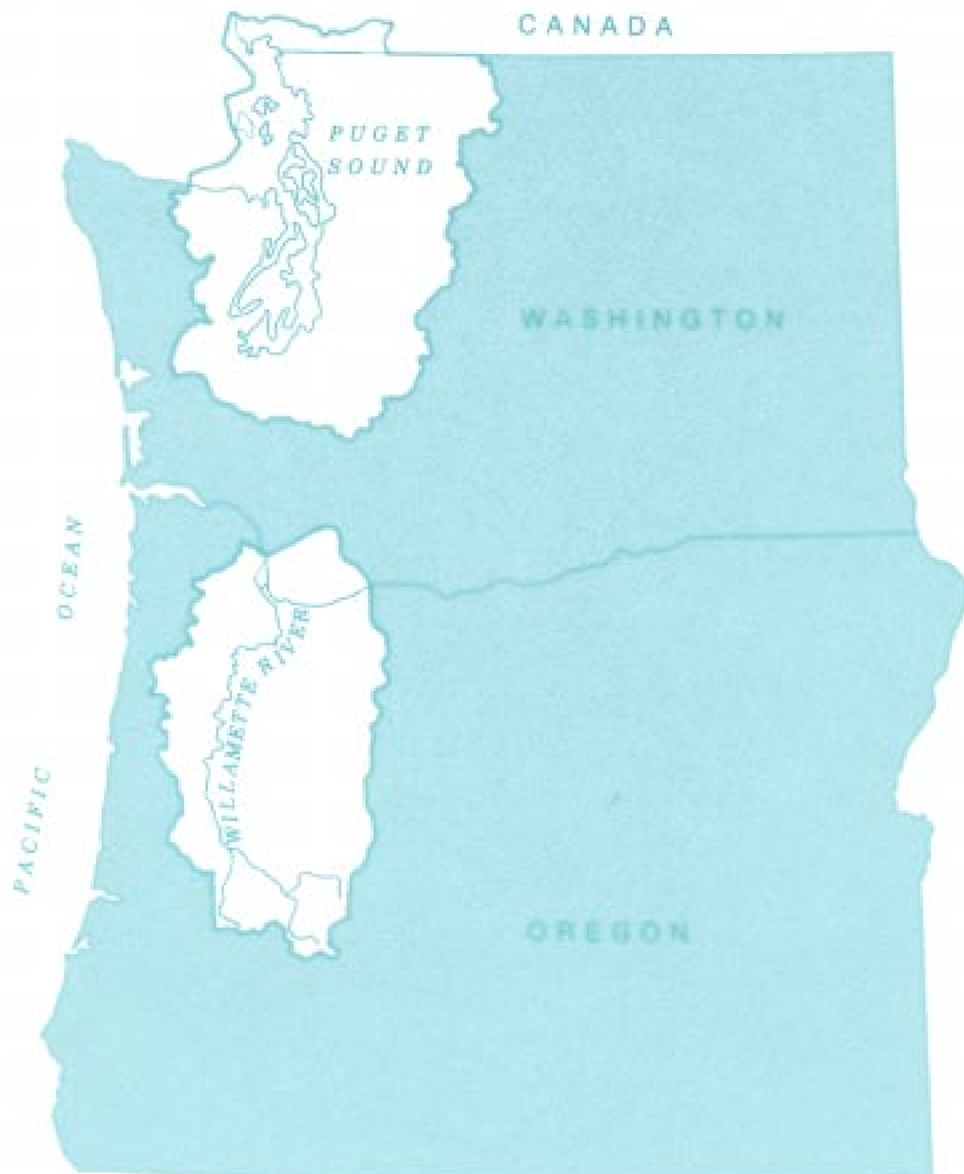
Ground-Water Pumpage in the Willamette Lowland Regional Aquifer System, Oregon and Washington, 1990

A contribution of the Regional Aquifer-System Analysis Program

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4111



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By CHARLES A. COLLINS and TYSON M. BROAD

U.S. Geological Survey
Water-Resources Investigations Report 96–4111

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
acre-foot (acre-ft)	1,233.5	cubic meter
cubic feet per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
square foot (ft^2)	0.0929	square meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
gallon (gal)	0.1337	cubic foot (ft^3)
million gallons per day (Mgal/d)	1.547	cubic feet per second (ft^3/s)

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

Ground-Water Pumpage in the Willamette Lowland Regional Aquifer System, Oregon and Washington, 1990

By Charles A. Collins *and* Tyson M. Broad

Abstract

Ground-water pumpage for 1990 was estimated for an area of about 5,700 square miles in northwestern Oregon and southwestern Washington as part of the Puget-Willamette Lowland Regional Aquifer System Analysis study. The estimated total ground-water pumpage in 1990 was about 340,000 acre-feet. Ground water in the study area is pumped mainly from Quaternary sediment; lesser amounts are withdrawn from Tertiary volcanic materials. Large parts of the area are used for agriculture, and about two and one-half times as much ground water was pumped for irrigation as for either public-supply or industrial needs. Estimates of ground-water pumpage for irrigation in the central part of the Willamette Valley were generated by using image-processing techniques and Landsat Thematic Mapper data. Field data and published reports were used to estimate pumpage for irrigation in other parts of the study area. Information on public-supply and industrial pumpage was collected from Federal, State, and private organizations and individuals.

INTRODUCTION

The Puget-Willamette lowland regional aquifer system is 1 of 29 aquifer systems being studied by the U.S. Geological Survey's Regional Aquifer System Analysis (RASA) program. The objectives of each RASA study of an aquifer system are to:

(1) describe the geologic framework,
(2) describe the hydrogeologic characteristics,
(3) describe the water budget,
(4) describe the ground-water flow system,
(5) describe the water-quality characteristics of the regional aquifer system, and
(6) construct a numerical ground-water model for simulation of the ground-water flow system.

Hydrogeological and geochemical information about the regional aquifer systems, combined with the analytical capabilities of the RASA program, provide area resource managers with the tools to understand and effectively manage the Nation's ground-water resources.

Information on 1990 ground-water pumpage was used by the RASA study for analyses of the regional ground-water flow system and water budget. This report presents estimates of ground-water pumpage for the part of the regional aquifer study area that is located in the lowlands of the Willamette and Sandy River Basins in Oregon and Clark County and western Skamania County in Washington (fig. 1). The regional aquifer consists mainly of Quarternary sediment contained in a north-south structural basin, which is formed of older Tertiary marine sediment and basalt flows. The regional aquifer supplies ground water for public-supply, irrigation, industrial, and domestic uses.

Location and Description of the Study Area

The Willamette Lowland RASA study area is located in northwestern Oregon and southwestern Washington (fig. 1). The part of the area in Oregon is bounded on the east by the crest of the Cascade Range, on the south by the drainage divide between the Willamette River and Umpqua River Basins, and on the west by the crest of the Coast Range. The part of the RASA study area in Washington includes all of Clark County and part of Skamania County. The RASA study area covers about 12,700 square miles and has broad alluvial valleys surrounded by rolling foothills that ascend to higher peaks of the Coast and Cascade Ranges. Elevations range from about 10 feet above sea level near the Columbia River to 11,235 feet at the peak of Mount Hood on the eastern border. Because parts of the RASA study area that are at higher elevations generally are located on State- or Federally owned forest lands that have few inhabitants and negligible ground-water usage, pumpage data in this report were obtained from wells located on the Willamette Valley floor and foothills, an area that covers about 5,700 square miles.

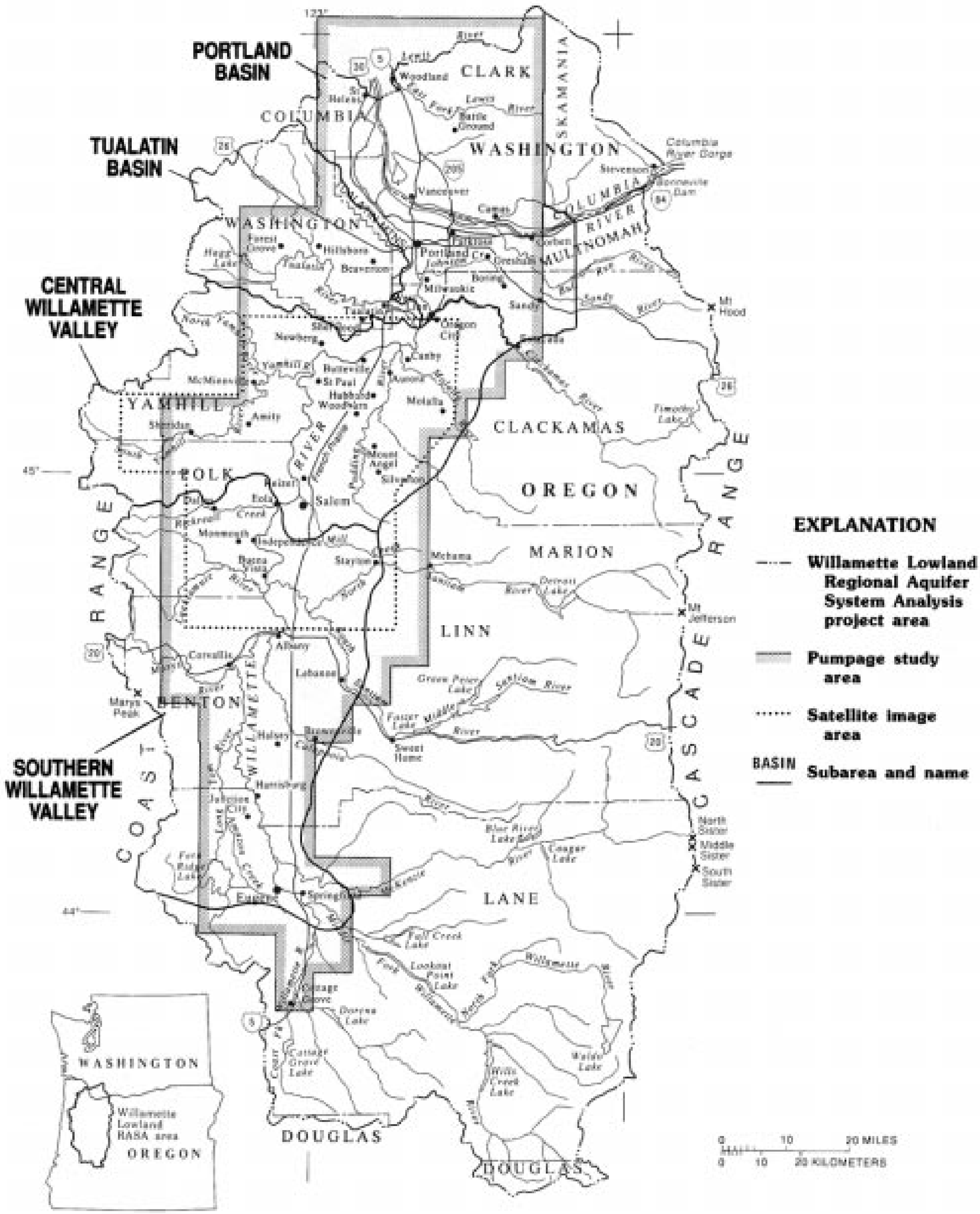

Figure 1. Location of the Willamette Lowland Regional Aquifer System Analysis project area, pumpage study area, subareas, and area covered by satellite image.

The Willamette River flows northward through much of the RASA study area and joins the Columbia River near the northwestern edge.

The RASA study area has a population of about 2.2 million. The metropolitan areas of Portland, Oregon, and Vancouver, Washington, are located in the northern part of the study area. Other major cities include Salem, Eugene, Corvallis, and Albany, Oregon.

The economy of the area is supported by agricultural, manufacturing, and service industries. A wide variety of crops are grown, including wheat, grass seed, corn, hops, vegetable row crops, mint, nursery stock, fruit, and hazelnuts. Several large canneries in the central Willamette Valley process local products. The economies of many communities in the area rely on the timber- and wood-products industries. Primary-metals and paper production occur at several locations, as do facilities associated with the electronics industry. Interstate highways, railroads, and the deep-water port in Portland provide access to national and international markets for locally produced goods.

Climate in the study area is humid marine, modified by the coastal ranges of Oregon and Washington. Precipitation generally falls as rain and ranges from nearly 200 inches in the Coast Range to about 40 inches on the Willamette Valley floor near Salem, Oregon. Most precipitation occurs from fall through spring; late spring and summer are warm and dry. For the period 1961–90, average monthly temperatures for Salem ranged from about 41°F (degrees Fahrenheit) in December to about 63°F in July (National Oceanic and Atmospheric Administration, 1992).

Purpose and Scope

This report describes the quantity and distribution of 1990 ground-water pumpage in parts of the Willamette Lowland RASA study area for major water-use categories. Recent information on ground-water pumpage was unavailable for much of the study area prior to the RASA project. Pumpage data are vital to the understanding of the regional ground-water flow system and water budget. Data for public-supply, industrial, and irrigation pumpage were collected from previous studies and during an inventory of selected wells during this study. Additional data were obtained from other government agencies, private companies, and individuals. Estimates of ground-water pumpage for domestic use were not made in this study.

Previous Studies in the Study Area

Assessment of ground-water resources in the Willamette lowland began in 1928 (Piper, 1942). More detailed ground-water studies of parts of the Willamette lowland began in the early 1950's. Since that time, more than 20 reports have been published by the U.S. Geological Survey (USGS). Many reports by other Federal and State agencies and private entities on the ground-water resources of the Willamette lowland are available (Morgan and Weatherby, 1992). Most of these reports describe the availability and distribution of ground water in parts of the study area; little information on the quantity and distribution of ground-water pumpage was available prior to the RASA study. The information available in earlier reports was obtained by using a variety of water-use estimation techniques, resulting in different levels of accuracy. Data were presented as total water pumped by major use category, such as irrigation, public supply, and industrial. These reports presented the total ground-water pumpage for a study area but did not distribute the withdrawals areally. Statewide estimates of ground-water supply and use by county and hydrologic unit (drainage basin) are available in Solley and others (1993) and Broad and Nebert (1990). The amounts and areal distribution of recent ground-water pumpage for the Portland Basin have been documented by Collins and Broad (1993).

Acknowledgments

Ground-water-pumpage data were obtained from many municipal and private water purveyors, industrial and commercial sources, and private well owners. The Oregon Water Resources Department and Washington Department of Ecology provided important information on ground-water rights. Appreciation is extended to Paul Seevers of Earth Resources Observation System Data Center, Sioux Falls, South Dakota, for classifying and calibrating the Landsat TM (Thematic Mapper) data for the pumpage study area. The cooperation of these groups and individuals is gratefully acknowledged.

GEOHYDROLOGY OF THE STUDY AREA

Quaternary sediment forms the major aquifer unit of the Willamette Lowland RASA study area. The sediment varies in areal extent and thickness and provides most of the ground-water supply. Water users in several isolated areas pump ground water from basalts of the underlying Tertiary Columbia River Basalt Group (Vaccaro, 1992).

Quaternary sediment and rocks of the Columbia River Basalt Group in the RASA study area are contained in a structural trough that extends from near Cottage Grove, in the southern part of the Willamette lowland, to the northern boundary near Woodland, Washington. The trough can be divided into four subareas: the Portland Basin, the Tualatin Basin, the central Willamette Valley, and the southern Willamette Valley subareas (fig. 1). These subareas have Quarternary sediment at the surface and are underlain by older Tertiary sedimentary and volcanic materials. The older rocks form the topographic and structural boundaries between the subareas. Older Tertiary sedimentary rocks have low permeability and act as geohydrologic boundaries to the overlying Columbia River Basalt Group and Quaternary sediment.

Water users in several areas obtain adequate supplies from permeable Columbia River basalts. The area surrounding Portland and approximately the eastern one-third of the central Willamette Valley subarea use ground water from the basalts for public supply and irrigation. Declining water levels in wells finished in the basalt have been reported in an area south and west of Beaverton and between Mount Angel and Stayton, Oregon.

Quaternary sediment underlying the Willamette Valley floor forms the main aquifer unit in the pumpage study area. Layers of clay, silt, sand, and gravel have been deposited as outwash from Cascade Range alpine glaciers, from backwater formed during catastrophic floods originating in the upper Columbia River Basin, and from recent alluvial deposition. Sediment thickness ranges from tens of feet to more than 1,000 feet.

The source areas for most Quarternary sediment are the adjacent highlands of the Coast and Cascade Ranges. Fine-grained materials from the Coast Range, carried by low-gradient rivers to the Willamette Valley floor, compose fine-grained deposits west of the Willamette River. These fine-grained deposits tend to have low permeability; yields of wells completed in the Quarternary sediment generally decrease westward from the Willamette River to the foothills of the Coast Range. East of the Willamette River, large alluvial fans at the mouths of canyons have thick deposits of coarse volcanic sediments that originated in the Cascade Range. Well yields are higher in these deposits than in the deposits from the Coast Range. Gannett and Caldwell (in press) provide a more detailed description of the geologic framework of the area.

DATA-COLLECTION TECHNIQUES

Water-rights data indicate that irrigated agriculture was the largest use of ground water in the area studied for this report. Owners of about 8,100 irrigation wells had water rights to pump a total of about 2,100 Mgal/d (million gallons per day) of ground water. Owners of wells that provided ground water for public supply had water rights to use about 920 Mgal/d from about 700 wells. Owners of about 500 industrial wells had water rights to pump about 250 Mgal/d.

The actual number of irrigation, public-supply, and industrial wells operated in any given year may be substantially less than the total number of wells indicated in the preceding paragraph. The quantity of ground water pumped per year also may be substantially less than the volume allowed by water rights. Age and productivity of a well, changes in land use, changes in the local economy, and local weather can affect the use of wells. An example is in northwestern Marion County, where large amounts of ground water were pumped for irrigation in 1960 (Price, 1967). In 1990, much of this area produced grass seed and was nonirrigated. Water-rights information does not reflect agricultural changes and is best used for determining the relative distribution and areal extent of ground-water use, rather than an absolute quantity of pumpage. Water-rights data also can provide a chronology of ground-water development in the study area (fig. 2). The rapid increase in the number of applications filed per year in the mid-1930's to about 1950 is probably due to changes in crops grown in the study area. Changes in irrigation technology, such as the development and use of aluminum irrigation pipe and more efficient sprinklers, enabled farmers to grow higher value crops that required supplemental water in addition to precipitation. Peaks in water-right applications after 1950 shown in figure 2 coincide with years of less than average rainfall and may be the result of farmers developing new or additional wells to maintain existing crops.

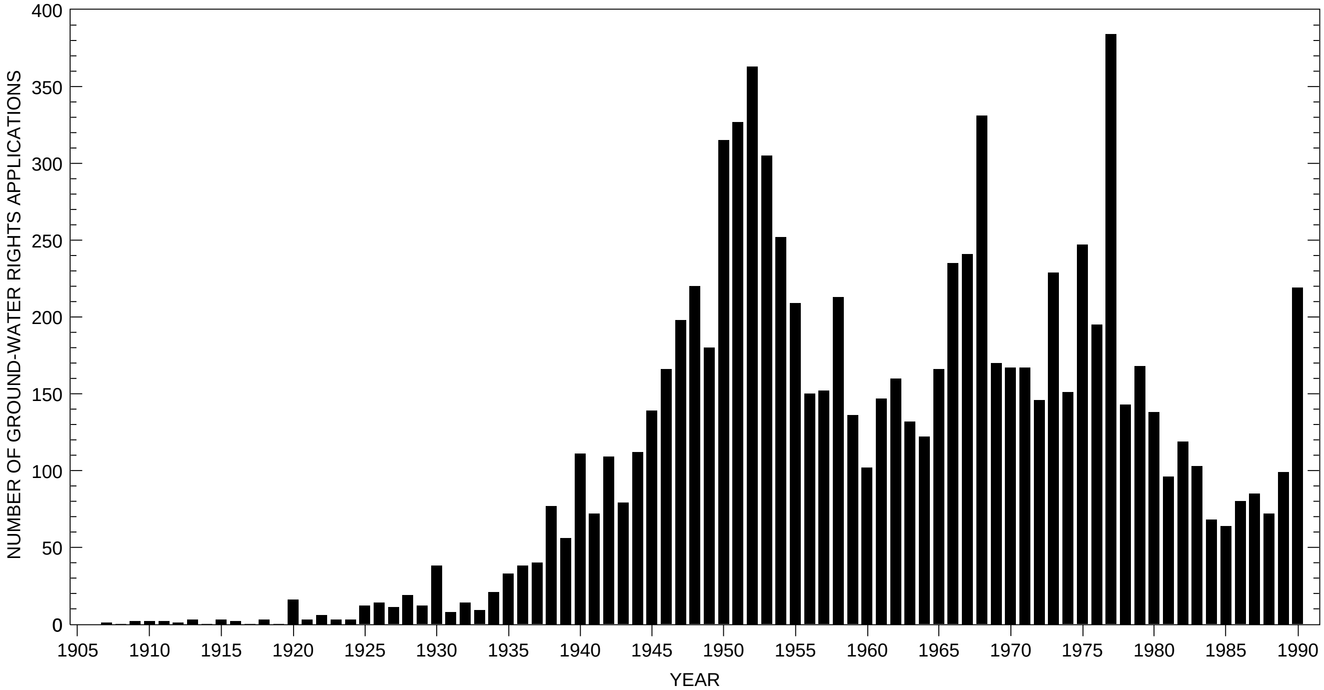

Figure 2. Number of water-rights applications per year.

It was not possible to locate and collect water-use data from all 9,300 wells with water rights in the study area. Therefore, guidelines were established for selecting, visiting, and collecting information from representative (field-located) wells and for collecting or estimating pumpage for public-supply, industrial, and irrigation users.

Selection of Representative Wells

Wells were selected to better understand the ground-water flow system and geologic framework and to assist with the description of the regional water budget. Well selection was based on location, well depth and construction, depth to water, discharge, lithology, and use of water. In general, only large-capacity public-supply, industrial, or irrigation wells were considered in the selection process. An average of one well for every 2 square miles was chosen throughout the study area. Additional wells were selected later to refine the understanding of the study area hydrogeology. Using the preceding criteria, 708 irrigation, 135 public-supply, and 122 industrial wells were selected.

Water-use data were collected during field visits to selected representative wells during the summer and fall of 1990. Information collected at each site included an accurate location of the site (plotted on 1:24,000-scale topographic quadrangle maps), elevation of land surface, depth to water, and status of the water level (pumping, recovering, or static). Pump-characteristics data that were collected included horsepower and type of pump (turbine, submersible, or centrifugal). Electric-power-meter readings and power-meter constants were recorded. If the pump was in use, the instantaneous power consumption was recorded. These data were used later to verify power-consumption rates.

Collection of Public-Supply Pumpage Data

Ground-water-pumpage data were available for many of the municipal users in the Oregon part of the study area. All public entities in Oregon (including municipal water systems) with water rights are required to report pumpage to the Oregon Water Resources Department. This information was collected for each well or surface-water intake on a monthly basis and stored in a database maintained by Oregon Water Resources Department. Information from this database was supplied to the USGS. Estimates of public-supply ground-water pumpage for Clark County, Washington, for 1987 and 1988 (Collins and Broad, 1993) were adjusted for conditions in 1990.

Most municipal wells in the study area are equipped with totalizing flowmeters and hour meters, which are read frequently and are kept in good mechanical condition. These systems were checked during field visits, when data on total-system-storage capacity, maximum and minimum volumes delivered per day, and population served were collected. Information also was collected about wells that were abandoned or used in standby mode. Public-supply pumpage data were considered to be the most accurate data available in the study area.

Nonmunicipal ground-water users, such as mobile home parks, are not required to report pumpage. Estimates of nonmunicipal usage, therefore, were based on data acquired from the Oregon State Health Division. These data included the number of water connections and the number of persons served by the supplier. An annual withdrawal estimate was derived by applying a per-capita withdrawal rate of 100 gallons per day (36,500 gallons per year) to the number of persons served. The rate of 100 gallons per day was obtained from an estimate of self-supplied domestic use in western Oregon (Broad and Nebert, 1990).

Collection of Industrial-Pumpage Data

Industrial ground-water-pumpage data were available from several sources and had a range of accuracies. Industrial water users were queried for total pumpage, period of record of the data, and method of data collection. These data were evaluated for accuracy.

Large industrial water users usually monitor their pumpage with in-line flowmeters, and the data generally are accurate. Some users maintained records on hours of operation and provided a reasonably accurate estimate of the pumpage rates. Estimates of industrial pumpage in the Portland Basin for the years 1987–88 were assumed to equal industrial pumpage in 1990. These estimates were considered of fair quality (Collins and Broad, 1993).

Estimates of industrial ground-water pumpage, for large and for small users in the study area, outside the Portland Basin, were made from water-rights information and waste-discharge permits. Water-rights information was used to locate the industrial wells. Discharges were obtained from permit-compliance forms and were used to estimate pumpage. An estimate of total pumpage was obtained by adding a percentage for consumptive use to the amount discharged. Generally, between 5 and 10 percent was applied on the basis of queries of similar industries or from the Census of Manufactures (U.S. Department of Commerce, 1986).

Collection of Irrigation-Pumpage Data

Estimation of ground-water pumpage for irrigation was a complex process as a result of the diverse crops grown and irrigation practices used in the study area. Existing estimates of ground-water pumpage were used where available. Collection of water-use data was a part of the field work in areas that had no recent information.

Locations of about 700 active irrigation wells were documented. The data collected included the type of sprinkler (hand-move line, wheel lines, solid set, or center pivot) and the number and size of sprinkler heads. The acreages and types of crops grown also were noted. These data were used to verify crop-water-application rates that had been developed for the study area.

Irrigation-pumpage estimates for the northern part of the study area were available for 1987–88 from the Portland Basin study (Collins and Broad, 1993). These pumpage estimates were calculated by using similar methodologies and probably are representative of 1990 conditions. Estimates were based on the product of crop acreages and an areally adjusted crop-water-application rate.

Crop-water-application rates were derived by combining crop-water-need coefficients with water-application efficiencies. Crop-water-need coefficients (net irrigation requirements) were determined by using the United Nations Food and Agriculture Organization modified Blaney-Criddle formula. The formula uses factors such as mean monthly air temperature, monthly percentage of daylight hours for a given latitude, length of the growing season, growth stage of the crop, minimum relative humidity, the ratio of actual to maximum possible sunshine hours, and daytime windspeed (Cuenca and others, 1992).

For this study, the crop-water-application rates were adjusted for each county in the study area. Crop acreages (U.S. Department of Commerce, 1989) were summed for each irrigated crop within the county.

Each irrigated crop had a crop-water-need coefficient that was used as a weighting factor. The county crop-water-application rate was the total of all irrigated crop acreages multiplied by the weighted crop-water requirement. Error in the pumpage estimates for this category may be ±50 percent when compared with pumpage estimates obtained from wells equipped with flowmeters.

Irrigation-application efficiencies for different methods of application were obtained from the U.S. Department of Energy (King and others, 1978) and averaged about 75 percent. Crop-water-application rates in the study area averaged about 1.5 feet per year but ranged from 1.38 to 1.60 feet per year depending on location, type of crop, and method of application.

Image-processing techniques, discussed in the section "Use of Remotely Sensed Data to Estimate Irrigation Pumpage," were used in conjunction with water-rights information to estimate ground-water pumpage for irrigation in the area covered by a satellite image, an area of about 4,800 square miles (fig. 1). The process used was as follows:

(1) Image-processing techniques were used to identify irrigated crops and determine their acreage.

(2) Crops identified were referenced to the State township, range, and section grid using geographic information system (GIS) computer software.

(3) The number of acres (per section) potentially irrigated by ground water, the number of acres per section potentially irrigated by surface water, and the total number of potentially irrigated acres per section was determined from water-rights data.

(4) The number of acres per section potentially irrigated by ground water was calculated by multiplying the number of irrigated acres per section by the ratio of acres of land having ground-water rights to total acres of land having water rights.

(5) Finally, the total ground-water pumpage for irrigation in a section was calculated by multiplying the estimated acres of land irrigated with ground water by the locally adjusted crop-water-application rate.

For example, image-processing techniques identified 120 acres of irrigated crops in a section. If the total number of acres of land with water rights in that section was 100, and there were 50 acres of land with ground-water rights within that same section, the number of acres irrigated with ground water would be 60 acres (120 acres multiplied by 50 acres divided by 100 acres). Using a crop-water-application rate of 1.5 feet of water per year, the estimate of ground water pumped for that section would be 90 acre-feet of water per year (60 acres multiplied by 1.5 feet per year).

For areas not covered by satellite image, the same method for determining the crop-water-application rate previously described was used. However, the location and areal extent of irrigated crops were determined by several other methods. The area south of Albany and east of the Willamette River (southern Willamette Valley subarea) has large areas of dryland farming and little ground water is used there. West of the Willamette River, in the flood plain between Corvallis and Junction City, most crops are irrigated. Adequate field-inventory data and some 1990 satellite imagery for this area were available. Estimates of ground-water pumpage were made by using these data and the appropriate crop-water-application rates. Ground-water pumpage for the areas near Eugene-Springfield and the Tualatin Basin subarea was estimated by using county crop statistics, water-rights information, satellite imagery, and land-use maps (Oregon Water Resources Department, 1978, 1979, and 1980).

USE OF REMOTELY SENSED DATA TO ESTIMATE IRRIGATION PUMPAGE

Collection of water-use data for most of the 8,100 irrigation wells in the study area was not possible; other methods to estimate irrigation pumpage were considered. Estimating pumpage from electrical-power-consumption records was not feasible, because utility companies required individual user consent prior to release of electrical-power-consumption data. Image-processing techniques were the most efficient way to identify irrigated acreage and to estimate ground-water pumpage.

Image-Processing Techniques

The Willamette lowland has a high diversity of crops. Because of this diversity and the size of the area, detailed crop data were not available. For this reason, Landsat TM digital data were acquired to create a land-cover map of the study area by using image-processing techniques. These techniques allow the identification of land-use cover types, such as agricultural crops, forests, cities, roads, water bodies, and nonagricultural areas. The Earth Resources Observation Systems Data Center in Sioux Falls, South Dakota, provided the image-processing expertise for developing the land-cover classification.

Optimum crop identification occurs when an early season and a late season image are used. The early season image contrasts dryland crops, which have developed much vegetative growth, with irrigated annual crops, which appear as bare soil. The late season image shows dryland crops as matured or harvested but shows irrigated annual crops as being near their growth peaks. On the basis of the Willamette lowland cropping patterns, the early image should be acquired in late April or early May and the late image in late July or early August.

Cloud-free images are preferred for land-cover classification. A May 9, 1990, image was available for the early season period. Cloudy weather in late summer precluded acquiring a cloud-free image during the optimum late season timeframe. Consequently, a satellite image obtained prior to the late summer optimum timeframe had to be selected. An image from July 4, 1990, was selected, although some cloud cover existed around the margins of the basin at that time. This image was chosen instead of the September 14, 1990, image, because there was less cloud cover in the northern part of the Willamette Valley, where much of the irrigated agriculture is located. The July image had less cloud interference in the northern Willamette Valley, but many annual vegetable crops had not developed to their growth peak.

Each image is about 115 miles wide by about 105 miles long and covers much of the Willamette Valley south of Oregon City. Each image consists of seven spectral bands: three in the visible, three in the near- and mid-infrared, and one in the thermal region of the electromagnetic spectrum. In the process of registering the images to a map base, the pixels (picture elements) were resampled to about 81 feet for the first six bands mentioned. Pixel size refers to the area on the ground for which the satellite records the reflected energy. The registration process also converted the image to a Universal Transverse Mercator projection, which allowed other data layers with the same coordinate system (ground data, urban boundaries, hydrography) to be combined with the image. Overlaying this additional information assists in the verification of the classification procedures.

Selection of Test Area

Landsat thematic mapping images cover a large area (11, 820 square miles) and require about 35 megabytes of computer storage for each spectral band. Typical classification methods commonly require three or more spectral bands and two or more acquisition dates. In order to reduce processing time and computer-storage requirements, a small representative part of the study area was selected to test classification methods.

The Willamette Valley contains a wide variety of land-use types and physiography. In selecting a representative test area, consideration was given to areas that had dryland and irrigated farming, valley areas and foothills, urban and suburban areas, and as much crop diversity as possible. The area finally selected, on the basis of the above criteria, was a 2,000 by 2,000 pixel area (about 960 square miles) with Salem at the approximate center.

Collection of Ground Data

To verify the accuracy of the land-cover map generated by image-processing techniques, field data were collected for representative crop types in the study area during the summer of 1990. Conversion of multiband digital data from Landsat TM sensors to a land-cover map may be accomplished by a number of processes; the process used depends on the product desired. The RASA study required a map showing the areal extent and distribution of the major irrigated crops in the Willamette Valley.

Field crews used orthophotographic maps to record land-cover information. Outlines of areas with various land covers were sketched onto maps between June and mid-October 1990. About 2,000 sites were visited by field crews during that period. Most sites visited were agricultural sites, but sites in areas that were predominantly forest, native grass and shrub, urban and suburban, and wetland also were inventoried. Site selection was designed to enable the documentation of differences in cover type, soils, local precipitation patterns, elevation, and farming practices. For the agricultural sites, representative sites with crops grown by dryland- and irrigated-farming methods were selected. Additional data, such as crop type, height, density, uniformity, and irrigation practices, were collected at the agricultural sites.

A few sites were revisited several times during 1990 to record crop growth, irrigation and cultivation practices, and dates of harvest. This information was helpful during verification of the image-processing work, because it provided details about variations within a crop that often lead to misclassification of areas within a field. Harvest residue from several crops was burned in the field instead of the traditional practice of plowing or disking the material into the soil. This practice also can lead to misclassification of crops. Some farms also practice double cropping: early crops were grown and harvested before midsummer, and another crop was planted late in the summer and allowed to mature into the fall. This practice complicates the development of a land-cover map and the estimation of ground-water pumpage for an area.

Many areas in the Willamette Valley have orchards and fields with crops that remain the same from year to year, such as fruits, berries, grapes, alfalfa, mint, and, to a large extent, grain and grass seed. Fields of annual crops, principally row crops, include corn, beans, cabbage, cauliflower, and several other vegetables. These crops tend to be rotated from season to season, depending on the local market demand. About 1,000 sites were revisited in the summer of 1991 to determine crop rotation patterns in the study area. These data were used as a measure of the stability of the crop acreages and the areal distribution of crops from year to year.

After collection of the ground data was complete, the outlines of fields were digitized and GIS coverages were created. Additional data collected for each field, such as crop type and irrigation practice, were entered into the database. The GIS coverage of ground data was then used to assist with the classification of the image and to verify the results of the classification.

Classification of Landsat Thematic Mapper Data

Classification of remotely sensed data to accurately identify agricultural crops was complicated. Variations, such as crop vigor, soil fertility and moisture content, elevation of fields, and microclimatic conditions affected the energy reflected by the land cover and received by the satellite sensors. Cloud cover, shadows, and variations within a single field may lead to misclassification of cover types.

Many techniques exist for classifying remotely sensed data. Because the focus of the current study was detection and delineation of croplands, efforts were concentrated on using combinations of Landsat TM bands 3, 4, and 5 that provide the best spectral information about growing plants. Four classification methods, which used combinations of these spectral bands and the early and late season images, were developed and tested on the area near Salem. Three of the methods were (1) using bands 3, 4, and 5 of the May image (May345); (2) using bands 3, 4, and 5 of the July image (July345); and (3) using bands 4 and 5 of both the May and July images (MayJuly4545). In the fourth method, a “mask” of areas identified as bare soil on the May image was applied over the July image (July mask), so that only areas that were bare soil in May would be classified on the July image. The rationale for use of this last method was that perennial crops like grain, grass seed, alfalfa, and mint would be growing rapidly by early May and would contrast with the bare-soil areas that generally are planted in annual crops, such as vegetable row crops. Each method had advantages and disadvantages. The May345 method showed the perennial crops well; areas used for growing annual crops appeared as bare soil. The July345 method gave better definition of areas growing annual crops but lost definition for some perennial crops. Many of the perennial crops were mature and were being harvested by this time. The MayJuly4545 method provided the best overall identification of land-cover classes but did not adequately differentiate the annual crops.

The distribution of land-cover classes from each classification method was compared to the areal distribution of crop types determined from the ground data. The land-cover classes were overlain with ground data, and data then were compiled on the accuracy of the match. The accuracy data were compiled only for areas where ground data was collected; those areas comprised about 1 to 5 percent of the study area. Where there was good correlation between ground data and specific land-cover classes, the identification of certain crop types from the Landsat images was possible. In this analysis, preference was given to the classification method that best identified the crops most likely to be irrigated in the study area. Of the four classification methods, the July mask method was determined to best identify areas of irrigated agriculture. This method classified only areas that were identified as bare soil in the May image, not nonirrigated parts of the image.

In order to provide a classification for the entire area, the July mask was merged with the MayJuly4545 composite to classify areas that were not bare soil during May (perennial crops). The MayJuly4545 method provided better identification of perennial crops (alfalfa and mint), dryland farming crops (grain and grass seed), forested areas, and water bodies. Cover classes are difficult to discern in urban areas, so these areas were masked from the data before the final classification procedure was done.

Regional Aquifer System Analysis Study Area Classification

After decisions regarding the best classification methods were made, the area of classification was expanded. The central Willamette Valley from Albany to Oregon City was the only area of the Landsat TM image that was nearly cloud free. Because the classification of croplands was of primary interest, the higher elevation areas within the image were removed by using a mask that outlined the boundary between the valley floor and the foothills.

On the basis of the results of the previous tests, the combination of the MayJuly4545 and July mask methods was applied to the Landsat TM image area. The MayJuly4545 method identified 36 land-cover classes and the July mask identified 16 cover classes. The resulting 52 land-cover classes created an image too complex to interpret accurately. Accuracy-of-identification statistics were then generated by comparing areas of ground data with comparable areas on the image. These statistics showed the relation between cover classes on the image and certain ground-cover types in the study area. For example, several land-cover classes were combined to form a single class that identified coniferous trees. By this method, the total number of land-cover classes was reduced to 12. The aggregated classes identify features such as water bodies, dryland farming, forested areas, and irrigated croplands.

A nominal filtering procedure was used to remove small clusters of pixels (less than 50 contiguous pixels, about 10 acres) to smooth the regions. The areas classified as irrigated cropland were summed within a section, the sum was multiplied by the proportion of water rights per section (represented by ground-water rights) (see “Data-Collection Techniques”), and that product was then multiplied by the crop-water-application rate. Pumpage within sections was summed by quarter township (9 square miles).

GROUND-WATER PUMPAGE IN THE STUDY AREA

Estimates of 1990 ground-water pumpage were made for the three major water uses: public supply, industrial, and irrigation. Pumpage for the three uses was aggregated by quarter township (9 square miles) and is referred to as “total ground-water pumpage” for the study area (fig. 3). Pumpage by quarter township is presented in table 1 (at back of report). The distribution of total ground-water pumpage is strongly influenced by the distribution of ground water that is pumped for irrigation. The Portland-Vancouver area is an exception; large industrial and public-supply withdrawals there tend to overshadow the minor amounts of ground water used for irrigation.

Public Supply

Public-supplied ground water is defined as water withdrawn by public and private water suppliers and delivered to users that do not have their own water supply for domestic, commercial, municipal, and industrial purposes (Solley and others, 1993). Other private systems that supply ground water to five or more residences, such as self-supplied housing developments, apartment complexes, and mobile home parks, were included in the Public Supply category. Data were collected for about 520 public-supply wells within the study area; about 71,000 acre-feet of ground water was pumped from these wells in 1990 (fig. 4; table 1 at back of report).

The city of Vancouver, Washington, pumped more than 23,000 acre-feet of water in 1990. Suppliers in the Springfield area (served by the city of Springfield and the Rainbow Water District) pumped about 10,500 acre-feet in 1990. Thirteen municipalities or public-water-supply utilities supplied more than 1,000 acre-feet in 1990, the next largest volume pumped in a single geographic area. Communities in Clark County, Washington, use ground water almost exclusively. A few communities in the study area supply a mixture of surface and ground water. The city of Portland has a well field as a backup to the Bull Run Watershed; the wells were not used in 1990.

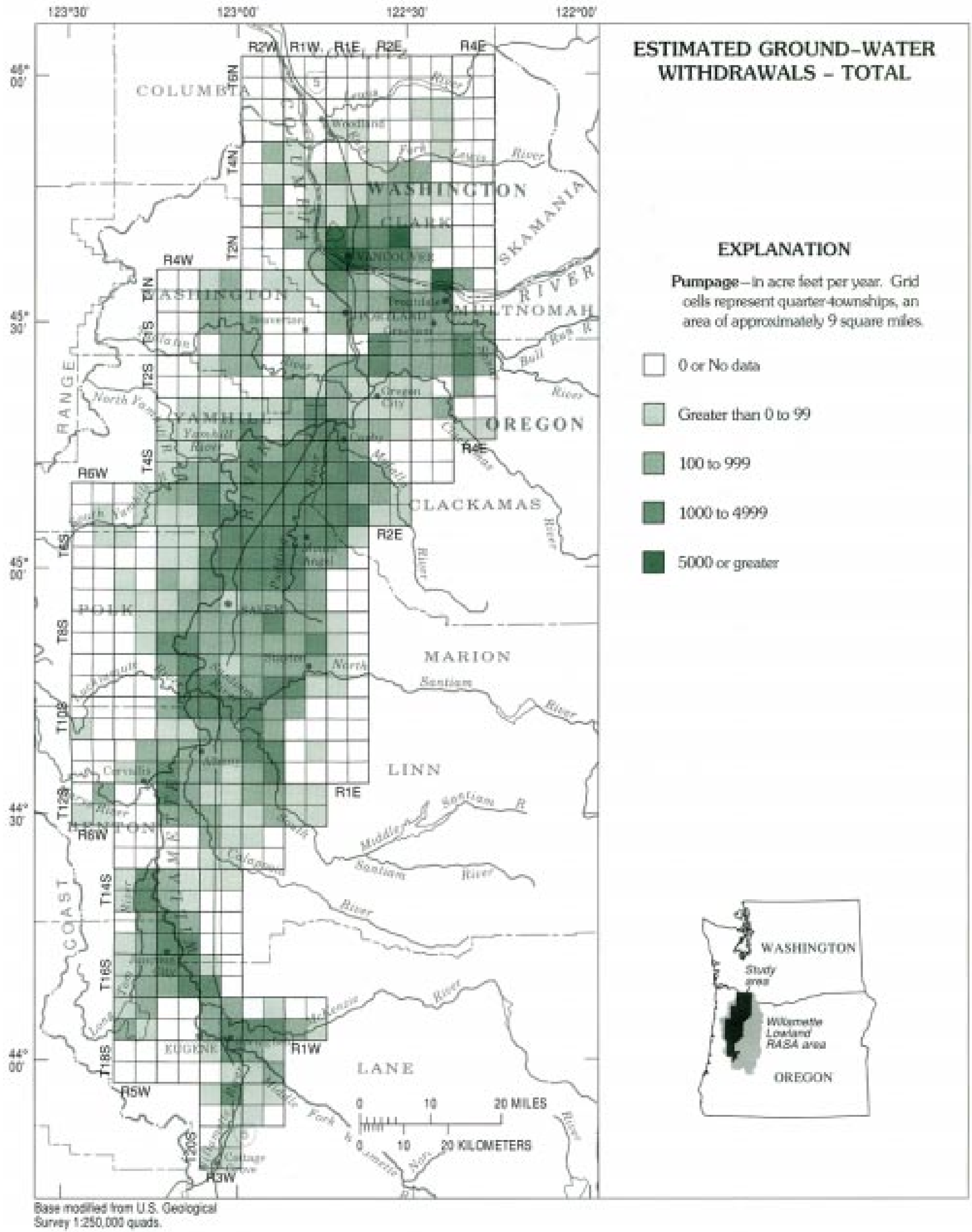

Figure 3. Areal distribution of estimated total ground-water pumpage for 1990.

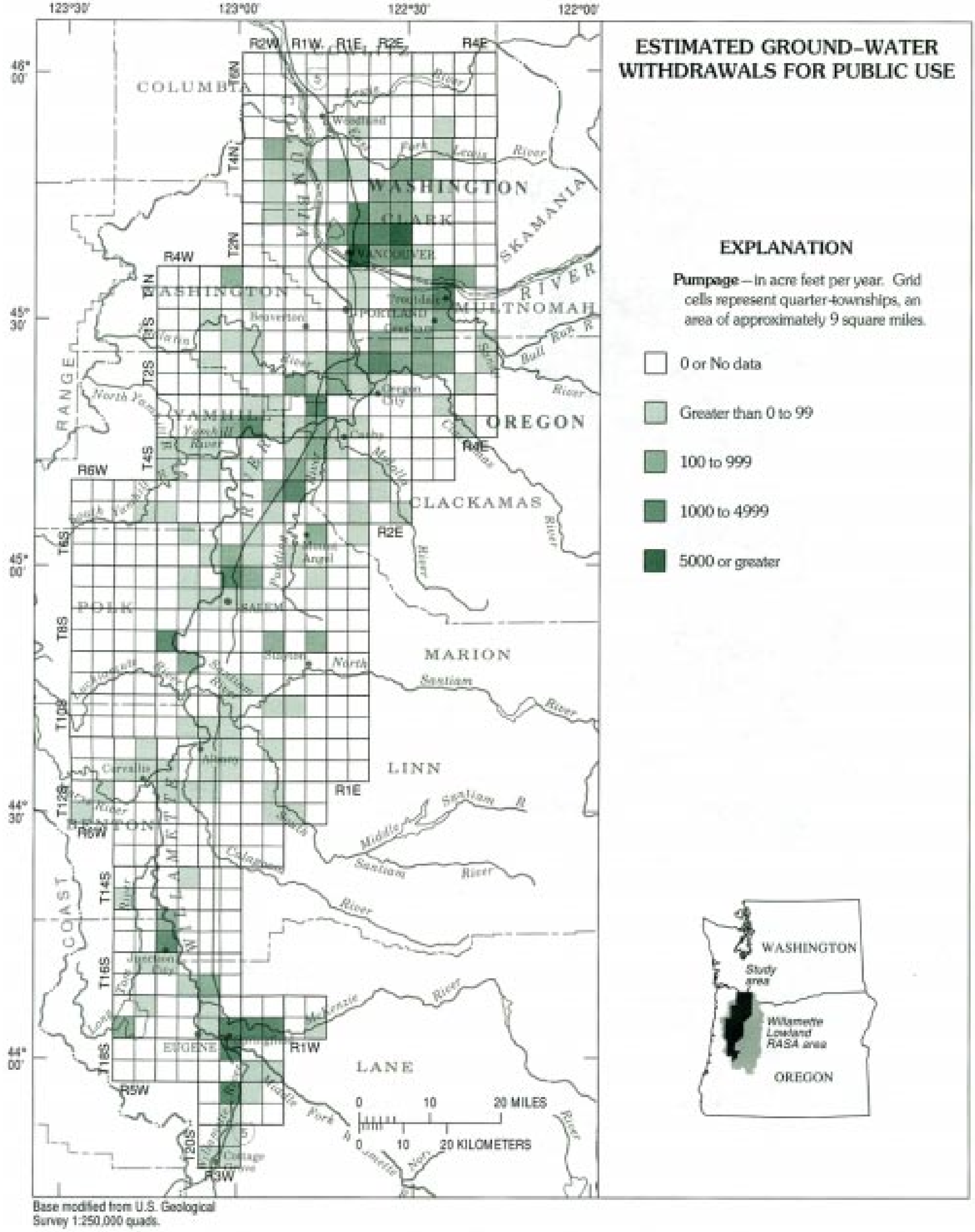

Figure 4. Areal distribution of estimated public-supply pumpage for 1990.

In addition to the city of Portland, several other suppliers have extensive well fields. In 1990, Vancouver had about 30 wells. Not all of the wells were in active use; the inactive wells were available on standby or for emergencies. Other public-water suppliers in the study area had 8 to 10 wells in their system, and some had only 1 or 2 wells.

Industrial

Industrial pumpage is ground water used in the processing, washing, cooling, and fabrication of a product. Industrial facilities that use ground water include vegetable canneries, aluminum smelters, and lumber and paper mills. Water used by commercial establishments for cooking, cleaning, and domestic use or for heating and (or) cooling of office buildings also is included in the industrial category.

Industrial pumpage, estimated for about 120 wells, totaled about 72,000 acre-feet in 1990 (fig. 5; table 1, at back of report). Data for about 90 wells were available from the Portland Basin study (Collins and Broad, 1993). The largest industrial ground-water pumpage in the study area occurred in Clark County, where one user pumped about 25,000 acre-feet per year. Other areas of significant industrial ground-water use were near Vancouver, Washington, and Portland, Woodburn, and Troutdale, Oregon. These areas either had one or more large users in close proximity (Vancouver, Troutdale, and Woodburn) or a large number of medium-sized users (Portland). There are several small- to medium-sized industrial/commercial centers in the middle and southern Willamette Valley subareas. Several commercial buildings in downtown Portland use ground water for heating and cooling.

Irrigation

Irrigation is water applied artificially to farms and horticultural crops and water used to maintain golf courses. Water used for watering livestock and dairy operations was included in this study. For 1990, about 195,000 acre-feet of ground water was pumped for irrigation and associated agricultural uses (fig. 6; table 1, at back of report).

The volume of irrigation water applied to crops within the study area was less than the volume allowed by State water law (Cuenca and others, 1992). In Oregon, 2.5 acre-feet of ground water per acre can be applied annually. An average of about 1.5 acre-feet per acre was applied to most crops in 1990.

Some nurseries used as much as 5 acre-feet of ground water per acre in 1990. Nursery stock grown in containers requires frequent watering because soil moisture is depleted relatively quickly in containers. Areas east and south of Gresham and between Canby and Salem had many nurseries. Because many types of plants were grown in small areas, identification of most nurseries from Landsat TM imagery was not possible. As a result, irrigation pumpage in areas that had many nurseries may have been underestimated.

The area with the largest use of ground water for irrigation is located north and east of Salem, along the Pudding River (fig. 1). About 85,000 acre-feet of ground water was pumped from this area in 1990. The area had a wide variety of irrigated crops, including vegetable row crops, hops, pasture grasses, and nursery plants. Vegetable row crops such as sweet corn and beans were grown for local food-processing plants.

Most irrigation water was applied with movable sprinkler equipment, including wheel lines, hand-move lines, big guns, center pivots, and lateral-roll lines. (Lateral-roll lines move across a field using equipment like that for a center pivot system but without the fixed pivot point.) Water is pumped with turbine pumps, although a few larger capacity submersible pumps are used. Large irrigation systems, such as big guns, wheel lines, center pivots, and lateral-roll lines, commonly require 500 to 1,000 gal/min (gallons per minute) to operate. Water is pumped to the fields with rigid 4- to 8-inch-diameter aluminum mainline, some of which is buried. Impact-head sprinklers were the predominant type used for irrigation, but a few farms used mist heads. Some of the mist-head systems use drop pipes to bring the sprinkler closer to the crop to reduce water loss resulting from evaporation and wind.

Less than 1 percent of the estimated irrigation pumpage was for watering livestock and for dairy operations. Clark County in Washington, as well as Columbia County and parts of the central Willamette Valley in Oregon, had large dairy operations that used ground water. Most water used for dairy washing was pumped to large holding ponds and used to irrigate forage crops.

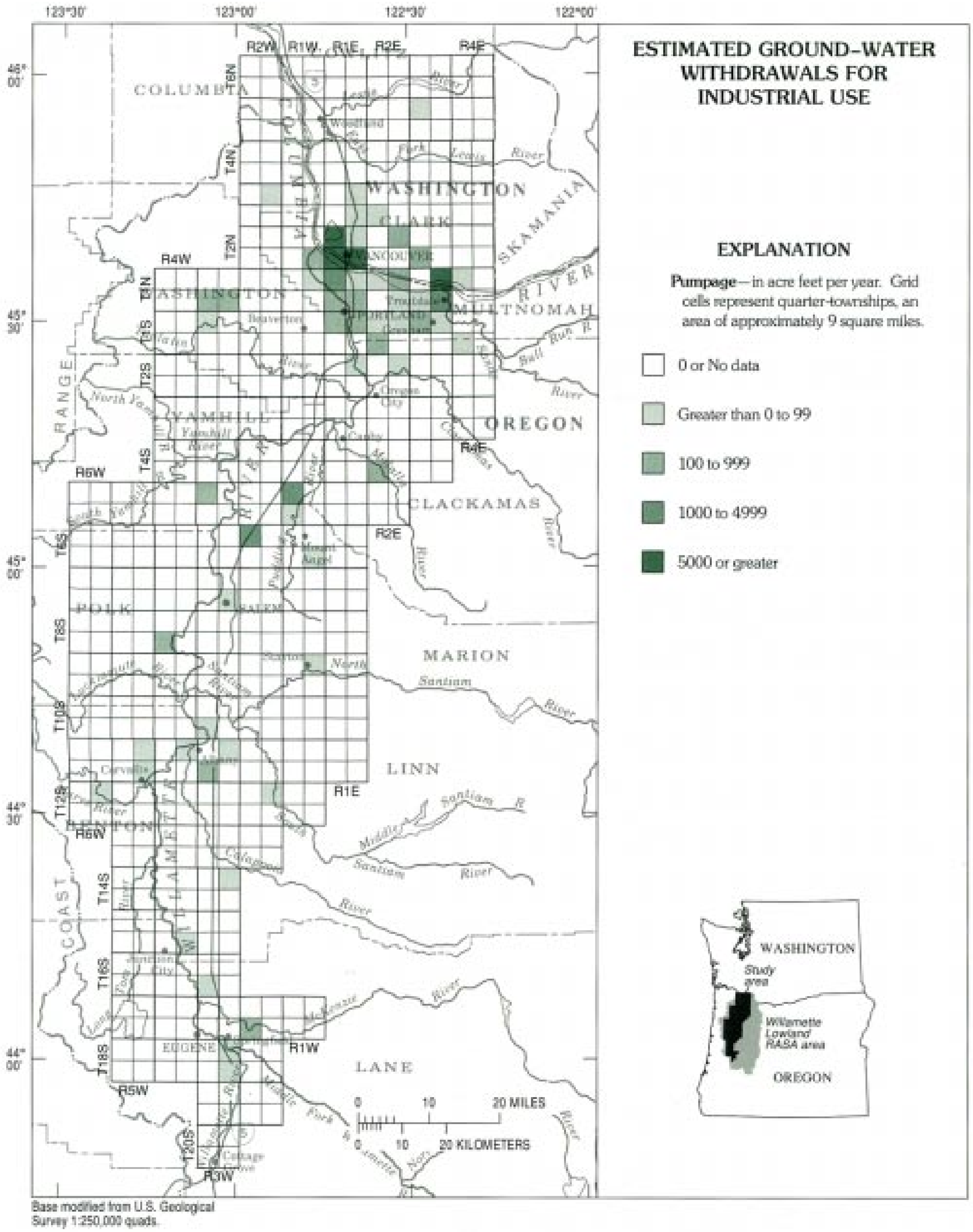

Figure 5. Areal distribution of estimated industrial pumpage for 1990.

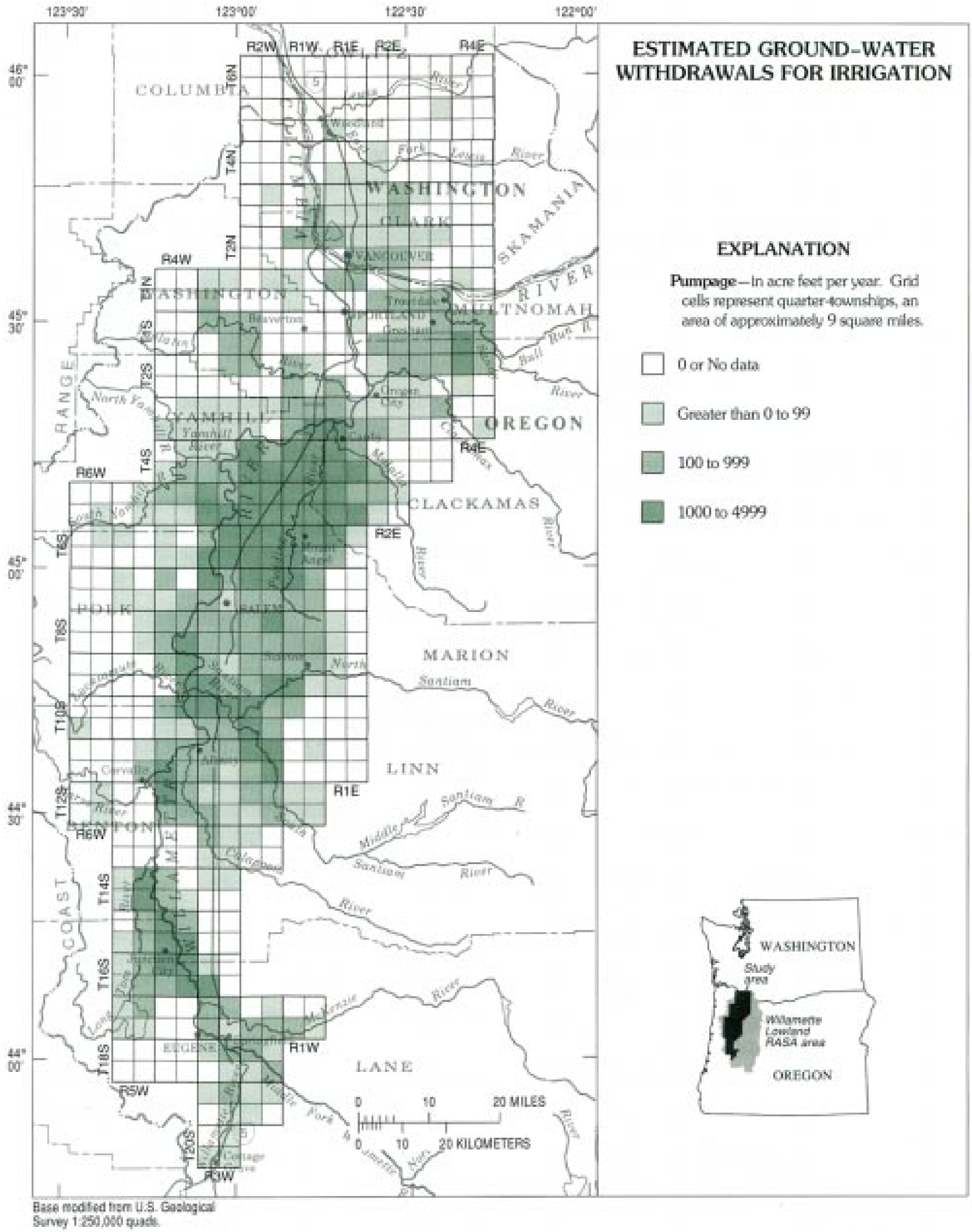

Figure 6. Areal distribution of estimated irrigation pumpage for 1990.

DATA ANALYSIS AND ESTIMATION OF ERROR

Information obtained from public-water suppliers was considered the most complete and accurate. Nearly all data were recorded from totalizing flowmeters. These devices had some error, but it was considered small. During 1990–91, most flowmeters on public-supply wells were in good mechanical condition. Information obtained from sites equipped with flowmeters was the most accurate available and was the standard against which other data were compared. Estimates of public-supplied ground water were considered to be accurate within ±5 percent (Collins, 1987).

For those systems that were not equipped with flowmeters, annual pumpage was estimated by multiplying the number of persons served by a factor of 36,500 gallons per year. The accuracy of these data was estimated to be within ±50 percent; however, the number of users and their pumpage was small compared to the total public-supply pumpage.

Ground-water data collected from industrial and commercial sources vary in accuracy, depending on the method used to obtain the data. Large industrial users recorded their pumpage with totalizing flowmeters or with system-operation timers. Several large users checked their system's capacity regularly to monitor volume pumped. The volume of water pumped by heating and cooling wells in downtown Portland was metered at the discharge point and was estimated to be accurate within 5 to 10 percent compared with data obtained from wells equipped with flowmeters. The volume for smaller industrial users was estimated by pump capacity and operating hours. The accuracy of these estimates varied, but the total volume pumped by these industrial users was small (less than 10 percent) in relation to the total industrial ground water pumped.

The estimates of ground water pumped for irrigation were the least accurate and were based on water-application rates for the major crop types. These rates were calculated from a modified Blaney-Criddle formula (Cuenca and others, 1992). Inaccuracies are the result of several factors:

- Not much data were available on whether wells and water rights were active in 1990.
- Crop-water-application rates were estimated for normalized climatic data.
- Identification of irrigated crops by the use of image-processing techniques was hindered by suboptimal timing of the late season image.
- Estimates of irrigation pumpage for 1990 may vary by ±50 percent.

SUMMARY

Data for ground-water pumpage were collected and compiled for three major water-use categories in the Willamette Lowland Regional Aquifer System Analysis study area in 1990. The three major uses were public supply, industrial, and irrigation. The data were collected as a part of the regional water budget.

Limited ground-water-pumpage data were available prior to this study, so techniques were developed to estimate pumpage for the three major water-use categories. The total annual pumpage for 1990 for the study area was about 340,000 acre-feet: about 58 percent of this pumpage was for irrigation use, about 21 percent was for public supply, and about 21 percent was for industrial use. The pumpage estimates were reported by area and type of use.

The accuracy of ground-water-pumpage data collected from public suppliers is considered to be ±5 percent. Data were recorded by totalizing flowmeters that were kept in good mechanical condition and read regularly. Ground water pumped for public supply was about 71,000 acre-feet per year for 1990.

Owing to the large volume of ground water pumped, data supplied by large industrial users were less accurate than public-supply data. Smaller industrial ground-water users rarely kept water-use records and estimated water use by pump- or system-capacity records and hours of operation. Their pumpage, as a percentage of the total ground-water pumpage for the study area, was small. Total estimated industrial ground-water pumpage was about 72,000 acre-feet for 1990, with an estimation of error of about ±10 percent.

Irrigation ground-water-pumpage data were estimated by several methods and were the least accurate. Landsat Thematic Mapper imagery was used to identify agricultural areas and irrigated cropland in the central part of the study area. For other parts of the study area, data on cropping patterns, aerial photographs, land-use maps, and water rights were used to identify irrigated cropland. Estimates of irrigation for the study area were compiled from irrigated-crop acreage and a water-application rate that was adjusted for local major crop groups and climatic conditions. Ground-water pumpage for irrigation was estimated to be about 195,000 acre-feet for 1990; that value is estimated to be accurate to within ±50 percent.

Irrigation pumpage was a large percentage of the total estimated ground-water pumpage in the central part of the Willamette Valley between Canby and Salem, Oregon. Industrial ground-water withdrawals were largest near the Columbia River in Clark County, Washington. The most heavily pumped area for public supply is north and east of Vancouver, Washington.

REFERENCES CITED

Broad, T.M., and Nebert, D.D., 1990, Oregon water supply and use, *in* National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Collins, C.A., 1987, Ground-water pumpage from the Columbia Plateau regional aquifer system, Oregon: U.S. Geological Survey Water-Resources Investigations Report 86–4211, 21 p.

Collins, C.A., and Broad, T.M., 1993, Estimated average annual ground-water pumpage in the Portland Basin, Oregon and Washington, 1987–88: U.S. Geological Survey Water-Resources Investigations Report 91–4018, 26 p., 4 over-size sheets, scale 1:100,000

Cuenca, R. H., Nuss, J.L., Martinez-Cob, Antonio, Katul, G.G., Gonzales, J.M., 1992, Oregon crop water use and irrigation requirements: Oregon State University Extension Service, Extension Miscellaneous 8530, 184 p.

Gannett, Marshall W., and Caldwell, Rodney R., in press, Geologic framework of the Willamette lowland aquifer system, Oregon and Washington: U.S. Geological Survey Professional Paper 1424–B.

King, L.D., Hellickson, M.L., Schmisseur, W.R., and Shearer, M.N., 1978, Projected energy and water consumption of Pacific Northwest irrigation systems: Prepared by Oregon State University for U.S. Department of Energy through Battelle Pacific Northwest Laboratories, PNL–RAP–33, 112 p.

Morgan, D.S., and Weatherby, D.G., 1992, Bibliography of hydrogeology for the Willamette Valley, Oregon: U.S. Geological Survey Open-File Report 91–473, 138 p.

National Oceanic and Atmospheric Administration, 1992, Climatological data annual summary, Oregon, 1992: Asheville, North Carolina, v. 98, no. 13.

Oregon Water Resources Department, 1978, Land use—Upper Willamette drainage basin, Oregon: Salem, Oregon, 1 map, scale 1:260,000.

———1979, Land use—Lower Willamette and Sandy drainage basins, Oregon: Salem, Oregon, 1 map, scale 1:260,000.

———1980, Land use—Middle Willamette drainage basin, Oregon: Salem, Oregon, 1 map, scale 1:260,000.

Piper, A.M., 1942, Ground-water resources of the Willamette lowland, Oregon: U.S. Geological Survey Water-Supply Paper 890, 194 p.

Price, Don., 1967, Ground-water resources in the French Prairie area—Northern Willamette lowland, Oregon: U.S. Geological Survey Water-Supply Paper 1833, 98 p.

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1993, Estimated use of water in the United States in 1990: U.S. Geological Survey Circular 1081, 80 p.

U.S. Department of Commerce, 1986, 1982 Census of manufactures, Subject series, Water use in manufacturing: U.S. Department of Commerce, Bureau of the Census, MC82–S–6, 72 p.

———1989, 1987 Census of agriculture, Geographic area series, Oregon State and County data: U.S. Department of Commerce, Bureau of Census, v. 1, part 37, AC87–A–37, 293 p.

Vaccaro, J.J., 1992, Plan of study for the Puget-Willamette Lowland Regional Aquifer System Analysis, western Washington and western Oregon: U.S. Geological Survey Water-Resources Investigations Report 92–4189, 41 p.

DATA TABLE

Table 1. Total, public-supply, industrial, and irrigation estimated annual pumpage within the Willamette Lowland Regional Aquifer System Analysis project area in 1990

[Figures may not add to totals because of independent rounding; location reported by township, range, and quarter township (9 square miles)]

Location	Annual ground-water pumpage, in acre-feet			
	Total	Public supply	Industrial	Irrigation
01N/01E-NE	540	35	70	430
01N/01E-NW	4,400	0	4,100	300
01N/01E-SE	910	5	910	0
01N/01E-SW	460	0	460	0
01N/01W-NE	3	0	3	0
01N/01W-NW	57	0	0	57
01N/01W-SE	0	0	0	0
01N/01W-SW	65	0	0	65
01N/02E-NE	250	0	230	20
01N/02E-NW	9	0	9	0
01N/02E-SE	1,200	600	58	520
01N/02E-SW	320	0	0	320
01N/02W-NE	54	0	0	54
01N/02W-NW	0	0	0	0
01N/02W-SE	0	0	0	0
01N/02W-SW	17	17	0	0
01N/03E-NE	27,000	2,000	25,000	0
01N/03E-NW	33	33	0	0
01N/03E-SE	4,000	1,300	2,600	120
01N/03E-SW	630	370	20	230
01N/03W-NE	290	200	0	93
01N/03W-NW	31	0	0	31
01N/03W-SE	120	0	120	0
01N/03W-SW	340	0	160	180
01N/04E-NE	0	0	0	0
01N/04E-NW	470	410	4	55
01N/04E-SE	0	0	0	0
01N/04E-SW	0	0	0	0
01S/01E-NE	690	0	650	47
01S/01E-NW	250	0	250	0
01S/01E-SE	0	0	0	0
01S/01E-SW	0	0	0	0
01S/02E-NE	580	470	68	44
01S/02E-NW	1	0	1	0
01S/02E-SE	460	16	0	450
01S/02E-SW	1,600	690	710	160
01S/02W-NE	0	0	0	0
01S/02W-NW	190	0	0	190
01S/02W-SE	0	0	0	0
01S/02W-SW	530	10	0	520
01S/03E-NE	640	380	26	240
01S/03E-NW	230	65	140	33
01S/03E-SE	660	57	0	600
01S/03E-SW	450	110	0	350
01S/03W-NE	230	0	0	230
01S/03W-NW	490	17	52	420
01S/03W-SE	240	20	0	220
01S/03W-SW	0	0	0	0
01S/04E-NE	230	0	0	230
01S/04E-NW	290	0	0	290
01S/04E-SE	720	34	0	680
01S/04E-SW	1,300	0	74	1,300
02N/01E-NE	3,400	3,200	88	22
02N/01E-NW	5,600	160	5,300	180
02N/01E-SE	19,000	11,000	7,200	160
02N/01E-SW	18,000	0	18,000	0
02N/01W-NE	370	0	0	370
02N/01W-NW	640	0	0	640
02N/01W-SE	330	0	330	0
02N/01W-SW	0	0	0	0
02N/02E-NE	7,700	7,200	470	2
02N/02E-NW	1,400	1,300	0	49
02N/02E-SE	1,200	1,100	0	110
02N/02E-SW	1,200	930	0	300
02N/03E-NE	8	0	0	8
02N/03E-NW	73	0	0	73
02N/03E-SE	0	0	0	0
02N/03E-SW	900	17	860	22
02N/04E-NE	0	0	0	0
02N/04E-NW	0	0	0	0
02N/04E-SE	0	0	0	0
02N/04E-SW	0	0	0	0

Table 1. Total, public-supply, industrial, and irrigation estimated annual pumpage within the Willamette Lowland Regional Aquifer System Analysis project area in 1990—Continued

Location	Annual ground-water pumpage, in acre-feet			
	Total	Public supply	Industrial	Irrigation
02S/01E-NE	130	110	24	0
02S/01E-NW	110	110	0	0
02S/01E-SE	12	12	0	0
02S/01E-SW	670	530	0	140
02S/01W-NE	33	2	0	31
02S/01W-NW	120	0	0	120
02S/01W-SE	51	5	0	46
02S/01W-SW	780	640	0	150
02S/02E-NE	250	120	6	130
02S/02E-NW	1,100	1,000	0	11
02S/02E-SE	61	0	0	61
02S/02E-SW	90	83	0	7
02S/02W-NE	0	0	0	0
02S/02W-NW	490	14	0	480
02S/02W-SE	0	0	0	0
02S/02W-SW	0	0	0	0
02S/03E-NE	380	240	0	140
02S/03E-NW	770	660	0	110
02S/03E-SE	0	0	0	0
02S/03E-SW	1	0	0	1
02S/03W-NE	170	0	0	170
02S/03W-NW	25	25	0	0
02S/03W-SE	0	0	0	0
02S/03W-SW	0	0	0	0
02S/04E-NE	230	83	0	140
02S/04E-NW	1,400	0	0	1,400
02S/04E-SE	0	0	0	0
02S/04E-SW	120	79	0	40
02S/04W-NE	0	0	0	0
02S/04W-NW	0	0	0	0
02S/04W-SE	0	0	0	0
02S/04W-SW	0	0	0	0
03N/01E-NE	26	0	1	25
03N/01E-NW	23	0	0	23
03N/01E-SE	2,700	2,600	26	2
03N/01E-SW	90	0	0	90
03N/01W-NE	35	0	0	35
03N/01W-NW	0	0	0	0
03N/01W-SE	250	0	0	250
03N/01W-SW	14	14	0	0
03N/02E-NE	690	430	0	260
03N/02E-NW	400	310	0	83
03N/02E-SE	620	440	0	180
03N/02E-SW	580	530	3	49
03N/02W-NE	130	95	26	11
03N/02W-NW	0	0	0	0
03N/02W-SE	3	3	0	0
03N/02W-SW	0	0	0	0
03N/03E-NE	63	63	0	0
03N/03E-NW	19	0	0	19
03N/03E-SE	0	0	0	0
03N/03E-SW	14	14	0	0
03S/01E-NE	13	0	0	13
03S/01E-NW	350	0	0	350
03S/01E-SE	920	33	0	880
03S/01E-SW	1,100	61	0	1,000
03S/01W-NE	1,500	1,200	0	300
03S/01W-NW	140	0	0	140
03S/01W-SE	2,300	310	0	2,000
03S/01W-SW	580	40	0	540
03S/02E-NE	65	0	0	65
03S/02E-NW	38	0	0	38
03S/02E-SE	2	0	0	2
03S/02E-SW	130	0	0	130
03S/02W-NE	22	11	0	11
03S/02W-NW	85	6	0	79
03S/02W-SE	10	10	0	0
03S/02W-SW	2,900	2,900	0	61
03S/03E-NE	150	7	0	140
03S/03E-NW	20	0	0	20
03S/03E-SE	0	0	0	0
03S/03E-SW	0	0	0	0

Table 1. Total, public-supply, industrial, and irrigation estimated annual pumpage within the Willamette Lowland Regional Aquifer System Analysis project area in 1990—Continued

Location	Total	Public supply	Industrial	Irrigation
	Annual ground-water pumpage, in acre-feet			
03S/03W-NE	38	0	0	38
03S/03W-NW	56	0	0	56
03S/03W-SE	310	300	0	11
03S/03W-SW	20	17	0	3
03S/04E-NE	0	0	0	0
03S/04E-NW	0	0	0	0
03S/04E-SE	37	0	0	37
03S/04E-SW	34	34	0	0
03S/04W-NE	34	0	0	34
03S/04W-NW	0	0	0	0
03S/04W-SE	4	0	0	4
03S/04W-SW	27	0	0	27
04N/01E-NE	0	0	0	0
04N/01E-NW	0	0	0	0
04N/01E-SE	86	4	0	82
04N/01E-SW	270	250	0	19
04N/01W-NE	0	0	0	0
04N/01W-NW	28	28	0	0
04N/01W-SE	24	24	0	0
04N/01W-SW	59	59	0	0
04N/02E-NE	0	0	0	0
04N/02E-NW	21	0	0	21
04N/02E-SE	140	140	0	0
04N/02E-SW	3	0	0	3
04N/02W-NE	200	200	0	0
04N/02W-NW	0	0	0	0
04N/02W-SE	84	84	0	0
04N/02W-SW	0	0	0	0
04N/03E-NE	26	26	0	0
04N/03E-NW	0	0	0	0
04N/03E-SE	0	0	0	0
04N/03E-SW	220	220	0	0
04S/01E-NE	760	0	0	760
04S/01E-NW	2,000	10	0	2,000
04S/01E-SE	1,400	8	0	1,400
04S/01E-SW	3,000	0	0	3,000
04S/01W-NE	1,300	160	0	1,200
04S/01W-NW	2,000	41	0	1,900
04S/01W-SE	1,600	34	0	1,600
04S/01W-SW	2,800	290	0	2,500
04S/02E-NE	0	0	0	0
04S/02E-NW	0	0	0	0
04S/02E-SE	0	0	0	0
04S/02E-SW	890	44	290	550
04S/02W-NE	860	0	0	860
04S/02W-NW	1,400	0	0	1,400
04S/02W-SE	2,200	0	0	2,200
04S/02W-SW	1,800	77	0	1,700
04S/03E-NE	0	0	0	0
04S/03E-NW	0	0	0	0
04S/03E-SE	0	0	0	0
04S/03E-SW	0	0	0	0
04S/03W-NE	39	0	0	39
04S/03W-NW	120	42	0	79
04S/03W-SE	910	0	0	910
04S/03W-SW	800	72	0	730
04S/04W-NE	75	3	0	72
04S/04W-NW	1	1	0	0
04S/04W-SE	540	0	0	540
04S/04W-SW	4	2	0	2
05N/01E-NE	0	0	0	0
05N/01E-NW	0	0	0	0
05N/01E-SE	99	99	0	0
05N/01E-SW	4	0	0	4
05N/03E-NE	24	0	0	24
05N/03E-NW	1	0	1	0
05N/03E-SE	31	31	0	0
05N/03E-SW	0	0	0	0
05S/01E-NE	980	0	0	980
05S/01E-NW	1,800	0	0	1,800
05S/01E-SE	1,100	3	0	1,100
05S/01E-SW	1,900	0	0	1,900

Table 1. Total, public-supply, industrial, and irrigation estimated annual pumpage within the Willamette Lowland Regional Aquifer System Analysis project area in 1990—Continued

Location	Annual ground-water pumpage, in acre-feet			
	Total	Public supply	Industrial	Irrigation
05S/01W-NE	2,000	0	0	2,000
05S/01W-NW	4,900	1,500	1,400	2,100
05S/01W-SE	1,900	0	0	1,900
05S/01W-SW	2,200	0	45	2,100
05S/02E-NE	5	0	0	5
05S/02E-NW	740	7	0	730
05S/02E-SE	11	11	0	0
05S/02E-SW	58	0	0	58
05S/02W-NE	2,600	600	0	2,000
05S/02W-NW	2,400	0	0	2,400
05S/02W-SE	2,800	94	0	2,700
05S/02W-SW	3,200	0	0	3,200
05S/03W-NE	890	0	0	890
05S/03W-NW	1,300	0	220	1,000
05S/03W-SE	1,900	0	0	1,900
05S/03W-SW	1,200	0	0	1,200
05S/04W-NE	370	0	0	370
05S/04W-NW	260	0	0	260
05S/04W-SE	26	0	0	26
05S/04W-SW	24	3	0	21
05S/05W-NE	18	0	0	18
05S/05W-NW	0	0	0	0
05S/05W-SE	35	23	0	12
05S/05W-SW	0	0	0	0
05S/06W-NE	0	0	0	0
05S/06W-NW	0	0	0	0
05S/06W-SE	28	0	0	28
05S/06W-SW	0	0	0	0
06S/01E-NE	47	17	0	30
06S/01E-NW	1,900	0	0	1,900
06S/01E-SE	0	0	0	0
06S/01E-SW	180	0	0	180
06S/01W-NE	3,300	540	0	2,800
06S/01W-NW	1,300	0	0	1,300
06S/01W-SE	620	0	11	610
06S/01W-SW	1,500	3	0	1,400
06S/02W-NE	3,600	0	0	3,600
06S/02W-NW	4,500	51	1,000	3,400
06S/02W-SE	2,500	0	0	2,500
06S/02W-SW	4,300	50	0	4,300
06S/03W-NE	3,300	0	0	3,300
06S/03W-NW	570	0	0	570
06S/03W-SE	3,700	620	0	3,100
06S/03W-SW	1,600	87	0	1,500
06S/04W-NE	12	12	0	0
06S/04W-NW	7	0	0	7
06S/04W-SE	98	0	0	98
06S/04W-SW	55	0	0	55
06S/05W-NE	0	0	0	0
06S/05W-NW	3	0	0	3
06S/05W-SE	0	0	0	0
06S/05W-SW	0	0	0	0
06S/06W-NE	17	0	0	17
06S/06W-NW	0	0	0	0
06S/06W-SE	0	0	0	0
06S/06W-SW	0	0	0	0
07S/01E-NE	0	0	0	0
07S/01E-NW	0	0	0	0
07S/01E-SE	0	0	0	0
07S/01E-SW	0	0	0	0
07S/01W-NE	140	3	0	140
07S/01W-NW	1,800	0	0	1,800
07S/01W-SE	270	0	0	270
07S/01W-SW	320	0	0	320
07S/02W-NE	2,400	0	0	2,400
07S/02W-NW	2,000	310	0	1,700
07S/02W-SE	990	0	0	990
07S/02W-SW	830	43	0	780
07S/03W-NE	3,000	2,500	0	550
07S/03W-NW	1,000	0	0	1,000
07S/03W-SE	60	5	18	37
07S/03W-SW	300	17	0	280

Table 1. Total, public-supply, industrial, and irrigation estimated annual pumpage within the Willamette Lowland Regional Aquifer System Analysis project area in 1990—Continued

Location	Annual ground-water pumpage, in acre-feet			
	Total	Public supply	Industrial	Irrigation
07S/04W-NE	42	42	0	0
07S/04W-NW	120	0	0	120
07S/04W-SE	500	82	0	410
07S/04W-SW	1	0	0	1
07S/05W-NE	0	0	0	0
07S/05W-NW	5	0	0	5
07S/05W-SE	41	0	0	41
07S/05W-SW	5	0	0	5
07S/06W-NE	0	0	0	0
07S/06W-NW	0	0	0	0
07S/06W-SE	0	0	0	0
07S/06W-SW	0	0	0	0
08S/01E-NE	0	0	0	0
08S/01E-NW	14	0	0	14
08S/01E-SE	0	0	0	0
08S/01E-SW	58	0	0	58
08S/01W-NE	260	0	0	260
08S/01W-NW	470	0	0	470
08S/01W-SE	1,200	220	0	930
08S/01W-SW	770	0	0	770
08S/02W-NE	1,400	0	0	1,400
08S/02W-NW	280	0	0	280
08S/02W-SE	650	180	0	470
08S/02W-SW	680	0	0	680
08S/03W-NE	370	0	0	370
08S/03W-NW	180	0	0	180
08S/03W-SE	270	0	0	270
08S/03W-SW	180	0	0	180
08S/04W-NE	860	0	0	860
08S/04W-NW	120	0	0	120
08S/04W-SE	1,600	0	0	1,600
08S/04W-SW	2,600	2,100	100	380
08S/05W-NE	6	0	0	6
08S/05W-NW	0	0	0	0
08S/05W-SE	12	0	0	12
08S/05W-SW	0	0	0	0
08S/06W-NE	0	0	0	0
08S/06W-NW	0	0	0	0
08S/06W-SE	0	0	0	0
08S/06W-SW	0	0	0	0
09S/01E-NE	0	0	0	0
09S/01E-NW	71	0	0	71
09S/01E-SE	0	0	0	0
09S/01E-SW	2	0	0	2
09S/01W-NE	650	0	11	640
09S/01W-NW	580	0	0	580
09S/01W-SE	60	0	0	60
09S/01W-SW	1,100	0	0	1,100
09S/02W-NE	330	0	0	330
09S/02W-NW	240	0	0	240
09S/02W-SE	2,600	0	0	2,600
09S/02W-SW	330	13	0	320
09S/03W-NE	31	0	0	31
09S/03W-NW	650	0	0	650
09S/03W-SE	550	5	0	550
09S/03W-SW	1,900	0	0	1,900
09S/04W-NE	2,500	210	0	2,300
09S/04W-NW	110	0	0	110
09S/04W-SE	1,700	0	0	1,700
09S/04W-SW	0	0	0	0
09S/05W-NE	0	0	0	0
09S/05W-NW	0	0	0	0
09S/05W-SE	0	0	0	0
09S/05W-SW	0	0	0	0
09S/06W-NE	0	0	0	0
09S/06W-NW	0	0	0	0
09S/06W-SE	0	0	0	0
09S/06W-SW	0	0	0	0
10S/01E-NE	0	0	0	0
10S/01E-NW	0	0	0	0
10S/01E-SE	0	0	0	0
10S/01E-SW	0	0	0	0

Table 1. Total, public-supply, industrial, and irrigation estimated annual pumpage within the Willamette Lowland Regional Aquifer System Analysis project area in 1990—Continued

Location	Annual ground-water pumpage, in acre-feet			
	Total	Public supply	Industrial	Irrigation
10S/01W-NE	0	0	0	0
10S/01W-NW	260	88	0	170
10S/01W-SE	0	0	0	0
10S/01W-SW	0	0	0	0
10S/02W-NE	240	2	0	240
10S/02W-NW	1,700	0	0	1,700
10S/02W-SE	170	0	0	170
10S/02W-SW	1,300	0	0	1,300
10S/03W-NE	2,900	2	0	2,900
10S/03W-NW	3,500	0	0	3,500
10S/03W-SE	740	45	0	700
10S/03W-SW	680	5	1	670
10S/04W-NE	2,900	0	0	2,900
10S/04W-NW	220	0	0	220
10S/04W-SE	76	16	0	60
10S/04W-SW	48	0	0	48
10S/05W-NE	0	0	0	0
10S/05W-NW	0	0	0	0
10S/05W-SE	0	0	0	0
10S/05W-SW	0	0	0	0
10S/06W-NE	0	0	0	0
10S/06W-NW	0	0	0	0
10S/06W-SE	0	0	0	0
10S/06W-SW	1	0	0	1
11S/01E-NE	0	0	0	0
11S/01E-NW	0	0	0	0
11S/01E-SE	0	0	0	0
11S/01E-SW	0	0	0	0
11S/01W-NE	2	0	0	2
11S/01W-NW	0	0	0	0
11S/01W-SE	0	0	0	0
11S/01W-SW	0	0	0	0
11S/02W-NE	1,300	3	0	1,300
11S/02W-NW	1,200	0	0	1,200
11S/02W-SE	2,400	0	0	2,400
11S/02W-SW	160	0	0	160
11S/03W-NE	220	5	11	200
11S/03W-NW	310	15	0	300
11S/03W-SE	37	16	0	21
11S/03W-SW	920	29	640	250
11S/04W-NE	210	0	30	180
11S/04W-NW	970	0	0	970
11S/04W-SE	320	0	0	320
11S/04W-SW	1,800	11	0	1,800
11S/05W-NE	140	79	34	24
11S/05W-NW	0	0	0	0
11S/05W-SE	950	35	55	860
11S/05W-SW	11	11	0	0
12S/01W-NE	3	0	0	3
12S/01W-NW	1	0	0	1
12S/01W-SE	1	0	0	1
12S/01W-SW	99	15	0	84
12S/02W-NE	230	3	22	210
12S/02W-NW	210	0	0	210
12S/02W-SE	160	34	0	130
12S/02W-SW	11	0	0	11
12S/03W-NE	10	0	0	10
12S/03W-NW	91	5	0	86
12S/03W-SE	41	0	0	41
12S/03W-SW	120	0	0	120
12S/04W-NE	190	2	0	190
12S/04W-NW	1,200	7	0	1,200
12S/04W-SE	150	0	0	150
12S/04W-SW	120	0	0	120
12S/06W-NE	120	30	33	52
12S/06W-NW	0	0	0	0
12S/06W-SE	9	0	0	9
12S/06W-SW	7	7	0	0
13S/02W-NE	0	0	0	0
13S/02W-NW	1	0	0	1
13S/02W-SE	0	0	0	0
13S/02W-SW	0	0	0	0

Table 1. Total, public-supply, industrial, and irrigation estimated annual pumpage within the Willamette Lowland Regional Aquifer System Analysis project area in 1990—Continued

Location	Annual ground-water pumpage, in acre-feet			
	Total	Public supply	Industrial	Irrigation
13S/03W-NE	24	0	0	24
13S/03W-NW	230	0	0	230
13S/03W-SE	87	0	0	87
13S/03W-SW	19	0	0	19
14S/03W-NE	91	0	1	90
14S/03W-NW	63	0	0	63
14S/03W-SE	0	0	0	0
14S/03W-SW	0	0	0	0
14S/04W-NE	50	50	0	0
14S/04W-NW	430	0	0	430
14S/04W-SE	16	0	0	16
14S/04W-SW	420	0	0	420
14S/05W-NE	3,300	0	0	3,300
14S/05W-NW	21	0	0	21
14S/05W-SE	2,500	0	0	2,500
14S/05W-SW	73	66	0	7
15S/04W-NE	170	0	0	170
15S/04W-NW	3,700	300	0	3,400
15S/04W-SE	1,100	0	2	1,100
15S/04W-SW	4,700	1,100	0	3,600
15S/05W-NE	820	0	0	820
15S/05W-NW	0	0	0	0
15S/05W-SE	220	0	0	220
15S/05W-SW	32	0	0	32
16S/03W-NE	0	0	0	0
16S/03W-NW	27	0	0	27
16S/03W-SE	0	0	0	0
16S/03W-SW	1,500	230	56	1,300
16S/04W-NE	2,200	0	0	2,200
16S/04W-NW	2,000	15	0	2,000
16S/04W-SE	2,700	4	0	2,600
16S/04W-SW	440	0	0	440
16S/05W-NE	180	6	0	170
16S/05W-NW	29	0	0	29
16S/05W-SE	570	0	0	570
16S/05W-SW	4	0	0	4

Location	Annual ground-water pumpage, in acre-feet			
	Total	Public supply	Industrial	Irrigation
17S/01W-NE	0	0	0	0
17S/01W-NW	0	0	0	0
17S/01W-SE	82	60	0	22
17S/01W-SW	270	0	0	270
17S/02W-NE	11	0	0	11
17S/02W-NW	0	0	0	0
17S/02W-SE	3,300	3,200	0	130
17S/02W-SW	2,800	2,300	370	150
17S/03W-NE	240	0	0	240
17S/03W-NW	830	14	0	820
17S/03W-SE	1,800	1,700	0	57
17S/03W-SW	170	24	0	150
17S/05W-NE	120	11	0	110
17S/05W-NW	11	0	0	11
17S/05W-SE	37	0	0	37
17S/05W-SW	130	100	0	27
18S/02W-NE	81	0	0	81
18S/02W-NW	200	0	0	200
18S/02W-SE	170	8	0	160
18S/02W-SW	53	5	0	48
18S/03W-NE	3,900	3,500	6	440
18S/03W-NW	15	0	0	15
18S/03W-SE	18	0	11	7
18S/03W-SW	0	0	0	0
19S/02W-NE	7	0	0	7
19S/02W-NW	99	4	0	95
19S/02W-SE	0	0	0	0
19S/02W-SW	1	0	0	1
19S/03W-NE	1,800	1,600	0	200
19S/03W-NW	35	0	0	35
19S/03W-SE	9	4	0	5
19S/03W-SW	0	0	0	0
20S/03W-NE	21	5	0	16
20S/03W-NW	0	0	0	0
20S/03W-SE	82	63	0	19
20S/03W-SW	21	4	0	17
Totals	339,605	71,025	72,417	195,369