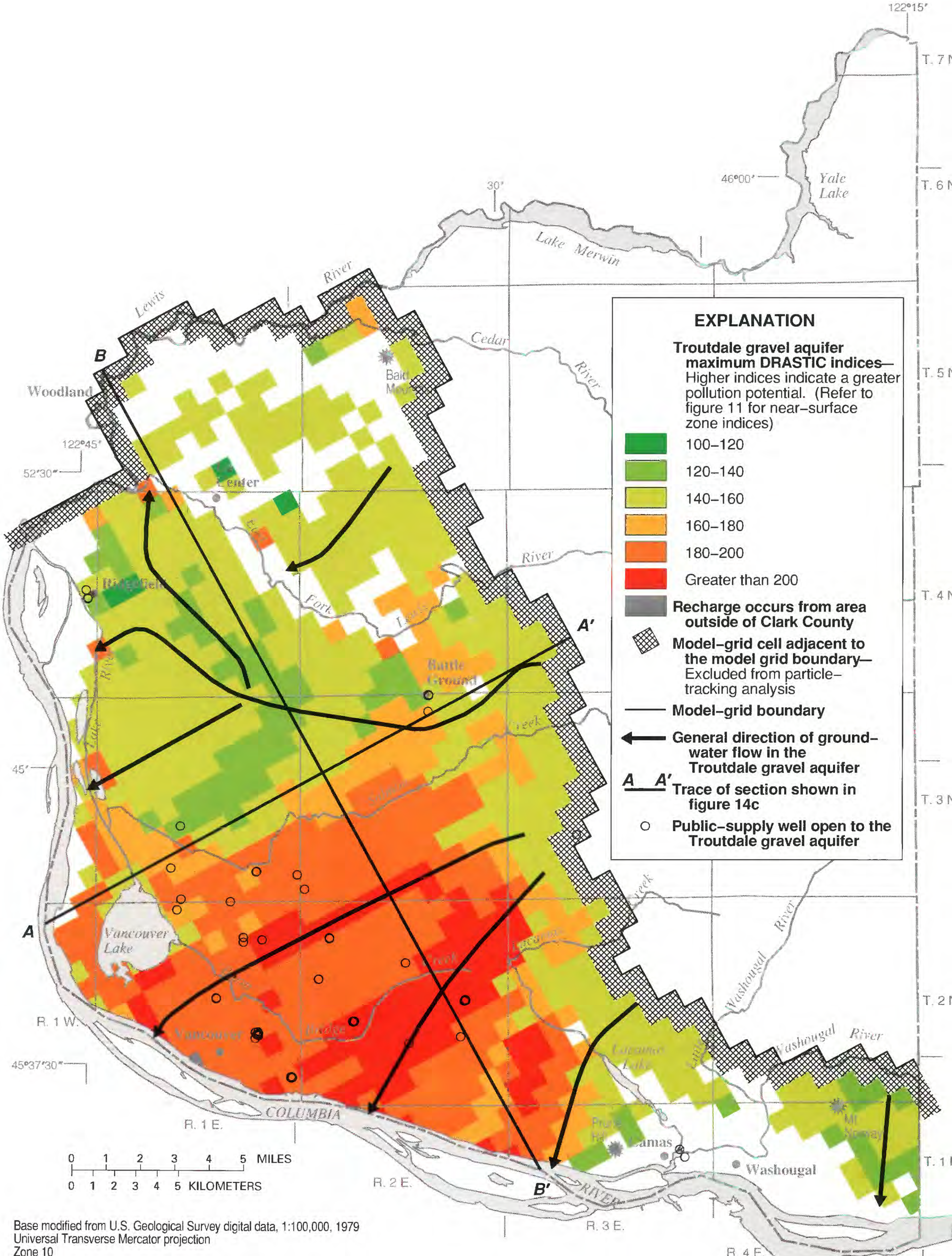


Figure 14B. Maximum DRASTIC indices for the Troutdale gravel aquifer, based on DRASTIC indices where particles recharge the Troutdale gravel aquifer.

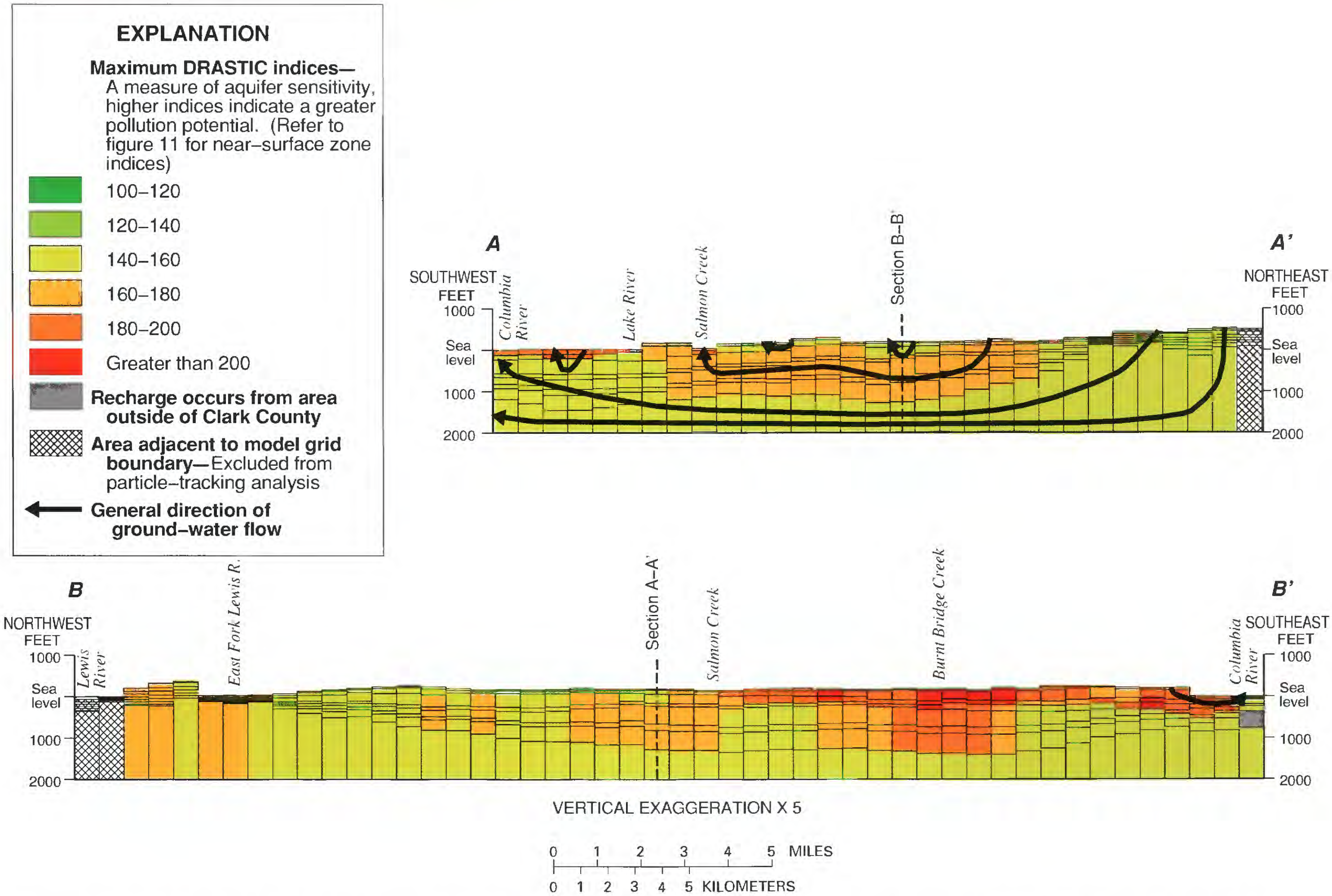


Figure 14C. Model sections showing maximum DRASTIC indices for the model cells along the sections, based on DRASTIC indices where particles recharge the model cells along the sections. (Section locations shown on figures 14A–B.)

The area of possible impact extends south and west from the area of recharge from on-site waste-disposal systems in the direction of ground-water flow towards the Columbia River. The effect of ground-water flow is more apparent in the Troutdale gravel aquifer (fig. 15B) from the two model cells with maximum rates of recharge at the water table from on-site waste-disposal systems of greater than 6 inches per year (fig. 12). On-site waste-disposal system effluent that recharges in these two cells extends into the Troutdale gravel aquifer south and west towards the Columbia River along the direction of ground-water flow.

A number of public-supply wells open to the unconsolidated sedimentary aquifer and Troutdale gravel aquifer are within the area of downgradient impact from on-site waste-disposal systems (figs. 15A and 15B). Therefore, these wells may eventually withdraw a component of water containing effluent from on-site waste-disposal systems. As previously noted in the section, "Uncertainties and Limitations," this analysis only simulates advective transport and does not consider hydrodynamic dispersion or retardation of the contaminants. The contaminants are assumed to be conservative and to move with the water. Degradation of ground-water quality due to on-site waste-disposal systems, however, is indicated by the observation of elevated nitrate concentrations in samples collected from wells and springs in the Vancouver urban area in the unconsolidated sedimentary aquifer and Troutdale gravel aquifer (Turney, 1990; Ebbert and Payne, 1985; Mundorff, 1964). On-site waste-disposal systems have been identified as the most likely source (Turney, 1990).

Estimated Age of Ground Water

Another indicator of ground-water vulnerability is the age of ground water, as estimated by the traveltime for water as it moves from a recharge area to a point of discharge. Parts of the ground-water flow system that contain ground water with ages less than the time since industrialization of the Clark County area (late 1800's, approximately 100 years ago) are at the greatest immediate risk to contamination from anthropogenic sources that may have been present at the upgradient recharge areas at the time the water recharged. This information also can be used to evaluate the vulnerability of developed and undeveloped ground-water resources.

The approximate age of ground water was determined for all model cells in Clark County by using backward particle tracking.

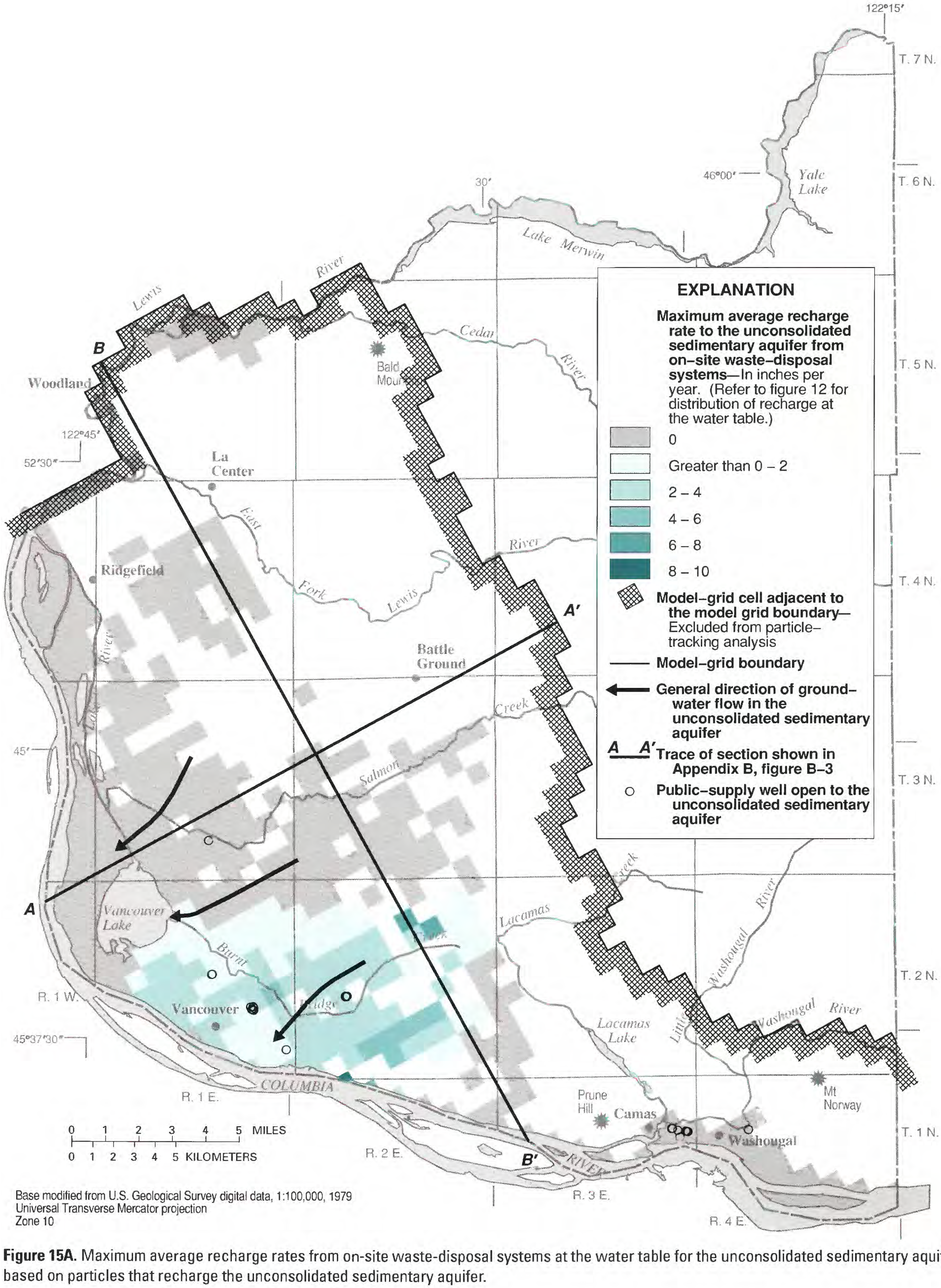


Figure 15A. Maximum average recharge rates from on-site waste-disposal systems at the water table for the unconsolidated sedimentary aquifer, based on particles that recharge the unconsolidated sedimentary aquifer.

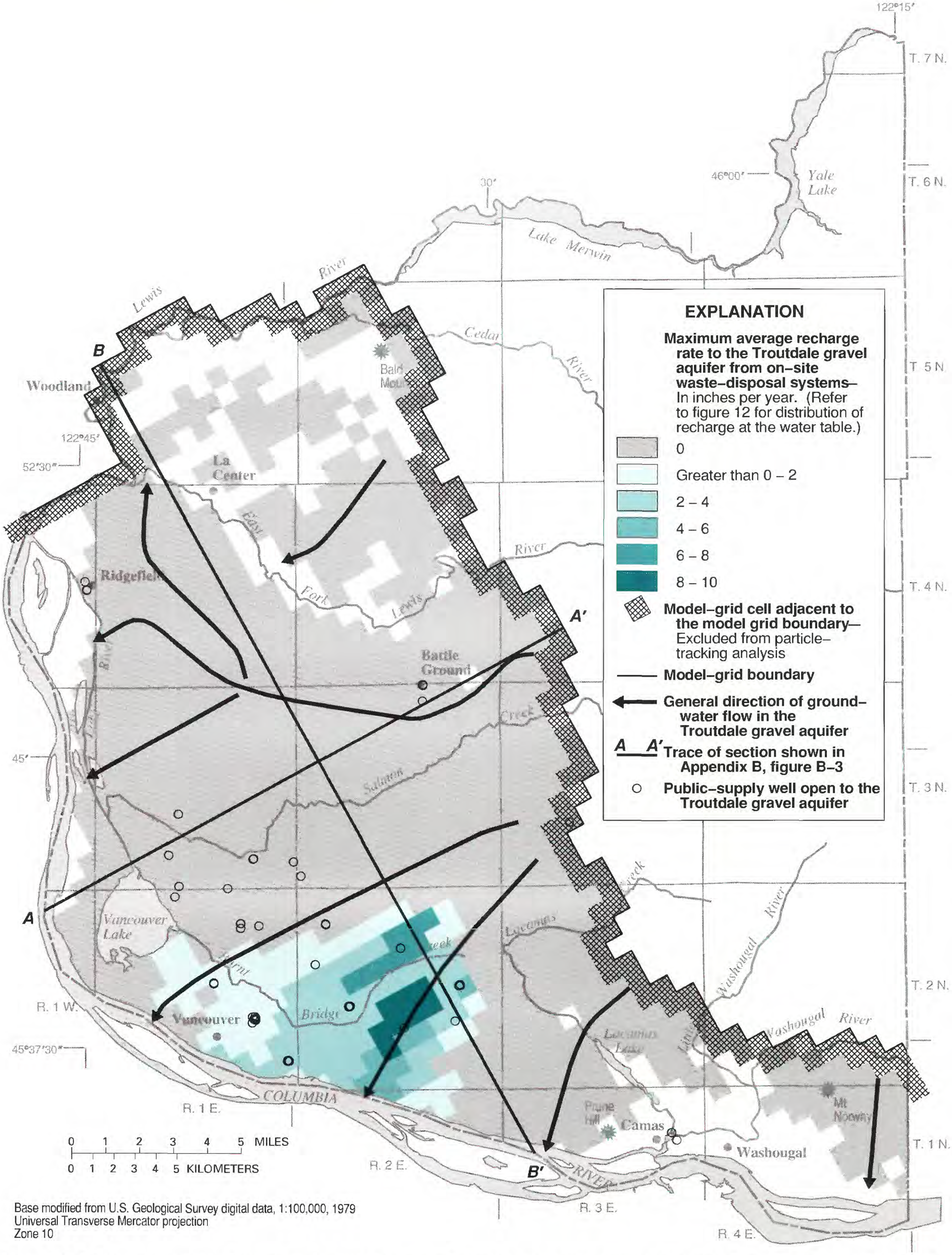


Figure 15B. Maximum average recharge rates from on-site waste-disposal systems at the water table for the Troutdale gravel aquifer, based on particles that recharge the Troutdale gravel aquifer.

Six particles in each cell were tracked backwards to their recharge points, and the minimum and maximum ground-water ages were calculated by using the particle traveltimes. Maps showing the minimum and maximum ground-water ages for a cell can be useful in determining whether a contaminant introduced at the recharge area has had sufficient time to travel downgradient and reach a particular part of the ground-water flow system.

Maps showing the distribution of minimum ground-water ages within a hydrogeologic unit emphasize the influence of particles with the smallest traveltimes. In a like manner, maps depicting the distribution of the maximum age of ground water within a hydrogeologic unit emphasize the influence of particles with the longest traveltimes. Comparison of the maps of minimum and maximum ages of ground water enables the determination of the range of possible ages for any part of the ground-water flow system. The minimum and maximum ground-water ages used in this study were calculated on the basis of the traveltimes of particles resulting from advective transport only. Other processes that were not considered, such as hydrodynamic dispersion or retardation, would be expected to cause some of the particles to travel more rapidly than the average interstitial velocity and some to travel more slowly.

Because particles that encountered a model cell adjacent to a no-flow boundary were stopped upon entering the cell, an underestimate of the traveltimes may have resulted. This underestimate of traveltimes provides for a greater measure of protection from the possibility of erroneously designating the age of water within a model cell as older and, therefore, less susceptible to anthropogenic contamination. An additional consideration is that the estimates of particle traveltime do not include the traveltime in the unsaturated zone, which also may result in an underestimate of the ground-water age.

The minimum and maximum ground-water ages derived from the particle-tracking program for each model cell were mapped for each hydrogeologic unit in Clark County and are presented in figures 16A–C for the unconsolidated sedimentary aquifer, the Troutdale gravel aquifer, and the older rocks, respectively. Maps of minimum and maximum ground-water ages are presented in Appendix C, figures C1–C3, for the undifferentiated fine-grained sediments, the Troutdale sandstone aquifer, and the sand and gravel aquifer, respectively.

The minimum ground-water age is less than 10 years throughout the extent of the unconsolidated sedimentary aquifer, with the exception of a few areas along the Columbia River at Vancouver (fig. 16A). The young minimum ground-water ages in these areas result from the occurrence of the aquifer at the surface and the presence of recharge areas for local and intermediate flow systems. The map of maximum ground-water ages for the unconsolidated sedimentary aquifer (fig. 16A) shows that most of the water has an age of less than 100 years, with the age of ground water increasing downgradient to the west and south.

The minimum and maximum ages of ground water in the Troutdale gravel aquifer (fig. 16B) increase to the southwest along the general direction of ground-water flow. Most of the ground water within the Troutdale gravel aquifer has a minimum age of less than 100 years, with many areas having ground water less than 10 years old. The occurrence of ground water with minimum ages of less than 10 years is correlated with the proximity of the unit to the surface and with the occurrence of recharge areas. Discharge areas for intermediate flow systems along parts of the East Fork Lewis River and Salmon Creek are indicated by the presence of water with estimated maximum ages older than those of the topographically higher adjacent area (fig. 16B).

Most ground water within the older rocks moves along the long flow paths of the regional flow system. Near the recharge areas along the foothills of the Cascades, the age of ground water within the older rocks ranges from less than 10 years to greater than 1,000 years (fig. 16C). At the discharge end of the system near the Columbia River, ages range from 1,000 years to greater than 10,000 years. The map of the minimum age of ground water in the older rocks shows a smooth transition in the age of ground water from the northeast to the southwest along the direction of ground-water flow in the regional flow system. The map of maximum age of ground water in the older rocks shows a large area of water with a maximum age greater than 10,000 years. This probably represents the bottom of the modeled ground-water flow system, with the age of ground water reflecting long flow paths that have traveled vertically through hydrogeologic units with low vertical hydraulic conductivities.

The effects of the local, intermediate, and regional flow systems on the age of ground water are illustrated in two model sections (fig. 16D): A-A', which is along the general direction of ground-water flow from northeast to southwest, and B-B', which extends from the northwest to the southeast and is perpendicular to the general direction of ground-water flow except in the vicinity of the Columbia and Lewis Rivers. The presence of areas of young ground water directly overlying areas of older ground water is the result of local flow systems that do not fully penetrate the entire flow system (fig. 16D). Intermediate flow is seen in both sections A-A' where younger water enters in the interior portions of the basin and flows to adjacent streams and rivers. For example, the intermediate flow system in section A-A', which has a recharge area located about 6 miles southwest of the northeast edge of the section, may discharge to both Salmon Creek and the Columbia River (fig. 16D). The presence of regional flow underlying local and intermediate flow systems is seen in section A-A' of both minimum and maximum ages of ground water (fig. 16D). The ground water within the regional flow system increases in age from young water that recharges in areas to the northeast to old water that discharges in areas to the southwest.

The maps and model sections of ground-water age reflect the occurrence of regional ground-water discharge. The areas with the oldest maximum ground-water ages (greater than 10,000 years) in the unconsolidated sedimentary aquifer occur along the Columbia River west of the city of Ridgefield and south of the city of Camas (fig. 16A). These areas are underlain by hydrogeologic units containing water with a maximum age of at least greater than 1,000 years (figs. 16C–D), indicating that these are areas of regional ground-water discharge. However, ground water with a maximum age greater than 10,000 years is not present in the unconsolidated sedimentary aquifer in the area adjacent to the Columbia River between the cities of Ridgefield and Camas, although it is present in the underlying older rocks (compare figs. 16A, 16C, and 16D). This suggests that regional flow from parts of Clark County moves beneath the Columbia River to discharge areas south and west of the Columbia River.

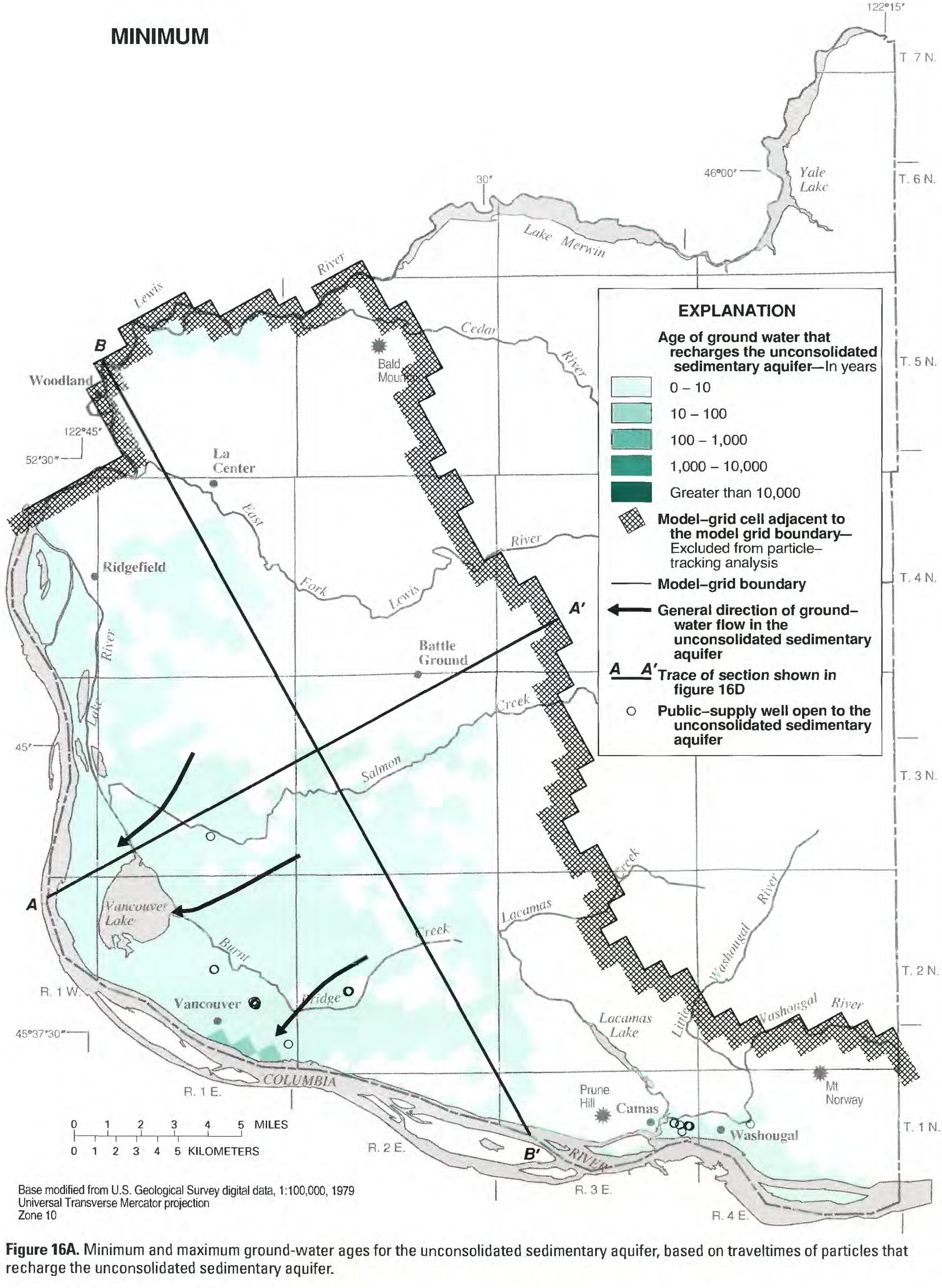
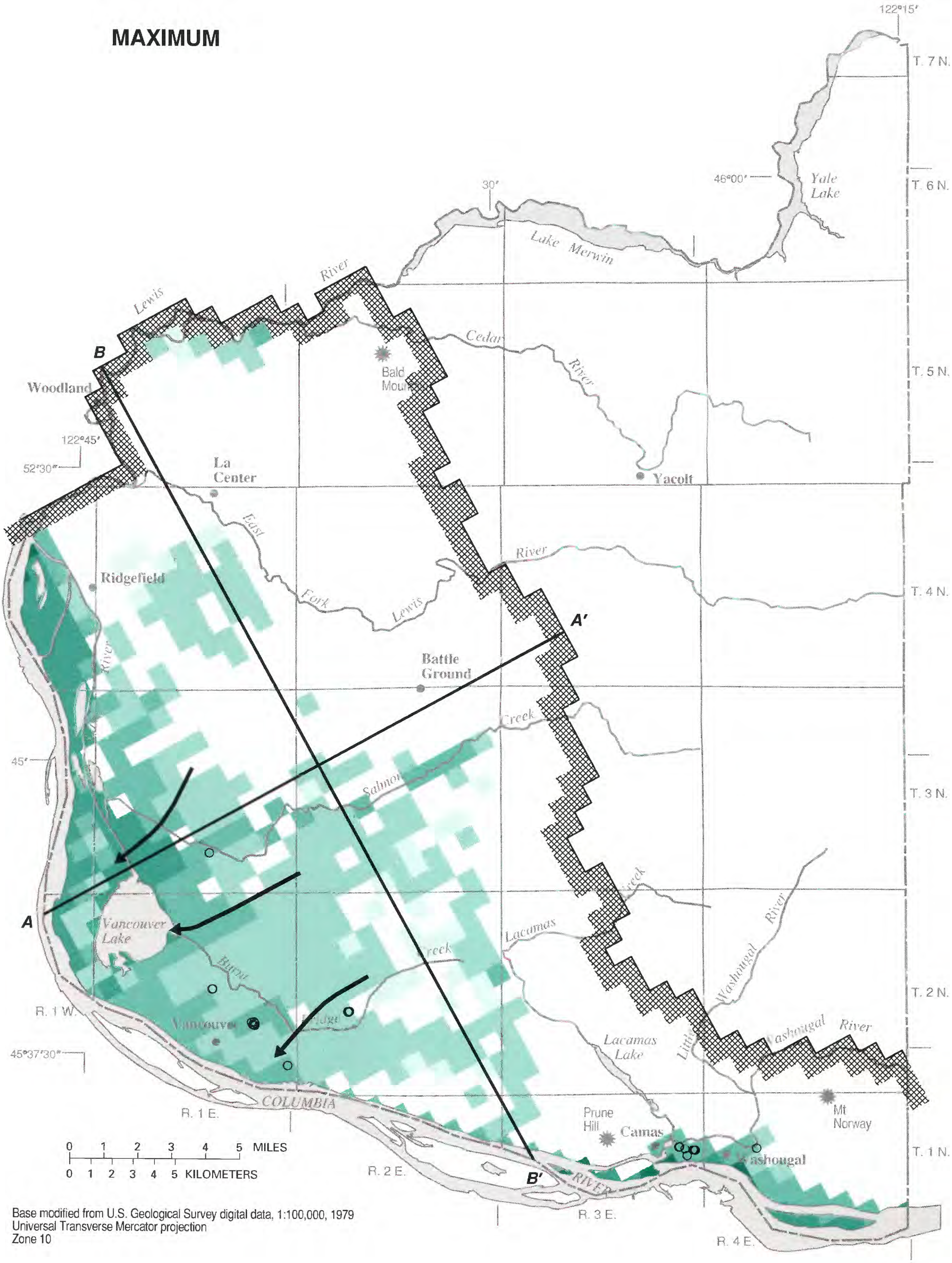


Figure 16A. Minimum and maximum ground-water ages for the unconsolidated sedimentary aquifer, based on traveltimes of particles that recharge the unconsolidated sedimentary aquifer.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1979
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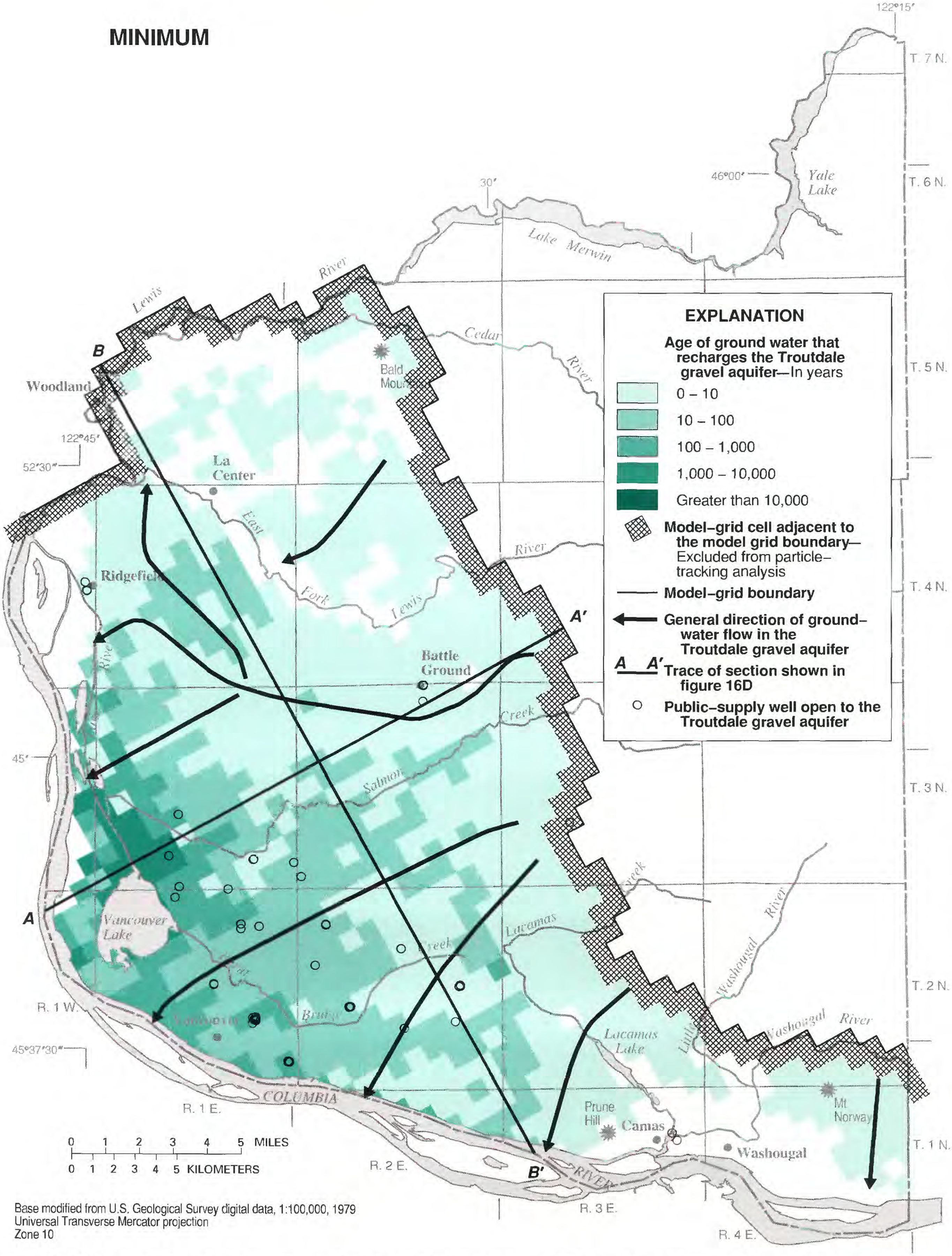
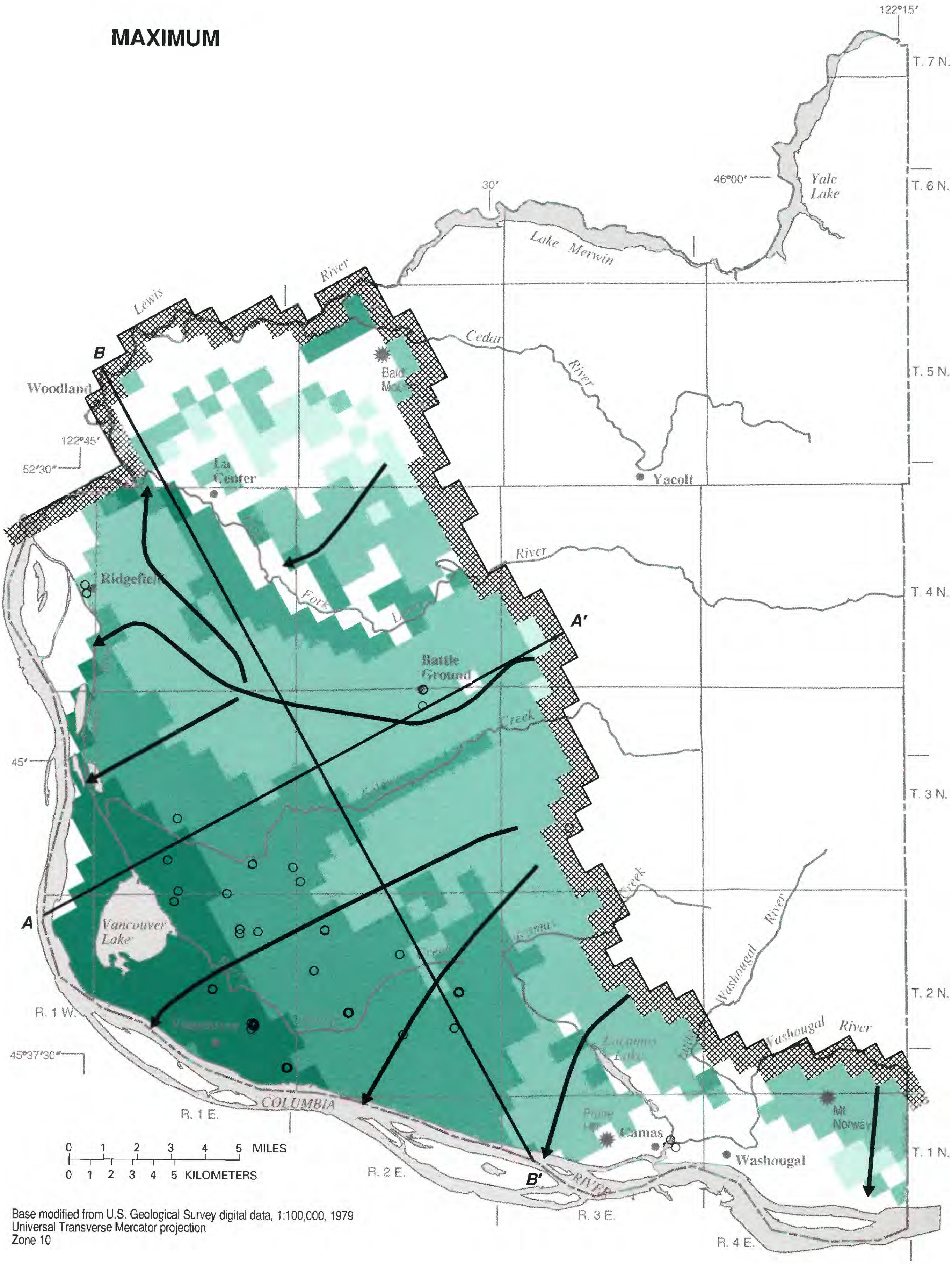


Figure 16B. Minimum and maximum ground-water ages for the Troutdale gravel aquifer, based on traveltimes of particles that recharge the Troutdale gravel aquifer.

MAXIMUM



Base modified from U.S. Geological Survey digital data, 1:100,000, 1979
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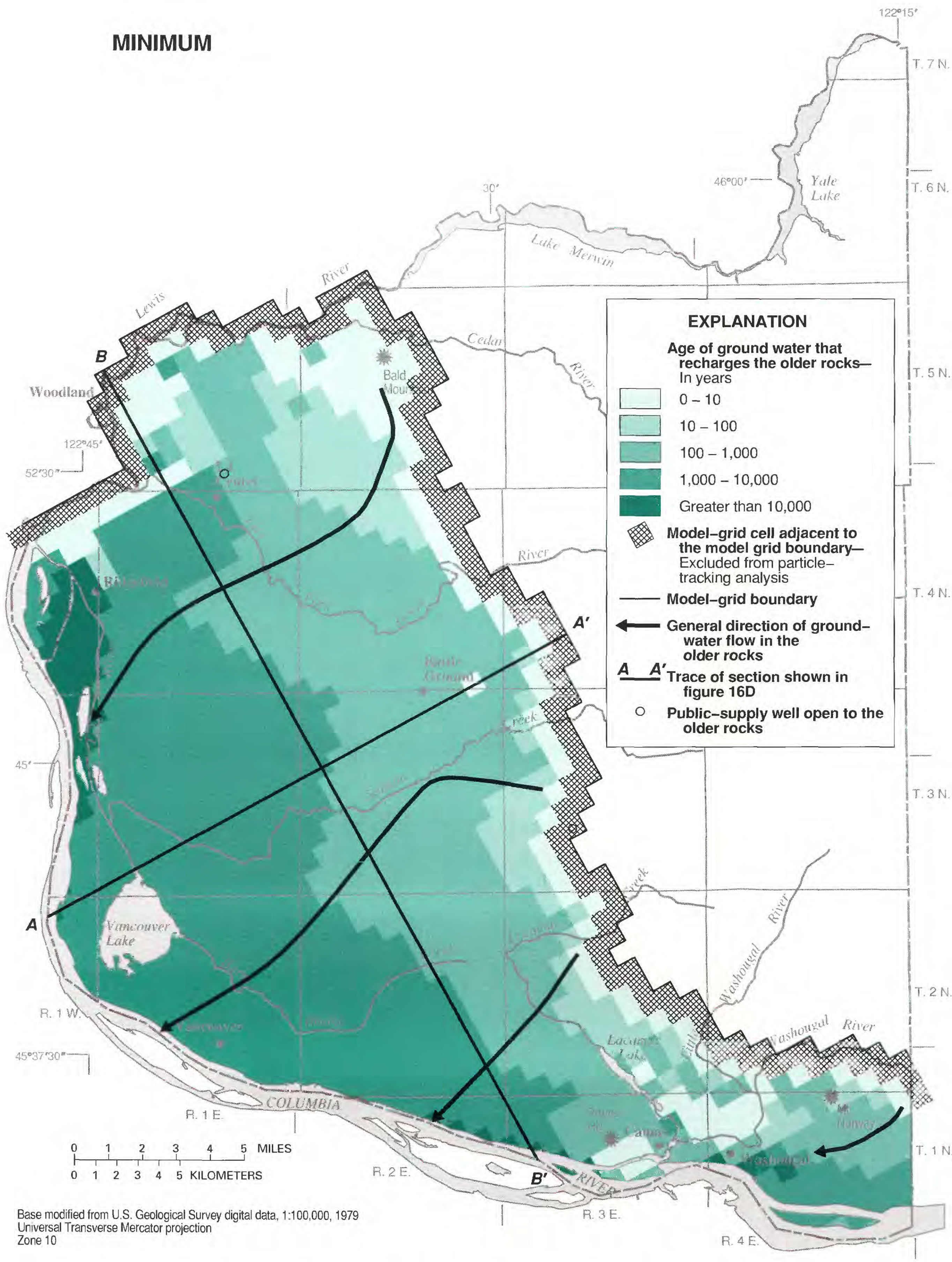
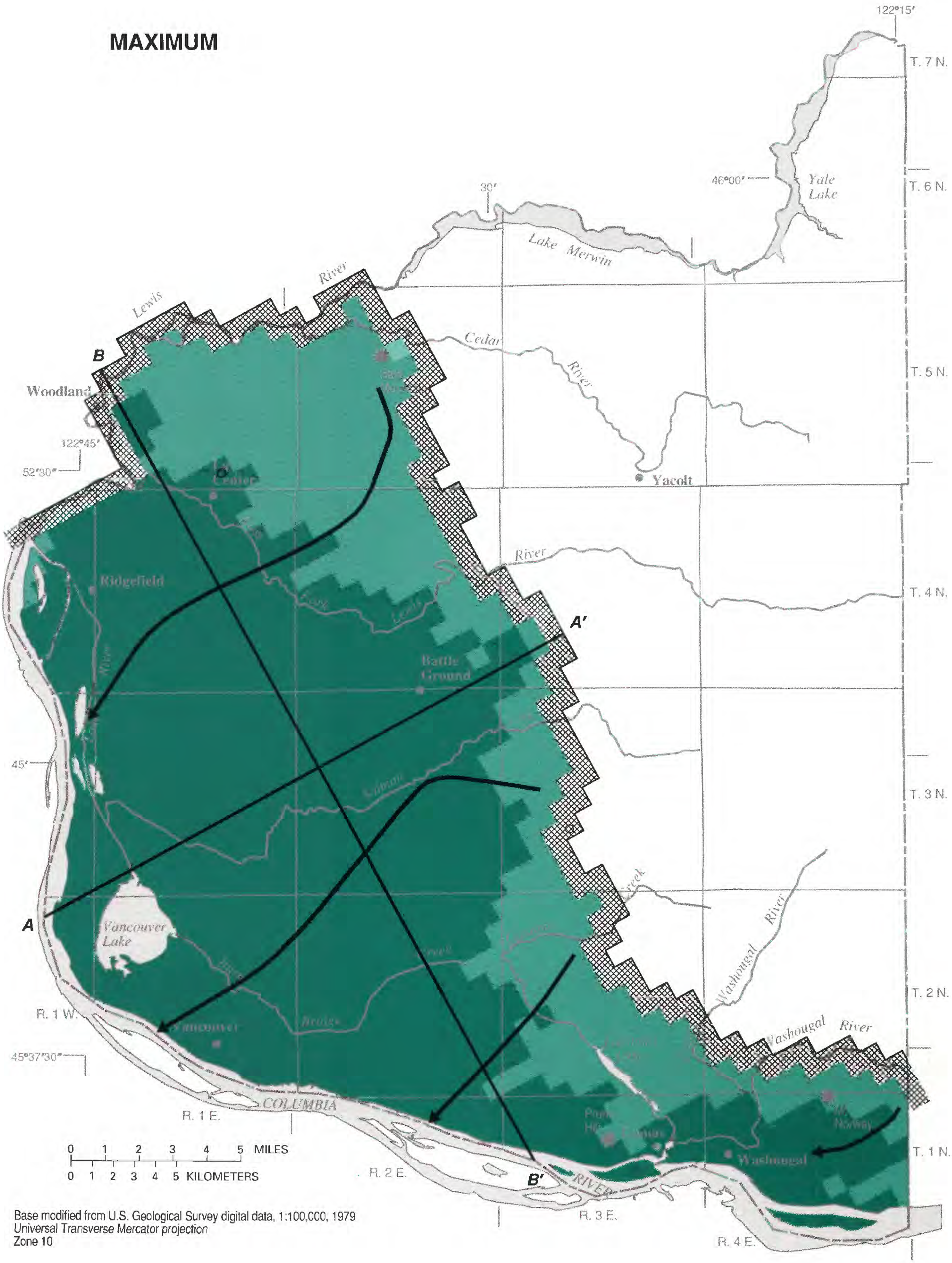


Figure 16C. Minimum and maximum ground-water ages for the older rocks, based on traveltimes of particles that recharge the older rocks.



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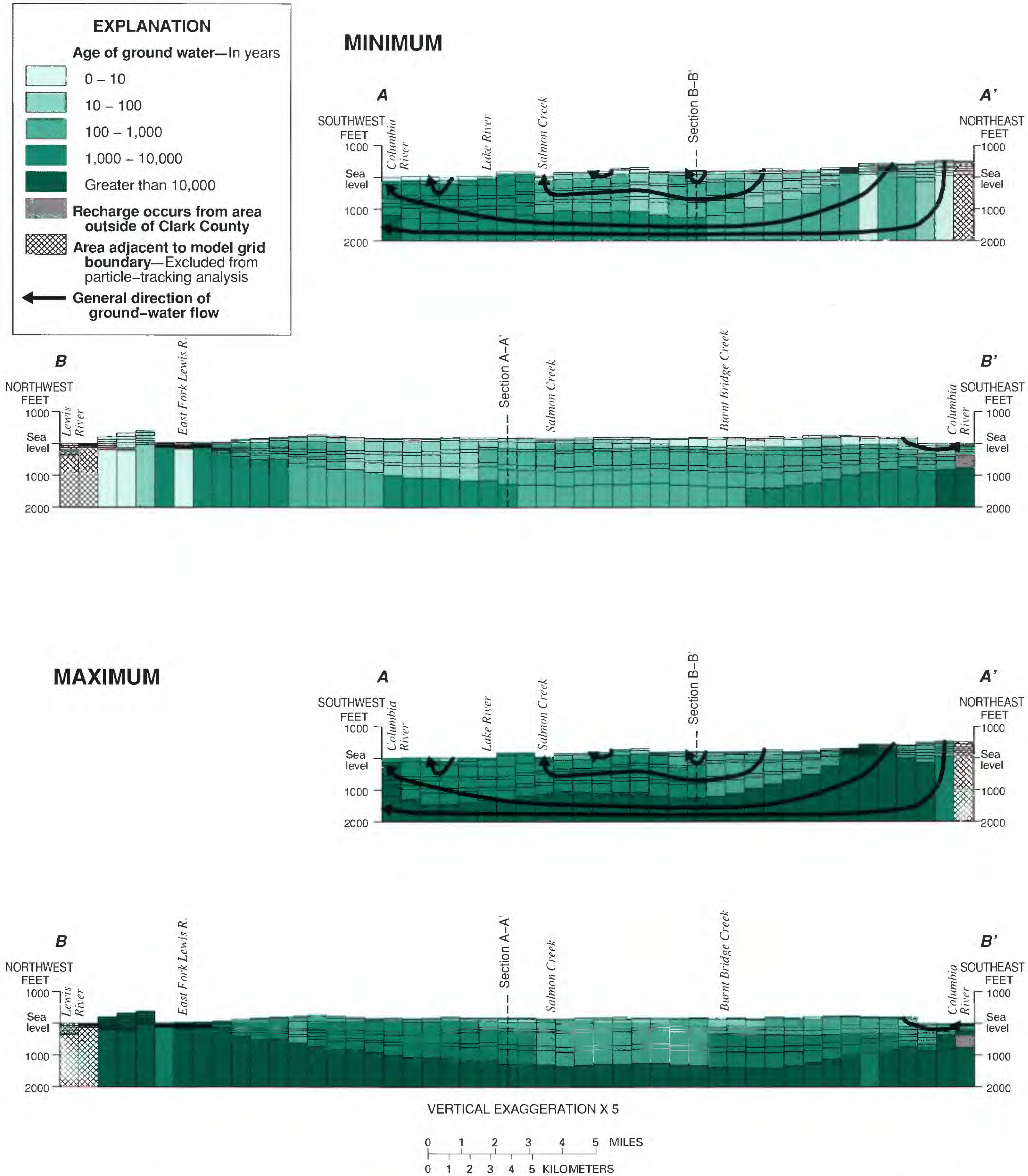

Figure 16D. Model sections showing minimum and maximum ground-water ages for the model cells along the sections, based on traveltimes of particles that recharge the model cells along the sections. (See section locations shown in figures 16A–C.)

As yet unpublished, results from other analyses using the ground-water flow model and particle-tracking program also indicate that the regional flow moves upward from the older rocks, beneath the Columbia River, through the overlying units, and discharges at the water table west of the Columbia River in the area of Sauvie Island between the Multnomah Channel and the Columbia River, between the Willamette River and the Columbia Slough, and between the Columbia Slough and the Columbia River (fig. 1).

Comparison of the maps of ground-water ages in a hydrogeologic unit with the location of public-supply wells open to that unit can be used to identify public-supply wells that may be withdrawing water that recharged in areas that may have been exposed to contamination. The public-supply wells in southwestern Clark County and in the vicinity of Camas and Washougal that are open to the unconsolidated sedimentary aquifer may be withdrawing water that has a component that is less than 10 years old on the basis of the minimum ground-water age (fig. 16A). A large number of the wells open to the Troutdale gravel aquifer may be discharging water that is less than 100 years old, and some of these may discharge water less than 10 years old (fig 16B).

A comparison of the locations of wells containing anthropogenically contaminated ground water in Clark County with the age of ground water, as determined by the particle-tracking program, provided a valuable check on the reliability and usefulness of this method for evaluating ground-water vulnerability. From a sampling of 20 wells in Clark County in 1988, Turney (1990) found substantial concentrations of organic compounds (including pesticides) in samples from 4 wells and the detection of trace levels of organic compounds in 6 other wells. Turney (1990) also reported that the Washington State Department of Social and Health Services had detected trace levels of organic compounds in samples collected in 1988 from two additional wells. Of the 12 wells that showed the presence of organic compounds, 10 are located within the area of the ground-water flow model. The particle-tracking program calculated a minimum ground-water age of less than 100 years for the water within the model cells representing the open intervals for 8 of the 10 wells. The minimum ground-water ages for the other two wells were calculated to be less than about 170 years. Turney (1990) states that "*** the presence of any of these organic compounds in ground water is due to anthropogenic activities and indicates some degree of contamination." The agreement between the occurrence of anthropogenic contamination in areas of the ground-water flow system where the ground water is young suggests that ground-water age is an important factor to consider when evaluating ground-water vulnerability.

SUMMARY AND CONCLUSIONS

A three-dimensional, regional ground-water flow model of the Portland Basin, Oregon and Washington (including most of Clark County), constructed using MODFLOW during a previous USGS study, was used in this investigation. This model was used with the particle-tracking program MODPATH to calculate three-dimensional pathlines and traveltimes of water particles moving through the simulated flow system. MODPATH was modified for this study to output data and results in the form of GIS (ARC/INFO) digital maps. These digital maps have associated digital attribute files that contain information such as starting and ending particle positions, hydrogeologic unit, traveltime, distance, and velocity. The modified version of MODPATH, known as MODTOOLS, does not change the method used to calculate particle pathlines or attributes, but enhances the ability to display and analyze the results of the particle-tracking program. This is a significant improvement, because it enables the use of the database, statistical, and display capabilities of the GIS and facilitates comparison with other types of spatial information.

For the particle-tracking analysis, each of the greater than 10,000 active model-grid cells in Clark County was populated with 6 particles, one at the center of each cell face, resulting in a total of about 60,000 particles. The particle-tracking program was used to track each particle backwards in time, through the simulated flow system, upgradient to its recharge point. The GIS then was used to select recharge points for specific parts of the ground-water flow system, summarize traveltime information, and relate characteristics of the recharge areas to downgradient parts of the flow system.

Chlorofluorocarbon (CFC)-age dating was used to compare traveltime estimates with the results of the particle-tracking program at 51 wells in the Portland Basin. There was a 76 percent agreement in predicting the presence of modern water in the 51 wells, as determined by using CFC-age dating and particle-tracking techniques. The effective porosity values used for the particle-tracking program were calibrated by comparing ground-water ages determined through the use of the CFC-age dating with ground-water ages calculated by the particle-tracking program, using different values of effective porosity. On the basis of results of these analyses, values of effective porosity of 1.09 times the baseline values provided the best agreement between the ground-water ages determined by the particle-tracking program and the CFC-age dates.

Recharge points for each hydrogeologic unit generally coincide with topographic highs or outcrops of the unit. Maps of the recharge points for each hydrogeologic unit were then overlaid with maps depicting aquifer sensitivity, as determined by DRASTIC (a measure of the pollution potential of ground water, based on the intrinsic characteristics of the near-surface unsaturated and saturated zones) and recharge from on-site waste-disposal systems. A large number of recharge areas were identified, particularly in southern Clark County, that have a high aquifer sensitivity, coincide with areas of recharge from on-site waste-disposal systems, or both.

Using the GIS, the characteristics of the recharge areas were related to the downgradient parts of the ground-water system that will eventually receive flow that has recharged through these areas. The aquifer sensitivity, as indicated by DRASTIC, of the recharge areas for downgradient parts of the flow system was mapped for each hydrogeologic unit. A number of public-supply wells in Clark County may be receiving a component of water that recharged in areas that are more conducive to contaminant entry. These maps illustrate a critical deficiency in the DRASTIC methodology—the failure to account for the dynamics of the ground-water flow system. DRASTIC indices calculated for a particular location thus do not necessarily reflect the conditions of the ground-water resources at the recharge areas for that particular location. Each hydrogeologic unit was also mapped to highlight those areas that will eventually receive flow from recharge areas with on-site waste-disposal systems. Most public-supply wells in southern Clark County may eventually receive a component of water that contains recharge from on-site waste-disposal systems.

Traveltimes for ground water were used to estimate the minimum and maximum age of ground water within each model-grid cell for all the hydrogeologic units. Areas with the youngest ground-water ages are expected to be at greatest risk to contamination from anthropogenic activities. Comparison of these maps with maps of public-supply wells in Clark County indicates that most of these wells may withdraw ground water that has a component less than 100 years old and, in many instances, less than 10 years old. Eight of 10 wells shown in previous studies to have water containing anthropogenic contamination were calculated to have a minimum ground-water age of less than 100 years, as calculated by the particle- tracking program. The agreement between the location of anthropogenic contamination with areas of the ground-water flow system where the ground water is young provides a valuable check on the reliability and usefulness of the particle-tracking program, and indicates that ground-water age is an important factor to consider when evaluating ground-water vulnerability.

The study was based on assumptions and limitations similar to those of the ground-water flow model (Morgan and McFarland, 1996) and the particle-tracking program. Among these assumptions is the simulation of the ground-water flow system as steady state using the 1987–88 time-averaged conditions such as climate, land use, and water use. Care must be used when interpreting the results, as changes in any of these conditions will influence the location of recharge areas, pathlines, and the age of ground water.

Results show that a single particle-tracking analysis simulating advective transport can be used to evaluate ground-water vulnerability for all or part of a ground-water flow system. This method can be applied to evaluate current ground-water resources, such as prioritizing wells for site-specific evaluation or upgradient water-quality monitoring, or to aid in the evaluation of undeveloped areas. The method can be used at any scale or discretization, and is directly transferable to other areas that use MODFLOW to simulate ground-water flow systems. Using the particle-tracking program with all of the cells in the ground-water flow model (or at least in the area of interest, such as Clark County) populated with particles and storing the results in a GIS format precludes, or at least reduces, the need to perform multiple particle-tracking analyses for distinct areas. GIS personnel and resource managers could select the parts of the ground-water flow system of interest and compare the results of the particle-tracking analysis with ancillary information stored in the GIS to determine recharge areas, characteristics of recharge areas, downgradient impact of land use at recharge areas, and age of ground water. This increased accessibility, combined with the flexibility of GIS, will facilitate the application of ground-water vulnerability analyses and ground-water modeling to the management of ground-water resources.

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APPENDIX A

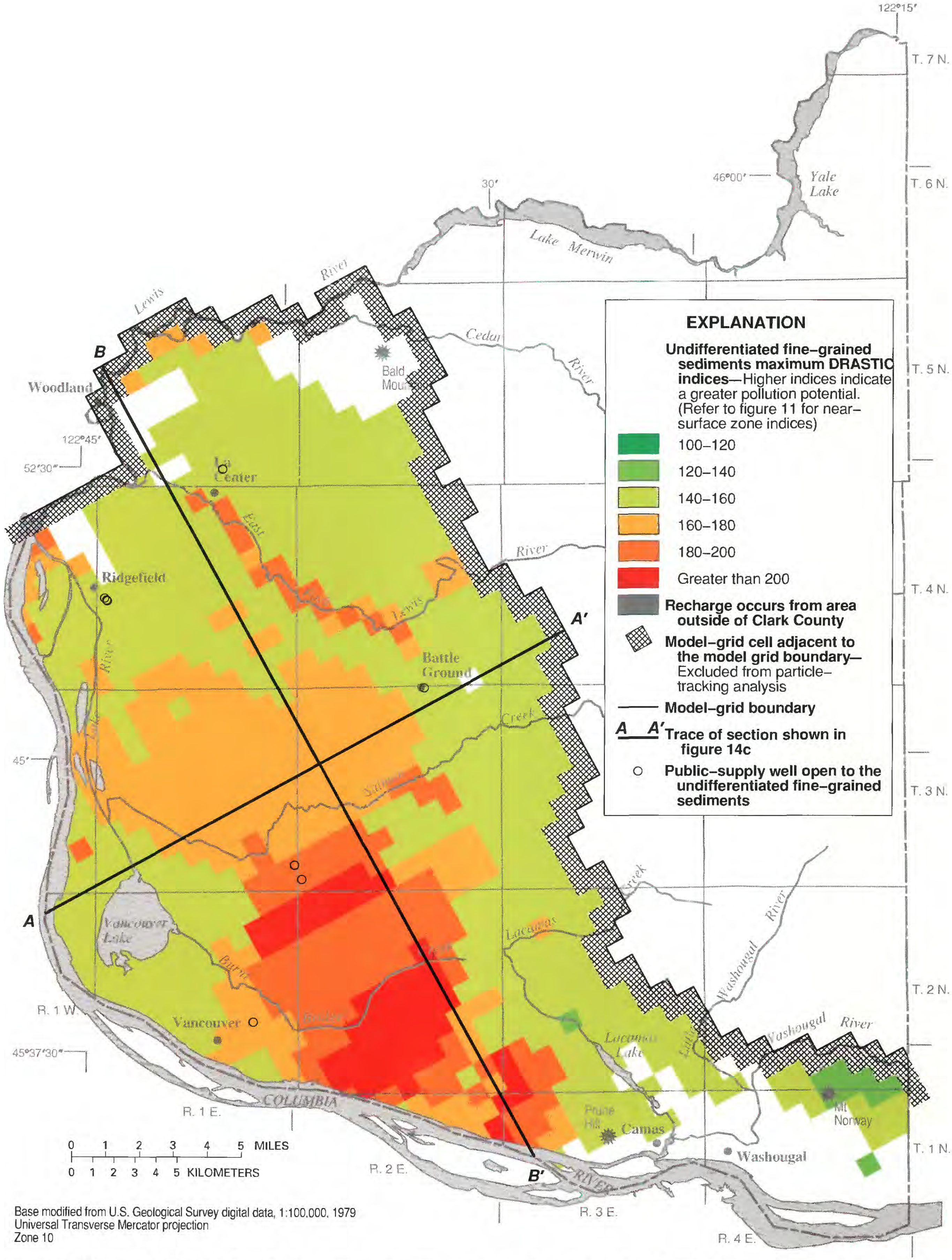


Figure A–1. Maximum DRASTIC indices for the undifferentiated fine-grained sediments, based on DRASTIC indices where particles recharge the undifferentiated fine-grained sediments.

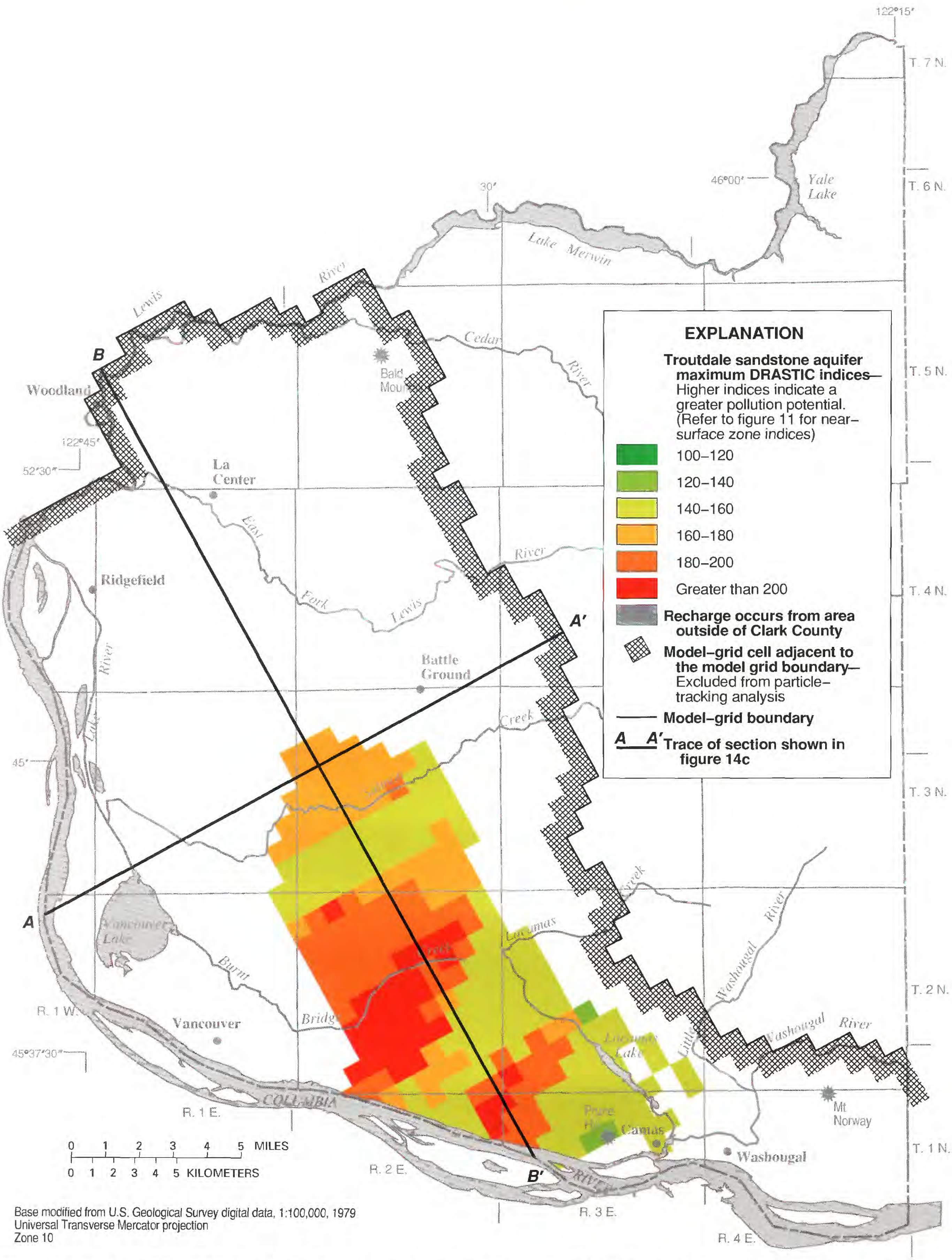


Figure A–2. Maximum DRASTIC indices for the Troutdale sandstone aquifer, based on DRASTIC indices where particles recharge the Troutdale sandstone aquifer.

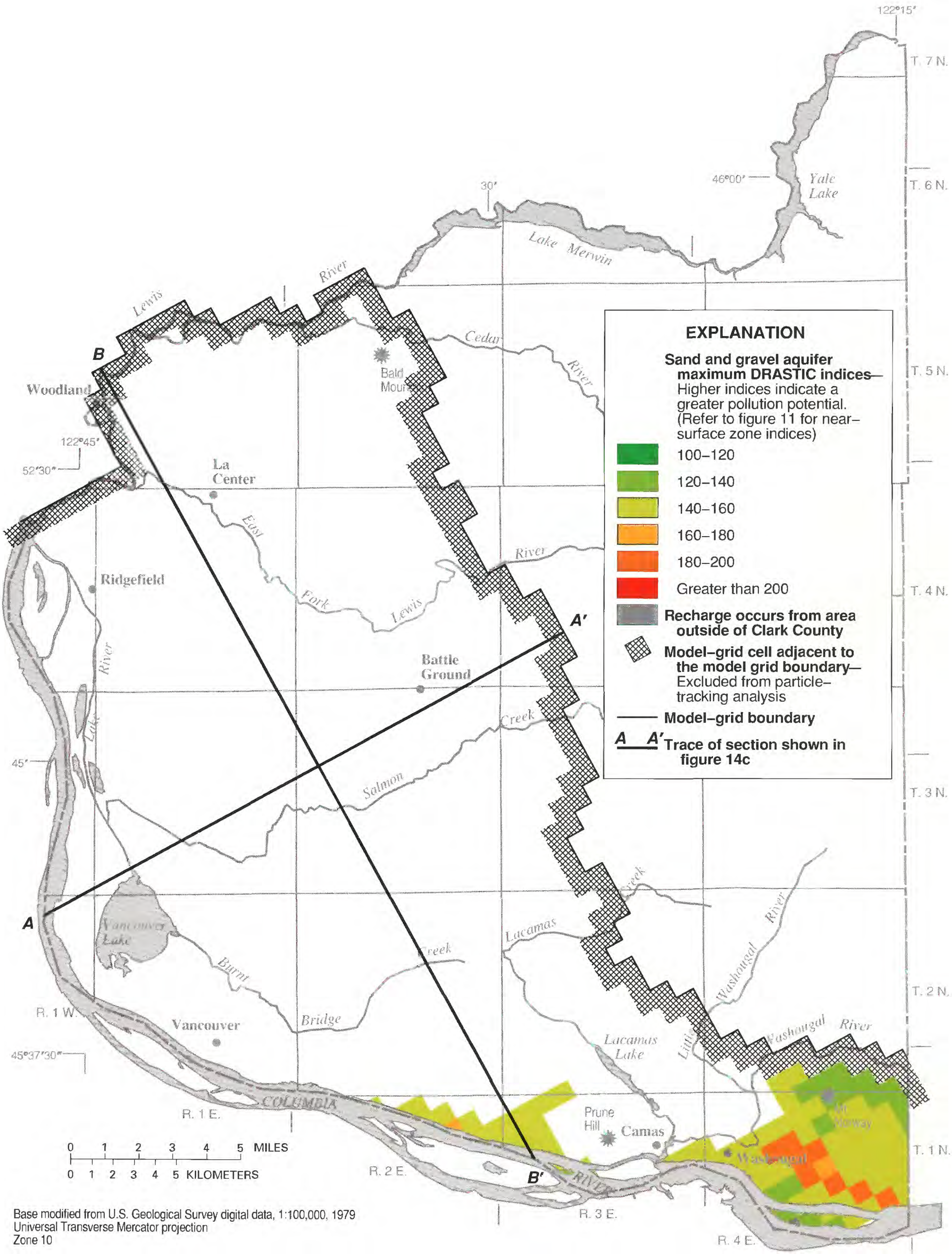


Figure A–3. Maximum DRASTIC indices for the sand and gravel aquifer, based on DRASTIC indices where particles recharge the sand and gravel aquifer.

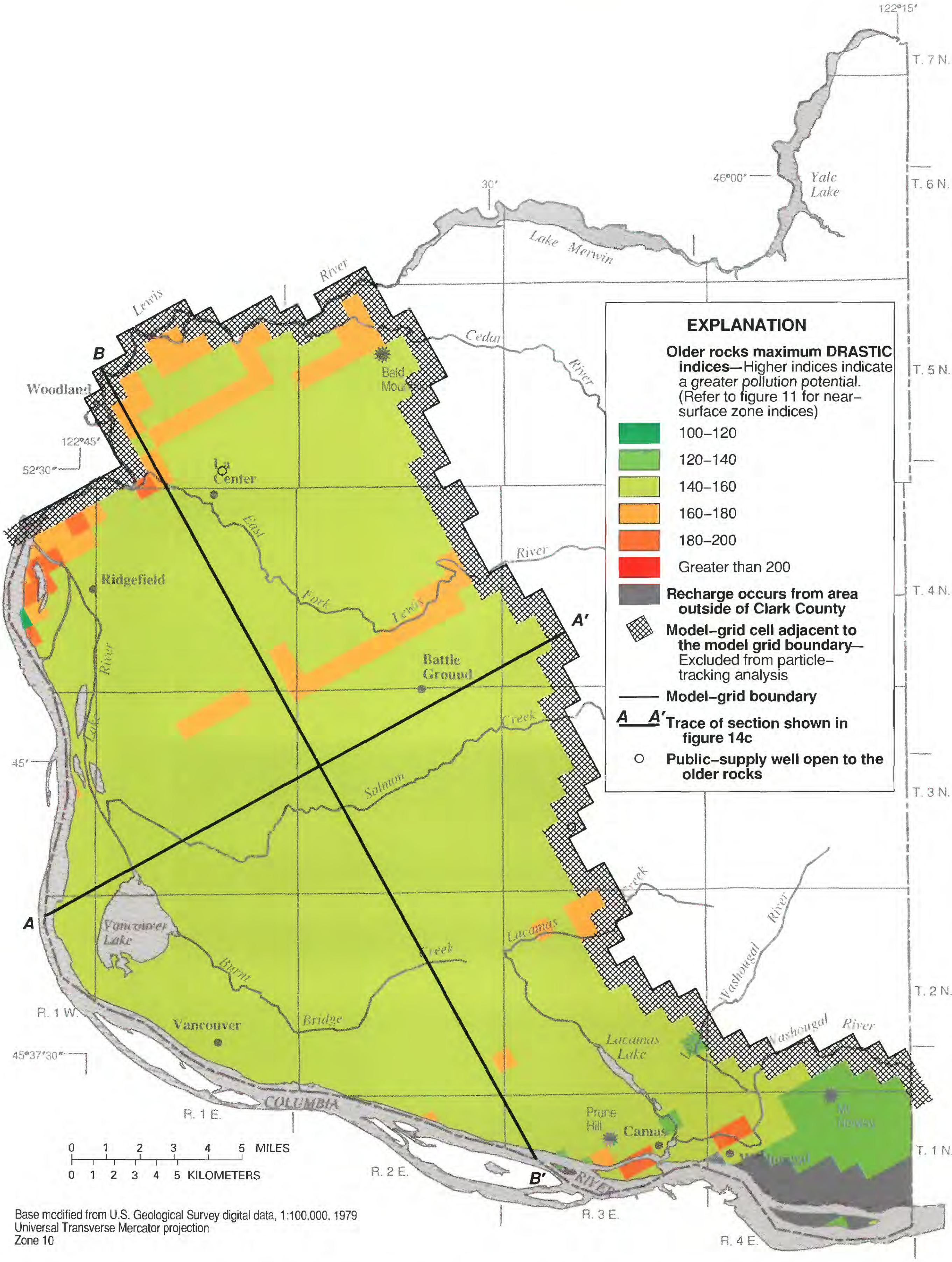


Figure A–4. Maximum DRASTIC indices for the older rocks, based on DRASTIC indices where particles recharge the older rocks.

APPENDIX B

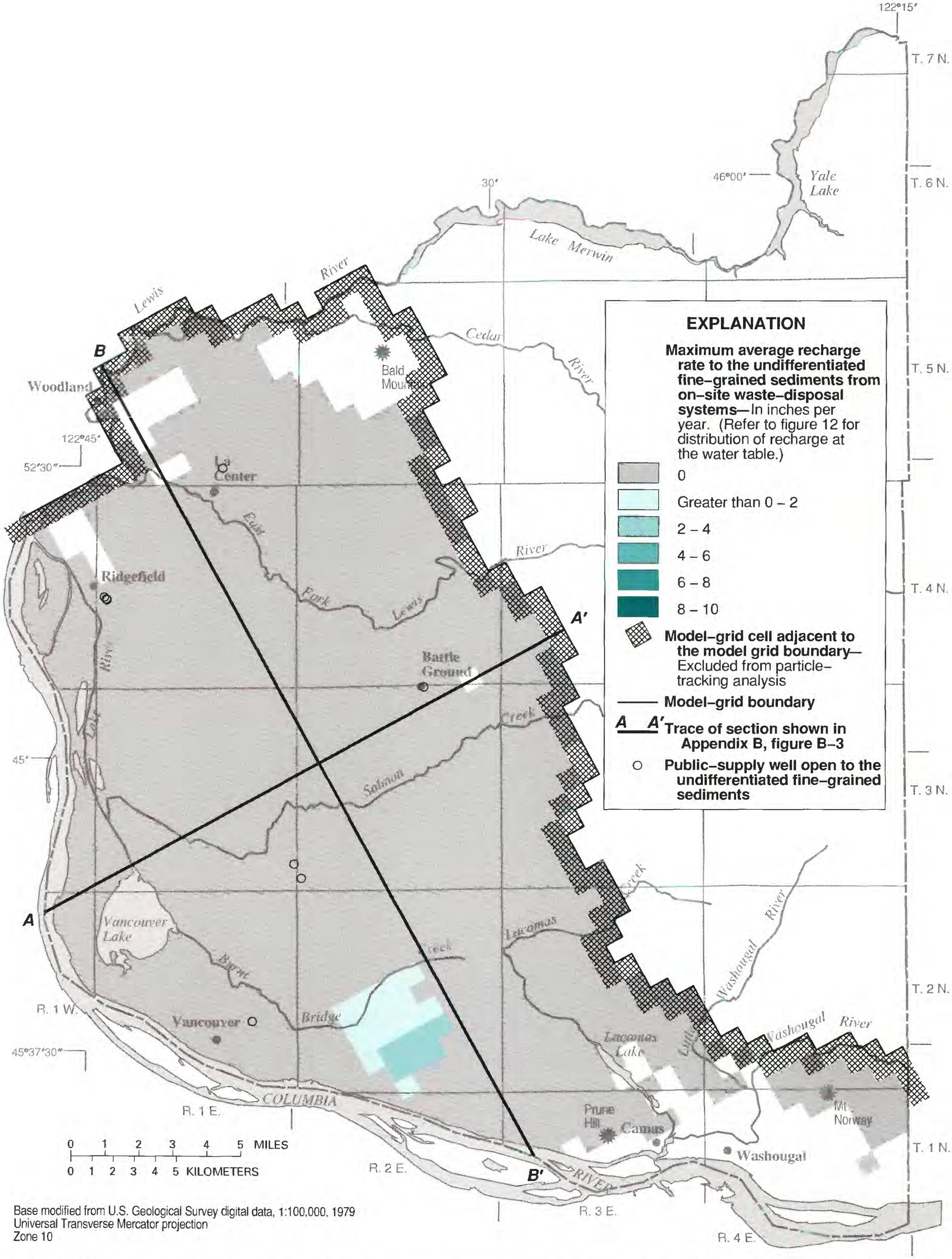


Figure B–1. Maximum average recharge rates from on-site waste-disposal systems at the water table for the undifferentiated fine-grained sediments, based on particles that recharge the undifferentiated fine-grained sediments.

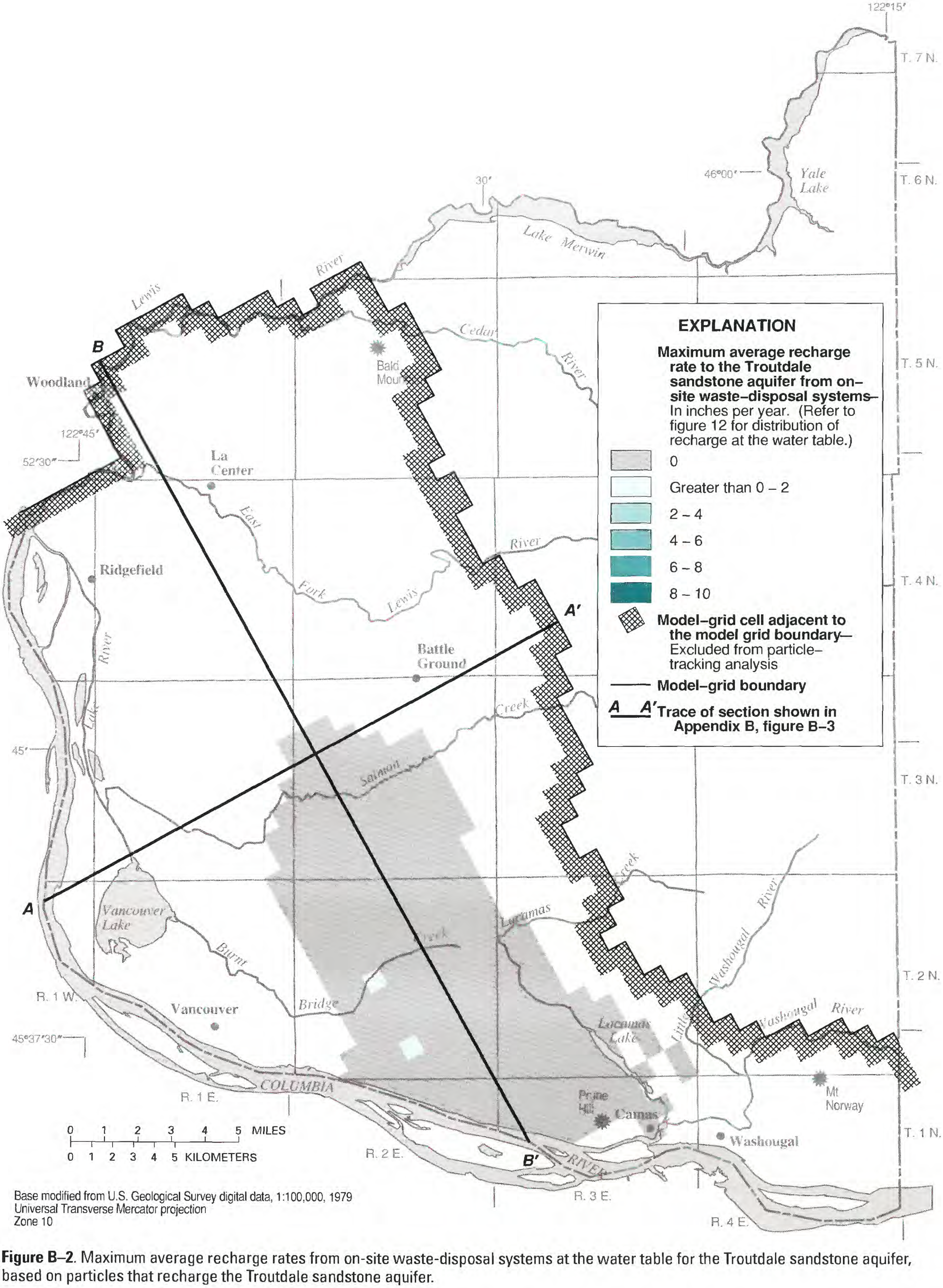


Figure B–2. Maximum average recharge rates from on-site waste-disposal systems at the water table for the Troutdale sandstone aquifer, based on particles that recharge the Troutdale sandstone aquifer.

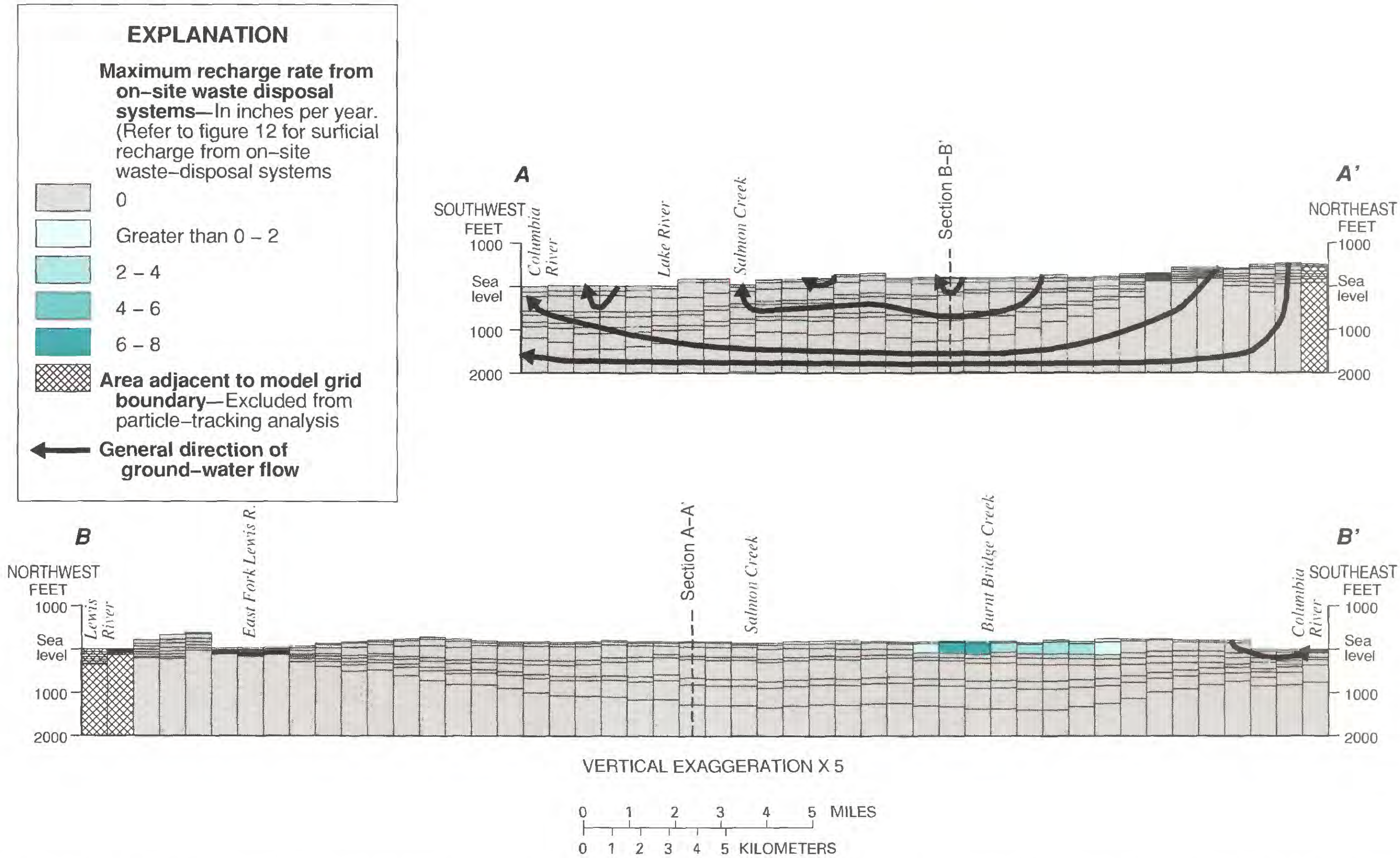


Figure B–3. Model sections showing maximum average recharge rates from on-site waste-disposal systems at the water table for the model cells along the sections, based on particles that recharge the model cells along the sections. (Section locations shown on Appendix B, figures B–1 and B–2.)

APPENDIX C

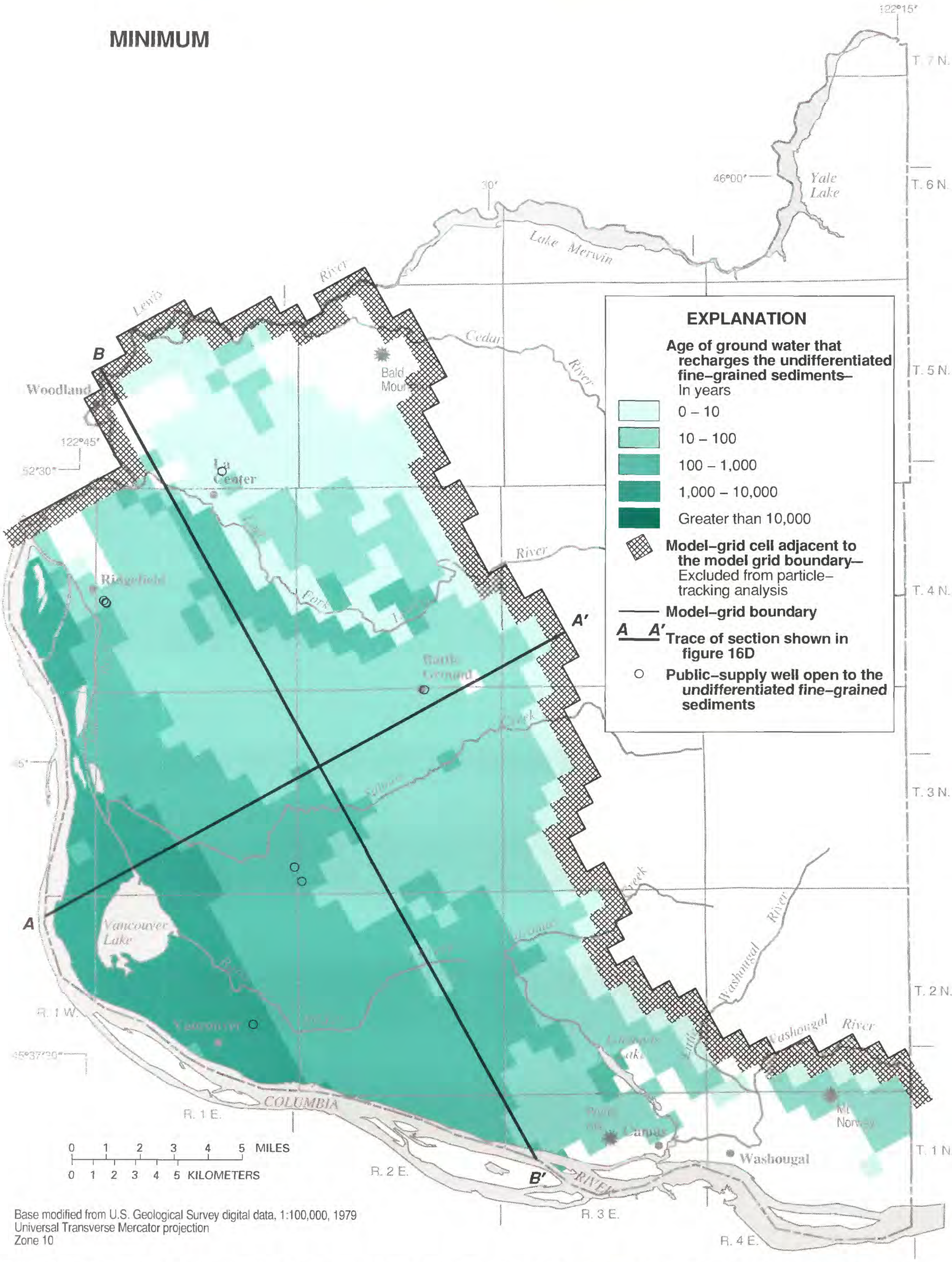
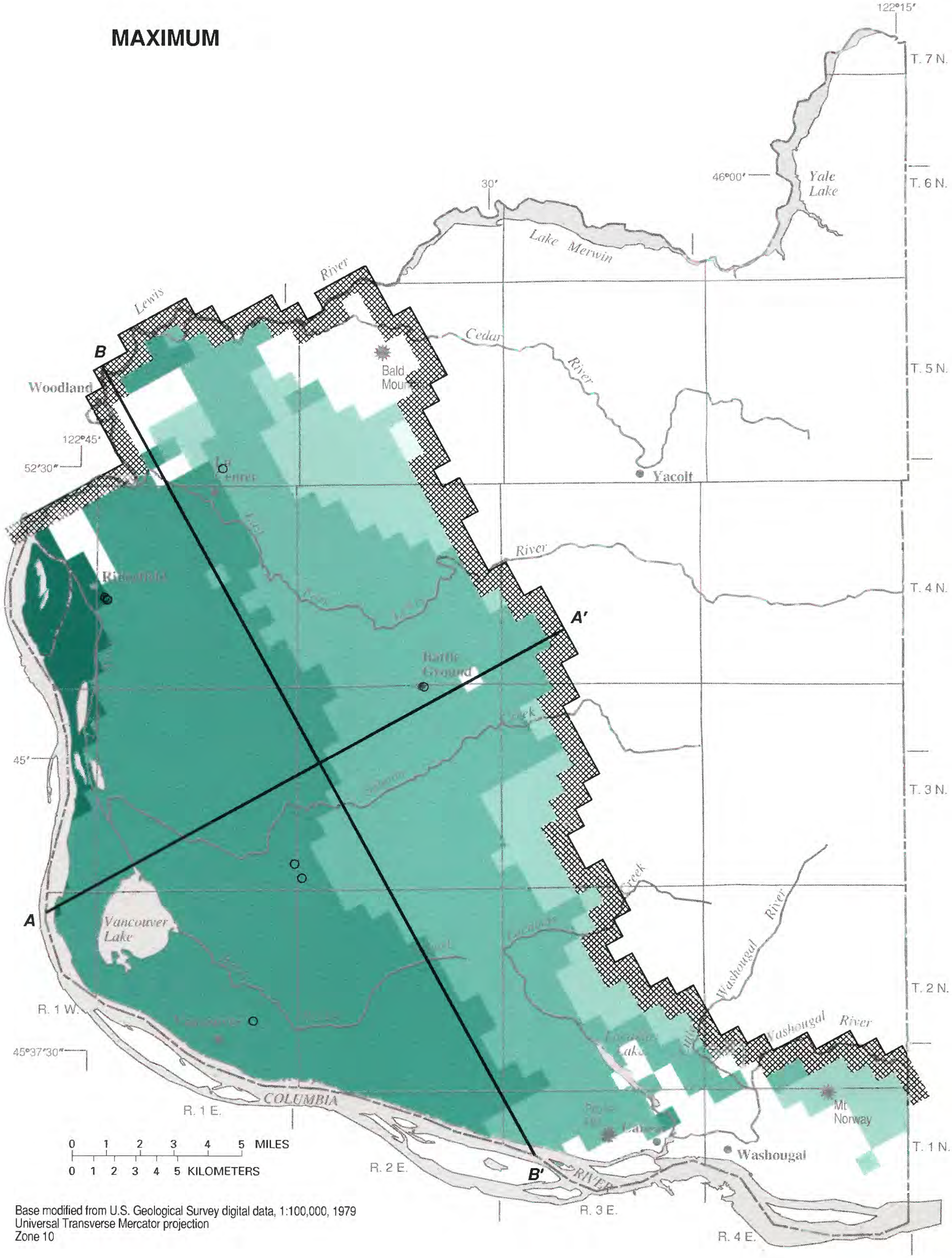


Figure C–1. Minimum and maximum ground-water ages for the undifferentiated fine-grained sediments, based on traveltimes of particles that recharge the undifferentiated fine-grained sediments.

MAXIMUM



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Zone 10

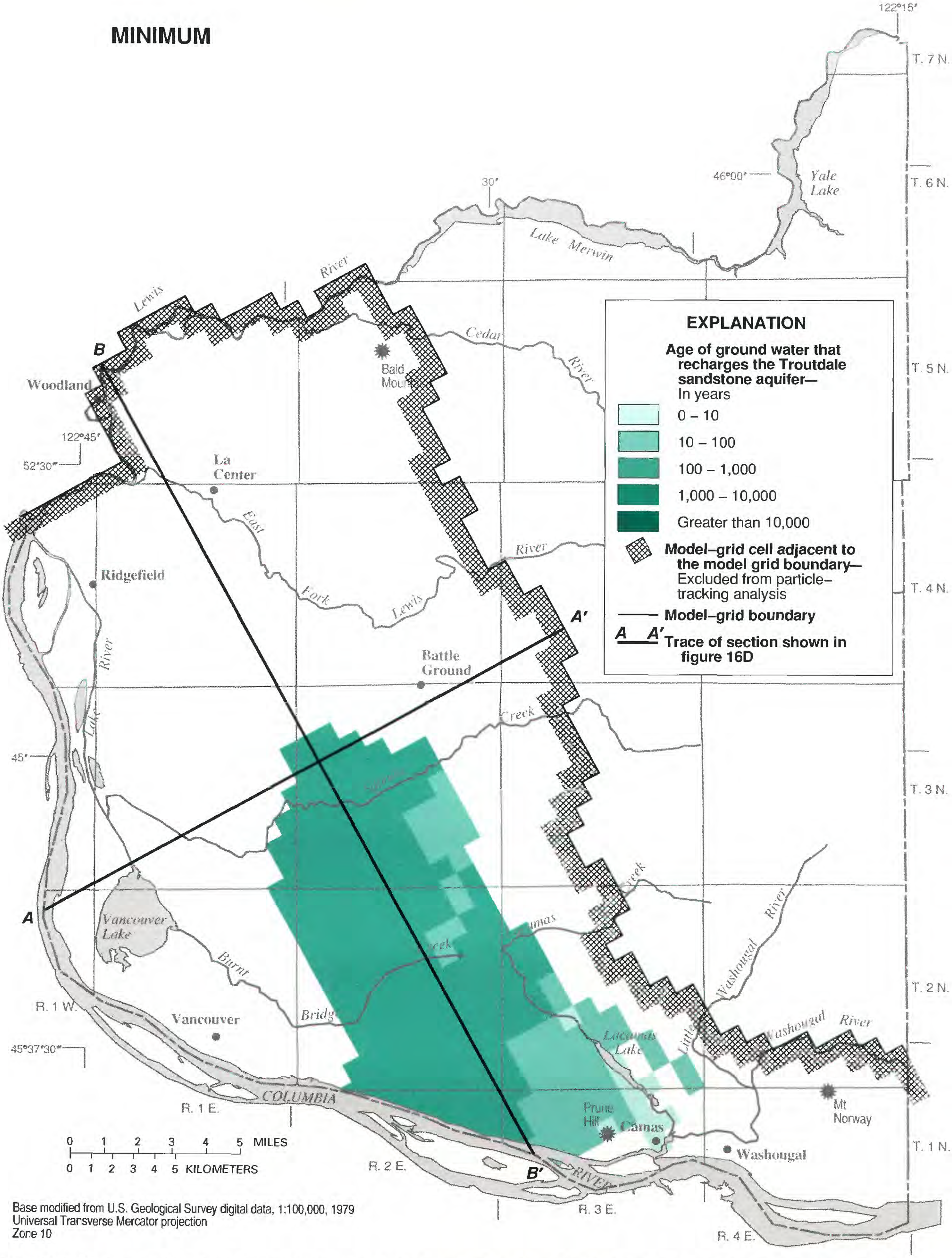
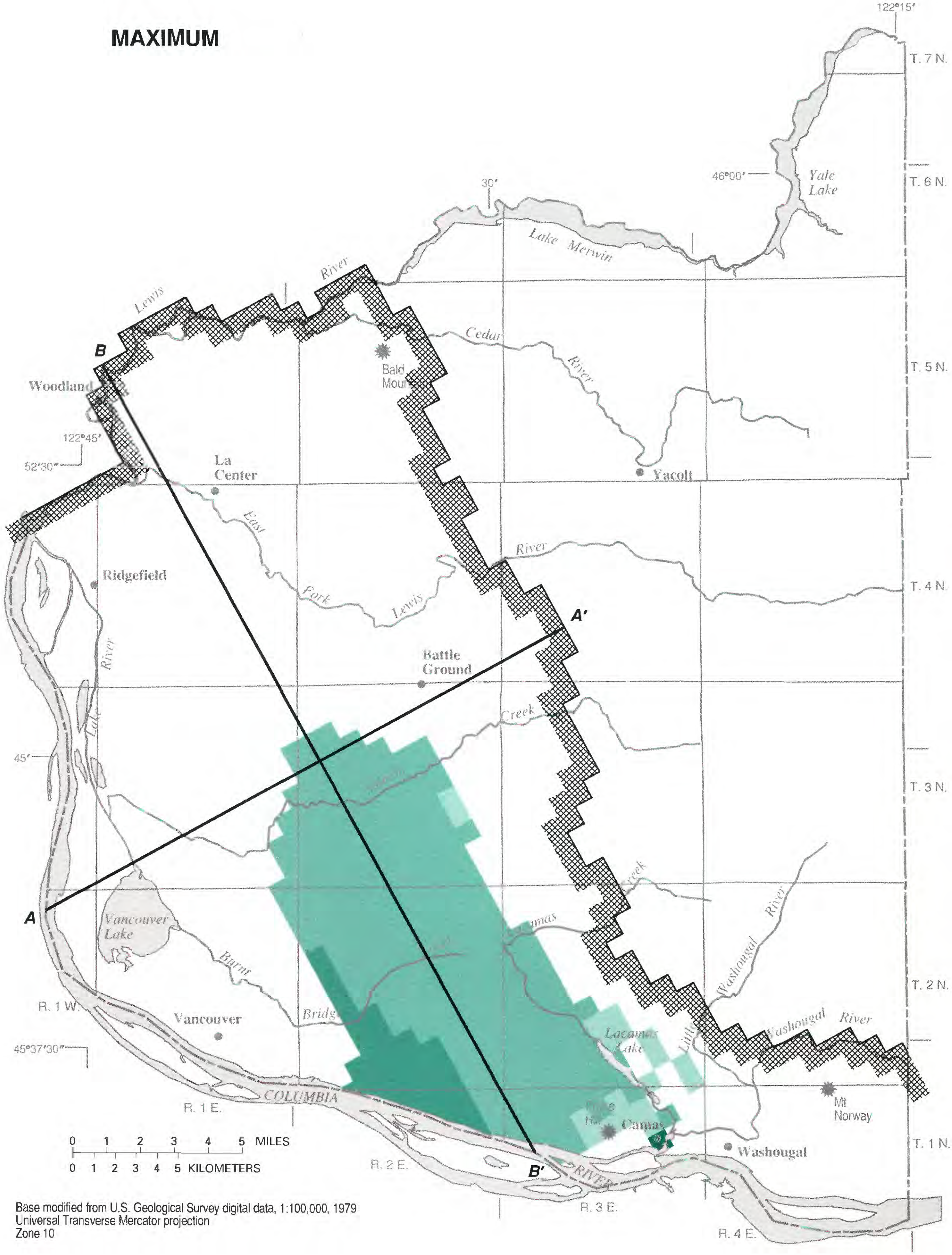


Figure C–2. Minimum and maximum ground-water ages for the Troutdale sandstone aquifer, based on traveltimes of particles that recharge the Troutdale sandstone aquifer.

MAXIMUM



Base modified from U.S. Geological Survey digital data, 1:100,000, 1979
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MINIMUM

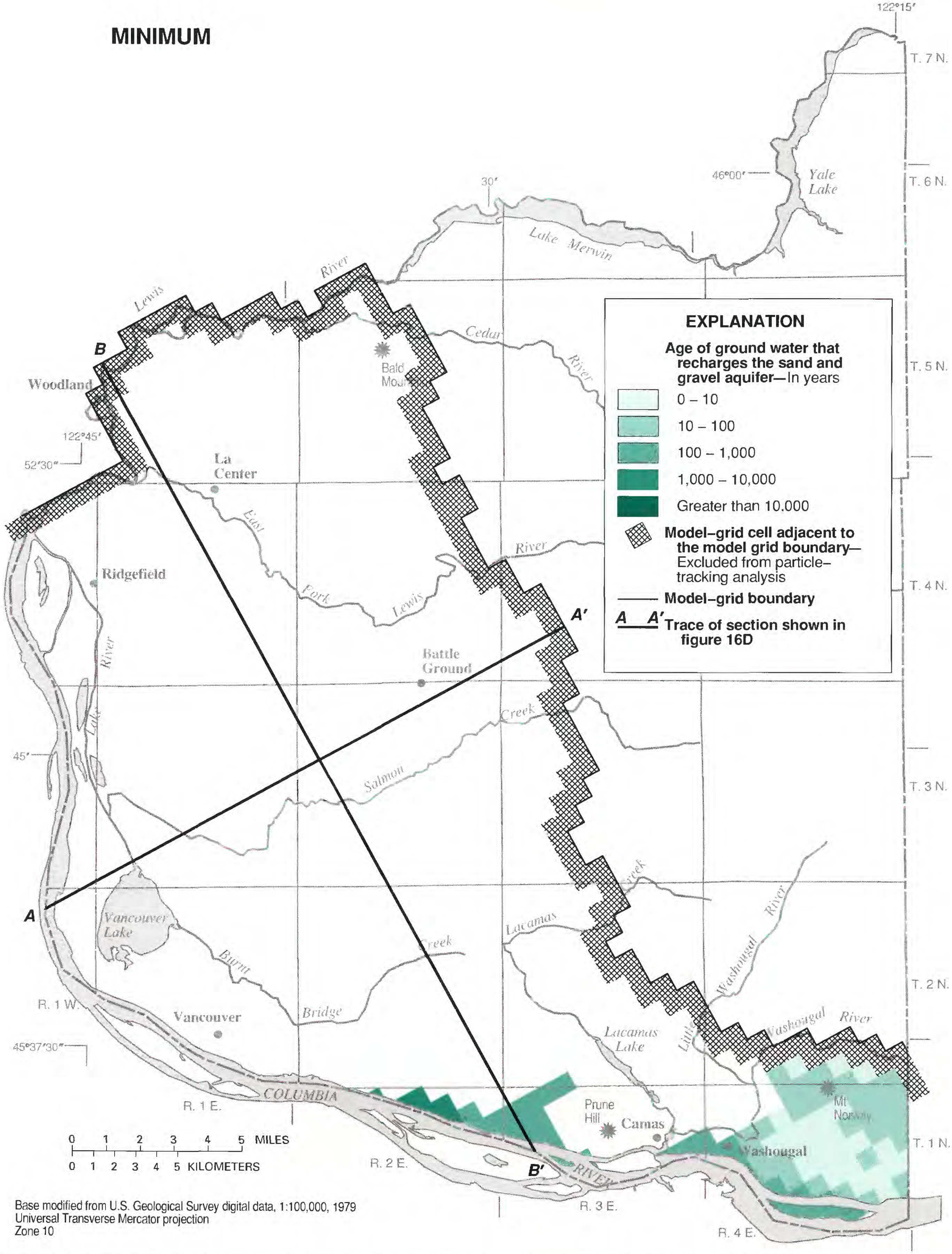
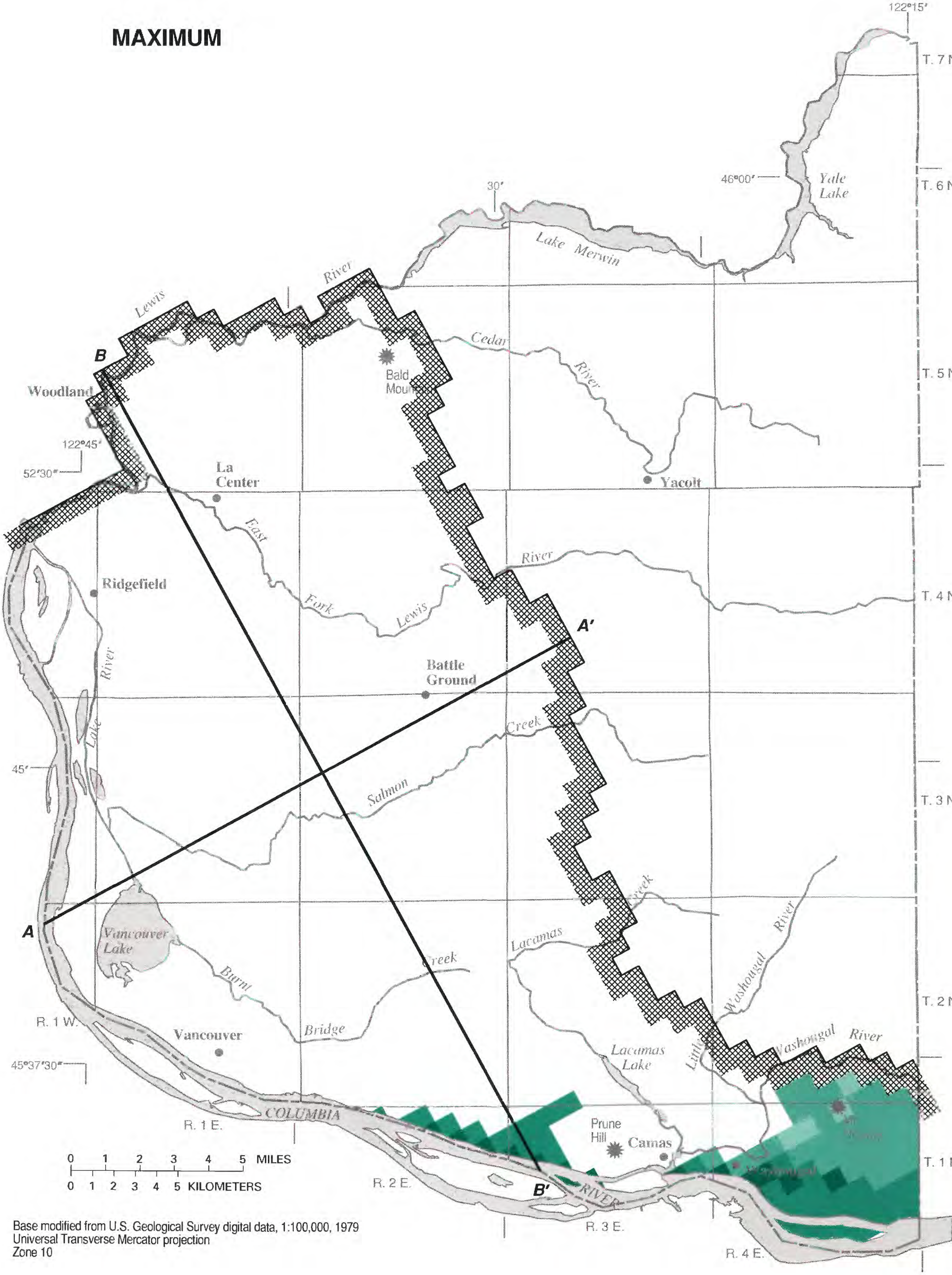


Figure C–3. Minimum and maximum ground-water ages for the sand and gravel aquifer, based on traveltimes of particles that recharge the sand and gravel aquifer.

MAXIMUM



Base modified from U.S. Geological Survey digital data, 1:100,000, 1979
Universal Transverse Mercator projection
Zone 10

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