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AN ABSTRACT OF THE THESIS OF

Evan S. Miles for the degree of Master of Science in Water Resources Science presented on March 14, 2011.
Title: A GIS Study of Benton County, Oregon, Groundwater: Spatial Distributions of Selected Hydrogeologic Parameters.

Abstract approved:

Michael E. Campana

Benton County has experienced substantial growth in the past 30 years, and is expected to continue growing (BCWP 2008). Continued development has occurred in the Willamette Valley, housing development in the nearby hills of the Coast Range is growing. New houses in the foothills of the Coast Range may not use municipal water supply and are generally supplied by domestic or community wells, which pump groundwater sourced from the local uplifted formation of the Siletz River Volcanics (SRV). Continued population growth is expected to rely heavily on the groundwater resources of the SRV.

The SRV are a series of accreted Tertiary submarine and subaerial basalt formations stretching from Northern California to Vancouver Island, composed of porous pillow basalt flows with interbedded semi-impermeable silts and shales. Flow occurs via basalt fractures and interflow zones in the SRV. The aquifer structure and flow mechanisms result in discontinuous perched and confined aquifers. Due to the structure and higher gradients of the flow zones in the SRV, aquifers are presumed to be heterogeneous, anisotropic, and leaky. Wells usually penetrate multiple saturated zones before sufficient yield is provided to supply a domicile.

The complex, unpredictable nature of the SRV has discouraged hydrogeologic studies, and the majority of studies are performed by consultants to evaluate a new water supply. The most recent comprehensive study of groundwater in Benton County that included the SRV as a water-bearing unit was a USGS Water-Supply Paper by F.J. Frank

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in 1974. The substantial recent development of the SRV has provided a large amount of new data, including well logs digitized by OWRD.

This thesis characterizes the SRV by developing hydrogeologic spatial datasets for Benton County. The study applies GIS methods to spatially distribute well log entries by Public Land Survey System (PLSS) units and by Address, resulting in a representative subset of the original data, with good spatial coverage, moderate resolution, and decent accuracy. Wells located within the SRV are spatially subset to provide insight about the formation, and spatial interpolations of common hydrogeologic parameters are performed leveraging the well distributions.

This study found that (relative to Benton County): the SRV have a lower well density, a higher percent of wells in the SRV have positive yields (84%), SRV wells have lower average well yields (19-22 gpm), appear to have a higher frequency of confined groundwater, and have much lower mean specific capacity (0.03 – 0.3 gpm/ft). More importantly, this study has taken a first step towards accomplishing some of the data needs established by Benton County. Additionally, fundamental LIDAR and spring location datasets were prepared for upper Oak Creek Watershed in association with this study, opening the door for subsequent topography-groundwater studies.

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A GIS Study of Benton County, Oregon, Groundwater: Spatial Distributions of Selected Hydrogeologic Parameters

by
Evan S. Miles

A THESIS

submitted to

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in partial fulfillment of
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degree of

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Master of Science thesis of Evan S. Miles presented on March 14, 2011.

APPROVED:

Major Professor, representing Water Resources Science

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Evan S. Miles, Author

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ACKNOWLEDGEMENTS

I would first like to thank my thesis committee for their interest, support and advice: Dr. Michael Campana, Dr. Roy Haggerty, and Dr. Jack Istok.

Additionally, Dr. Todd Jarvis provided the stimulus to work on this project and lended some of his experience in industry and academia.

Adam Stebbins was continually enthusiastic to further knowledge of Benton County’s groundwater.

Benton County, Oregon Water Resources Department, and OSU’s College of Forestry kindly provided much of base data used in these analyses.

I would like to thank the OSU Department of Geosciences and Oregon Explorer for opportunities to develop and apply my GIS knowledge, which proved crucial for this undertaking.

Most of all, I am grateful for my lovely wife Kathleen, who has encouraged me all along the way.

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1. INTRODUCTION

Benton County is situated between the Willamette River to the East, which forms the border of Benton County, and the Oregon Coast Range to the West. The County has experienced substantial growth in the past 30 years, and is expected to continue growing (BCWP 2008). Its setting has led to continued development in the Willamette Valley, but has also increasingly led to housing developments in the nearby hills of the Coast Range.

In the Willamette Valley, access to municipal water supply is easily developed, and few of the newer residences tap the groundwater within the sandstones and siltstones beneath them. For houses in the foothills, however, municipal water supply is not feasible due to substantial hydraulic differences. These homes generally are supplied by domestic or community wells, which pump groundwater sourced from the local uplifted formation of the Siletz River Volcanics (SRV), which supports the eastern flank of the Coast Range. Continued population growth is therefore expected to rely heavily on the groundwater resources of the SRV.

The SRV are a series of accreted Tertiary submarine and subaerial basalt formations stretching from Northern California to Vancouver Island. Due to their marine origin, the SRV is composed of porous pillow basalt flows with interbedded semi-impermeable silts and shales. Flow occurs via basalt fractures and interflow zones in the SRV. This structure and flow mechanism results in discontinuous perched and confined aquifers. Additionally, due to the structure and higher gradients of the flow zones in the SRV, aquifers are presumed to be heterogeneous, anisotropic, and leaky. Wells usually penetrate multiple saturated zones before sufficient yield is provided to supply a domicile.

The complex, unpredictable nature of the SRV has made hydrogeologic studies difficult, and the majority of such studies are site-based studies performed by consultants hired to evaluate a water supply. The most recent comprehensive study of groundwater in Benton County that included the SRV as a water-bearing unit was a USGS Water-Supply Paper by F.J. Frank in 1974. There has been substantial recent development of the

SRV, providing a large amount of new information on the formation. In particular, the Oregon Department of Water Resources (OWRD) has digitized well logs for the State of Oregon, allowing improved assessment of regional groundwater conditions.

This thesis aims to develop improved hydrogeologic datasets for Benton County, focusing on the Siletz River Volcanics to characterize the formation. The study applies GIS methods to spatially distribute well log entries by Public Land Survey System (PLSS) units and by Address. Wells located within the SRV can then be characterized as a distinct spatial subset of Benton County to provide insight about the formation. In addition, spatial interpolations of common hydrogeologic parameters are performed leveraging the well distributions. This allows a visual inspection of the spatial variability of the Siletz River Volcanics and Benton County as a whole.

2. BACKGROUND

The USGS Water-Supply Paper written by F.J. Frank in 1974 remains the standard reference for groundwater information in Benton County. Frank's clear summaries of the County's hydrogeology correctly anticipated contemporary groundwater development and concerns. Since 1974, additional data has become available in the forms of new well logs, hydrogeologic consulting reports, county-wide water assessments, and basin-wide groundwater characterizations. This chapter of the thesis intends to supplement Frank's work with contemporary sources of data, specifically acknowledging the Siletz River Volcanics as an increasingly-important source of groundwater.

Section 2.1 considers the three study areas of this thesis: Benton County as a while, the Siletz River Volcanics-related formations within Benton County, and Oak Creek Watershed. Section 2.2 summarizes the state of groundwater in four sections: Occurrence and Availability are discussed in Section 2.2.1; Recharge and Water-Level Fluctuations are considered in Section 2.2.2; Groundwater Quality is summarized in Section 2.2.3; Groundwater Data Needs are mentioned in Section 2.2.4.

2.1 Study Areas

Benton County is situated in Northwest Oregon and encompasses parts of the Coast Range and the Willamette Valley. This investigation considers three extents within Benton County: the entire county, the extent of local geologic formation the Siletz River Volcanics, and the watershed of Oak Creek. The geography and geology of each of these study extents will be described in Sections 2.1.1, 2.1.2, and 2.1.3, respectively. Figure 2.1 shows the location of each study extent for this thesis.

2.1.1 Geography and Geology of Benton County

Benton County is one of Oregon's smallest counties at 679 square miles (Oregon Blue Book 2011). It is bounded on the East by the Willamette River and contains drainage areas for the Mary's River, the Luckiamute River, Muddy Creek, and the Long

Tom River (tributaries to the Willamette), as well as the Alsea River, which drains to the coast. Benton County is bordered by Polk County to the North, Linn County to the East, Lane County to the South, and Lincoln County to the West. In the Public Land Survey System, Benton County is measured with respect to the Willamette Meridian, and contains land from Township 15 South, Range 9 West to Township 10 South, Range 3 West. Figure 2.2 includes a satellite image of the County, a topographic hillshade, and the County's populated places and roads. Figure 2.3 shows land use/land cover for the County.

The county was reported to have a population of over 82,835 individuals in 2005 (OCR 2010), containing several modest population centers. Incorporated cities within Benton County are Corvallis (pop. 55,125), North Albany (6,984, 2000 Census), Philomath (4,640), Adair Village (930), and Monroe (690) (Oregon Blue Book 2011). Additional communities are Alpine, Alsea, Bellfountain, Kings Valley, Lewisburg, and Wren. The county has grown approximately 5.7% from 2000 to 2009 according to the US Census (United States Census Bureau 2010). The 1990 Census counted 70,811 residents of Benton County, corresponding to a 17.0% population growth over 15 years (OCR 2010).

The climate of Benton County is considered modified Mediterranean, with warm and dry summers and cool, wet winters. The hottest months are July and August, with monthly average temperatures over 80 degrees Fahrenheit. The coldest and wettest month is January, with temperatures from 33 to 46 degrees Fahrenheit and mean monthly precipitation over 6.5 inches. Total precipitation for Corvallis averages nearly 41 inches on an annual basis, with an average on 6 inches of snowfall. A climatograph for Corvallis is shown in Figure 2.4 (WRCC 2010). It is additionally important to note that Benton County's summer is characterized by a 30-60 day drought with minimal precipitation (Frank 1972). Corvallis's elevation of 224 ft MSL is fairly representative of the Willamette Valley, but the high point of Oregon's Coast Range lies within Benton County: the summit of Mary's Peak at 4097 ft. The mountains of the coast range often attain heights over 2000 ft, and these peaks receive a larger portion of seasonal snow due to their elevation.

Two predominant natural features define the topography of Benton County. To the West, the Coast Range is a jumble of deformed marine terranes accreted to the North American Plate by the subduction of the Juan de Fuca and other marine plates (Duncan 1982). The foothills of these peaks extend North-East and South from the middle of Benton County. From these foothills, the Willamette Valley extends East for nearly 50 miles into Linn County and to the Cascade Range, a volcanic arc also associated with the Cascadia Subduction Zone. The Willamette Valley may be characterized as a large alluvial plain being filled with debris from the Coast and Cascade Ranges by the tributaries of the Willamette River (Frank 1972, Yeats et al. 1996).

Much of Benton County itself drains into the Willamette River, the 13th largest river in the conterminous United States. The county contains drainage areas for several major Willamette tributaries, including: the Mary's River, the Luckiamute River, Muddy Creek, and the Long Tom River. In addition, the Southwest corner of Benton County drains into the Alsea River, which flows West through the Coast Range into the Pacific Ocean.

Geologically, Cascadia Subduction Zone has most influenced the formation of the region (Gannett and Caldwell 1998). The subduction of the Farallon, Kula, Juan de Fuca, and Pacific plates has led to the formation of the Cascade Range of volcanoes from Northern California to Southern British Columbia (Gannett and Caldwell 1998). The Willamette Valley formed as a fore-arc depression in parallel to this process (Gannett and Caldwell 1998), located between the volcanoes to the East and formations accreted to the North American Plate from the subducting oceanic plates to the West (O'Connor et al. 2001). Uplift led to draining of the depression at least 15 mya (O'Connor et al. 2001), and for the past 2.5 million years the Valley has been filled by streams (Yeats et al. 1996) draining the Siskiyou Mountains (from the South), the Cascade Range (East), and the Coast Range (West). Floods from Glacial Lake Missoula have also played an important role distributing silts and alluvium throughout the Valley, depositing up to 35m (O'Connor et al. 2001).

Benton County's eastern lowland area contains marine siltstones and sandstones overlayed by a series of alluvial and silt deposits. To the West, the uplifting Oregon Coast Range is delineated from the Valley alluvial deposits by the Corvallis Fault, which does not show contemporary evidence of slip (Goldfinger 1990). The Coast Range is a deformed mixture of marine sediments, submarine volcanics, and igneous intrusives (Yeats et al. 1996, Gannett and Caldwell 1998). Figure 2.5 produced by Benton County (BCWP 2008) delineates the major formations in the County.

2.1.2 Siletz River Volcanics Study Area

The portion of the Siletz River Volcanics within Benton County was the extent of several GIS analyses performed in this study (Figure 2.6). Much of the area of the SRV related units in Benton is publicly owned forest, including the Siuslaw National Forest, and maintained for uses such as timber harvest and municipal water-supply source area (BCWP 2008). Additionally, several small communities are located above SRV bedrock, and larger municipalities (Corvallis and Philomath) are directly adjacent to the unit.

The local SRV formation has become increasingly important for water supply in the last 30 years. Growth of Benton County has largely occurred near the communities and municipalities adjacent to the SRV, and housing development has occurred especially in the foothills of the Coast Range (BCWP 2008). Due to the elevation of these houses, municipal water supply is not feasible, resulting in increasing concentrations of domestic wells in the SRV (BCWP 2008). Benton County has developed a map of estimated well concentrations, Figure 2.7.

The local unit of Siletz River Volcanics is part of a regional series of formations, extending from Northen California to Vancouver Island. These accreted submarine and subaerial basalts form the backbone and basement of the Coast Range (Duncan 1982). Figure 2.8 shows the distribution of related units, according to Duncan (1982). The formations originated as a sequence of spreading-center hot-spot volcanoes on the Kula and Farallon plates about 55 mya (Duncan 1982). As the plate spread, a chain of seamounts and islands was formed, composed of the submarine and subaerial basalts. About 30 mya, this massive submarine formation ("Siletzia") reached the Cascadia Subduction Zone, and was accreted to the North American Plate, accompanied by marine sediments. The continued addition and uplift of marine-sourced material has led to the formation of the heterogeneous Coast Range (Yeats et al. 1996, Gannett and Caldwell 1998).

Locally, the SRV is an important source-area substrate for many streams and rivers. Figure 2.9 shows the regional distribution of the SRV formations and watersheds of important gaged streams. Table 2.10 summarizes the stream gage records maintained by the USGS for local watersheds with high portions of SRV source area. The Coast Range watersheds often fall into a temperate rainforest climate with over 80 inches of precipitation annually (WRCC 2010).

2.1.3 Oak Creek Study Area

Additionally, field work was carried out in a 4th-order watershed of 13 square miles (IWW 2008) near Corvallis to locate the headwater springs of the stream (Figure 2.11). Oak Creek is a tributary to the Mary's River, and 40% of its watershed is owned by Oregon State University. Land use includes agriculture, pasture, recreational forest, logging and research forest, and part of OSU's urban campus (IWW 2008). In particular, the watershed's Main Stem Sub-basin (3.92 square miles) includes part of McDonald-Dunn Forest, a research forest owned by OSU. This study examines the locations and distributions of headwater springs in Oak Creek's Main Stem Sub-Basin.

The Oak Creek Watershed, and particularly the Main Stem Sub-basin, is a useful study site for many reasons. Land use is well-documented and static. Due to its large university ownership, several class studies have worked to understand the water resources of the Watershed. The Sub-Basin's bedrock is the Siletz River Volcanics, and its Coast Range headwaters receive a higher annual precipitation (70-75 inches) than the Willamette Valley, while the lower portion of Oak Creek flows through Quaternary alluvial terraces and typifies the Willamette Valley (IWW 2008). 1m-resolution Digital Elevation Models are available covering the watershed as a whole. Although Oak Creek does not have a stream gage, efforts have been made to compare Oak Creek's discharge to that of the Mary's River (IWW 2008).

2.2 Groundwater of Benton County

The Benton County Water Project: Phase 1 recently estimated that only 10-20 percent of the County's water needs are sourced from groundwater (BCWP 2008). However, the report also acknowledged that Benton County has experienced substantial growth, which is forecast to continue. As much of this growth is expected to occur in the foothills of the Coast Range, the groundwater resources of upland aquifers are anticipated to be increasingly harnessed. This section of the study summarizes the state of groundwater in Benton County, with particular emphasis on the Siletz River Volcanics.

2.2.1 Occurrence and Availability

Groundwater occurrence and availability is constrained by the geologic composition of Benton County. This section will begin by characterizing the principal hydrogeologic units shown in Figure 2.5. In recent years, regional geologic and hydrogeologic studies have thoroughly characterized the history and subsurface of the Willamette Valley (Yeats et al.. 1996, Gannett and Caldwell 1998, Woodward et al.. 1998, O'Connor et al.. 2001, and Conlon et al.. 2005), and models have synthesized the basin's water quality (Orzol et al. 2000, Mutti 2006) and flowpaths (Craner 2007).

These studies have generally focused on the Willamette Valley, considering the Coast Range substrate as lateral confining units. As this study focuses instead on the distribution of hydrogeologic parameters within Benton County, the simpler framework developed by Benton County and based on Frank (1974) is instead applied. Important hydrogeologic units within the County are then (according to increasing age) the young alluvium (QYAL), the older alluvium (QOAL), marine siltstones and sandstones (TSS), and the Siletz River Volcanics (TSR). The suitability of each of these units for groundwater development will be summarized sequentially. A conceptual block diagram prepared by Dr. Todd Jarvis of OSU gives some perspective of the County's substrate (Figure 2.12).

Wells producing water from the QYAL generally have the highest yields (hundreds of gallons per minute) in Benton County. This young unconsolidated deposit of sand, gravel, and cobbles up averaging 35 ft of thickness and is the active floodplain of the Willamette River (Frank 1974). The unit's shallow groundwater table actively exchanges water with the River, allowing for very large yields locally. These deposits are suitable for municipal and agricultural development, although they are also extremely vulnerable to groundwater contamination. Frank (1974) characterizes specific capacities in the tens and hundreds of gpm per ft, but notes that the unit's heterogeneity leads to lower production in some areas.

The QOAL underlies the QYAL, and is exposed further west in the Willamette Valley. Accumulated as former river terraces over many thousands of years, the QOAL is formed of interconnected lenses of sand and gravel, and is generally finer than the QYAL (Frank 1974). The QYAL and QOAL formations are separated by several feet of the Willamette Silt, an aquitard attributed to the Missoula Floods (Conlon et al. 2005). The QOAL directly overlies eroded siltstones and sandstones, giving it extremely variable thickness. The substrate composition and well yields are also highly variable, but wells generally yield moderate quantities of water (50-100 gpm), while specific capacities are in the single digits (Frank 1974). The unit is suitable to supply domiciles and small farms, but Benton County has received complaints of water loss in the unit (BCWP 2008).

Consolidated Tertiary marine siltstones and sandstones (TSS) underlie the QOAL and form many of the Coast Range's foothills and much of western Benton County (Figure 2.5). For the purpose of this study, the Tyee and Spencer Formations are considered a single hydrogeologic unit due to their similar properties (Frank 1974). The TSS and TSR units have been combined as the Basement Confining Unit for many Willamette-focused groundwater studies as they are generally less conductive of water

(Gannett and Caldwell 1998, Woodward et al.. 1998, O'Connor et al.. 2001, Conlon et al.. 2005, Craner 2007). Composed of fine siltsone, sandstone, and shale, the TSS are an important water-bearing unit for Benton County due to their proximity to population centers. These formations generally yield small quantities of water only suitable for domestic use (Frank 1974, BCWP 2008).

Finally, the marine volcanics (TSR) called the Siletz River Volcanics underlie the majority of the area (Yeats et al. 1996) and support the mountains of the Coast Range. Delineated from the eastern portion of the County by the Corvallis fault, this is an important source of water for residents in the Coast Range, and will be increasingly important in the future. The SRV are composed of submarine and subaerial pillow basalts (Duncan 1982) interbedded with marine silts and shales (Yeats et al. 1996). Flow occurs via fractures in the pillows as well as via basalt interflow zones (EGR 1994, Braun 1995, EGR 1998). The semi-impermeable interbedded marine silts may act as confining units, resulting in perched water tables and confined lenses of groundwater.

The heterogeneity and fracture-flow of the unit makes planning difficult, because the aquifer structure is variable. Yields in the TSR are generally sufficient for domiciles (Frank reports mean yields of 10-20 gpm), and can be improved by drilling deeper wells to penetrate multiple water-bearing zones (Frank 1974). Nonetheless, housing development in the low-storage aquifer has led to concerns of potential well interference and overuse, as the unit is the only viable source of water for many County residents (BCWP 2008). Specific capacities according to Frank (1974) are about 0.5 gpm/ft, and average well depths are nearly 200 ft to access sufficient water.

2.2.2 Recharge and Water Level Fluctuations

Recharge to Benton County's groundwater occurs primarily by fall and winter precipitation, although within the Willamette Valley recharge may also occur due to irrigation return and bank storage, depending on conditions. Following the area's characteristic summer drought, the soil becomes wetted by autumn rainfall (Figure 2.4), and the soil is generally saturated by November (Frank 1974), allowing infiltration to the subsurface. The subsequent late spring and summer result in water level declines, as groundwater flows downgradient and discharges at springs. Recharge rates estimated for the Willamette Valley by Woodward (1998) were between 18.1 in. and 21.4 in., while Braun Intertec Northwest (2005) reports a study that estimated 27 – 35 in. of recharge annually in the SRV.

The annual recharge-discharge cycle is evident in monitoring wells, but varies in depth and timing by hydrogeologic setting. Figures 2.13 and 2.14 show USGS monitoring well records in Benton County, exhibiting a clear annual cycle. The well exhibited in Figure 2.13 penetrates the QOAL near Philomath and shows an annual fluctuation of 6-7 ft, which is comparable to Frank's estimate of 10-12 ft. The well exhibited in Figure 2.14 penetrates the TSS West of Blodgett and shows an annual fluctuation of 7 ft. Meanwhile, data from Cascade View County Service District wells (Figure 2.15) in the SRV Northwest of Lewisburg shows variable fluctuations. Some wells fluctuate about 10 ft annually, while a deeper well fluctuates about 100ft annually. The study referenced by Braun Intertec Northwest indicated average annual fluctuations greater than 35 ft, also penetrating the SRV.

2.2.3 Groundwater Quality

Undisturbed, Benton County's groundwater is generally within prescribed health limits (Orzol et al. 2000). Additionally, regional groundwater quality monitoring is improving substantially in the Willamette Valley, but thorough documentation still does not exist for much of the County. Some aquifers within the County are more vulnerable to groundwater contamination, particularly closer to the Willamette River.

High rates of anthropogenic nitrate have been documented in the Southern Willamette Valley, including a portion of Benton County adjacent to the Willamette River (Mutti 2006). The affected zone encompasses the unconfined QYAL units, whose boundaries delineate the Southern Willamette Valley Groundwater Management Area formed by Oregon's Department of Environmental Quality (BCWP 2008).

The QOAL unit is documented to contain generally high quality water, although moderate to high concentrations of iron and manganese have been encountered (Frank 1974). Poor water quality has been observed in the TSS formations, which begin to exhibit saline water at depths over 100 ft. These formations have low permeability that limits freshwater exchange, allowing the rocks to retain saline content in the older marine substrate. (BCWP 2008)

Within the SRV, water quality has generally been satisfactory. According to samples tested by Braun Intertec Northwest (1995), water in the SRV is low in dissolved solids, and a low level of iron was the only detectable metal. Although neighboring formations in the Coast Range have exhibited high concentrations of Arsenic, samples in Benton County have not exceeded the Maximum Contaminant Level (MCL) set by the Environmental Protection Agency (Hinkle and Polette 1999). Occasional samples test positive for Volatile Organic Compounds at a very low level (EGR 1994). Coffin Butte Landfill performs groundwater monitoring to meet its environmental protection requirements, and reports background water quality of drinking water standards (Tuppan 2009). A related formation of the Siletz River Volcanics near Dallas, Oregon, has exhibited increasing salinity at depths of 2000 ft (Golder 2005).

2.2.3 Groundwater Data Needs

As a part of the Benton County Water Project, County planners have been considering their current future needs in terms of groundwater data (BCWP 2008). Several of the questions necessitate a social study, but a subset of the questions have technical hydrogeologic aspects (list adapted from BCWP 2008):

A. How to determine or refine groundwater boundaries and impacts upon the resource?
B. Data on estimated water use from domestic and community wells was developed and should continue and be expanded to better understand groundwater demand.
C. Determine the amount of water used across parcel sizes, property ownership, and microclimates within the county. This could occur through collaboration with community utilities, well-level monitoring and reporting by volunteers.

D. Identify the specific location of domestic, deepened, and abandoned wells within the county.
E. Well-to-well interference issues were identified throughout the county within Marine Sediment and Sandstone and the Siletz River Volcanics Principal Hydrogeologic Areas.
F. Develop a method to determine aquifer and well yields and the social methods for dealing with current and potential conflicts (e.g. incentive, regulatory, etc.).
G. Inventory the storage and management methods used by private and community groundwater users to better understand the range of existing best management practices and possible water supply solutions for groundwater users.
H. Compile well-level data from federal, state, and local sources with increased state and federal monitoring being promoted by Benton County through observation wells and voluntary groundwater monitoring/reporting.
I. Compile and review well water quality monitoring records at the county level from state, university, and federal records. This could include residents directly reporting water quality from private wells.

In addition, Benton County was able to identify several areas of concern, where study and monitoring should take priority (Lin et al. 2009). The areas included were (shown in Figure 2.16):

1. Thousand Oaks area: This area has a lot of well deepenings, complex geology and neighbors have already expressed concern over the new Pettibone/Thousand Oaks partition. The exact location of the Corvallis fault is unknown here, so a determination of a larger area was made to monitor on both sides of the fault.
2. Brandis: New subdivision and reported problem area by residents.
3. Wren Hill: Developer and hydrogeologist have already been monitoring for a year and have agreed to share monitoring data with Benton County within these volcanics.
4. Alpine: Sedimentary rock, well drillers comments about dropping water levels, combined with several deepened wells.

A potential fifth area immediately south of Corvallis city limits requires additional information and research in order to determine if it will be included as a priority monitoring area.

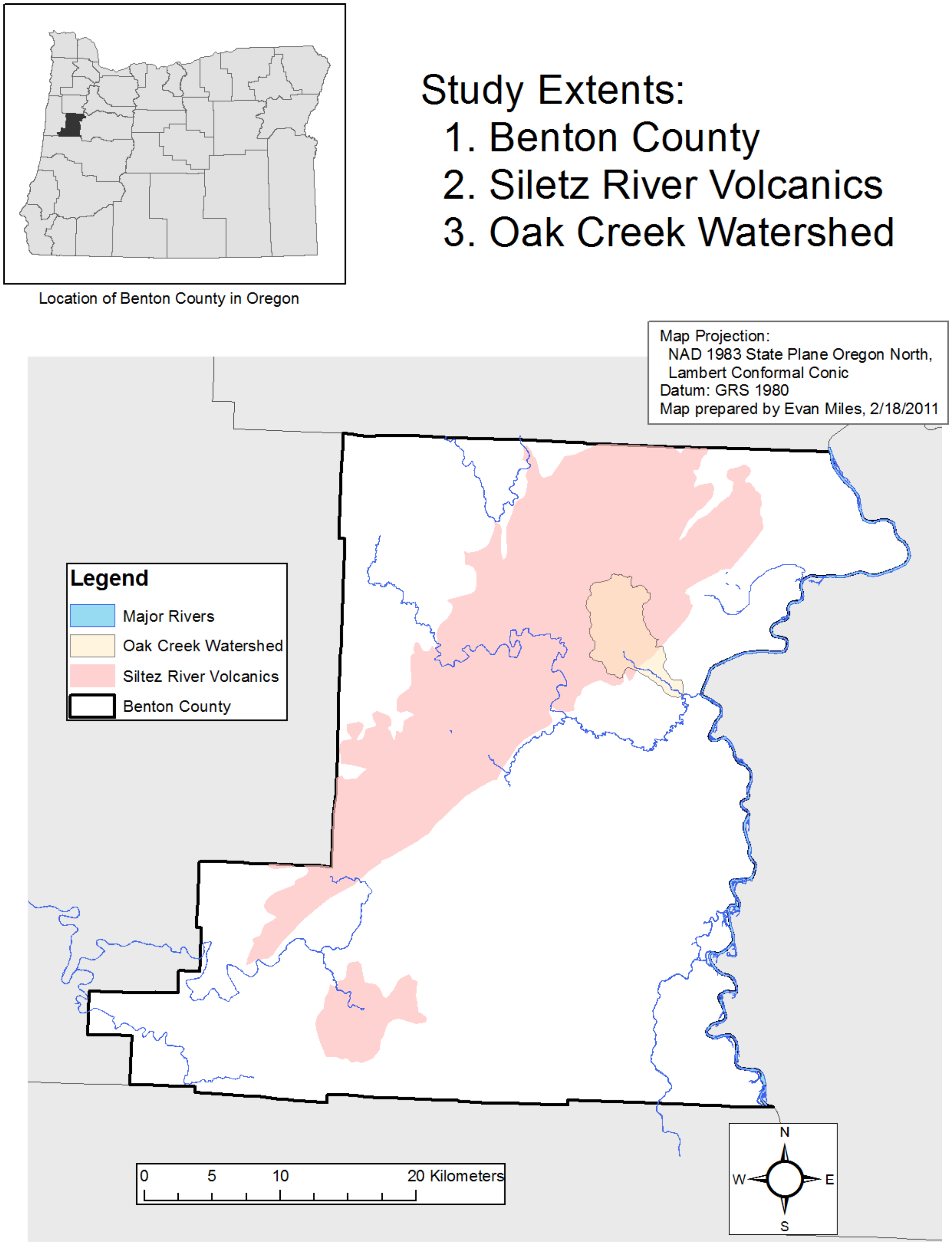


Figure 2.1 Extent of study areas analyzed in this paper.

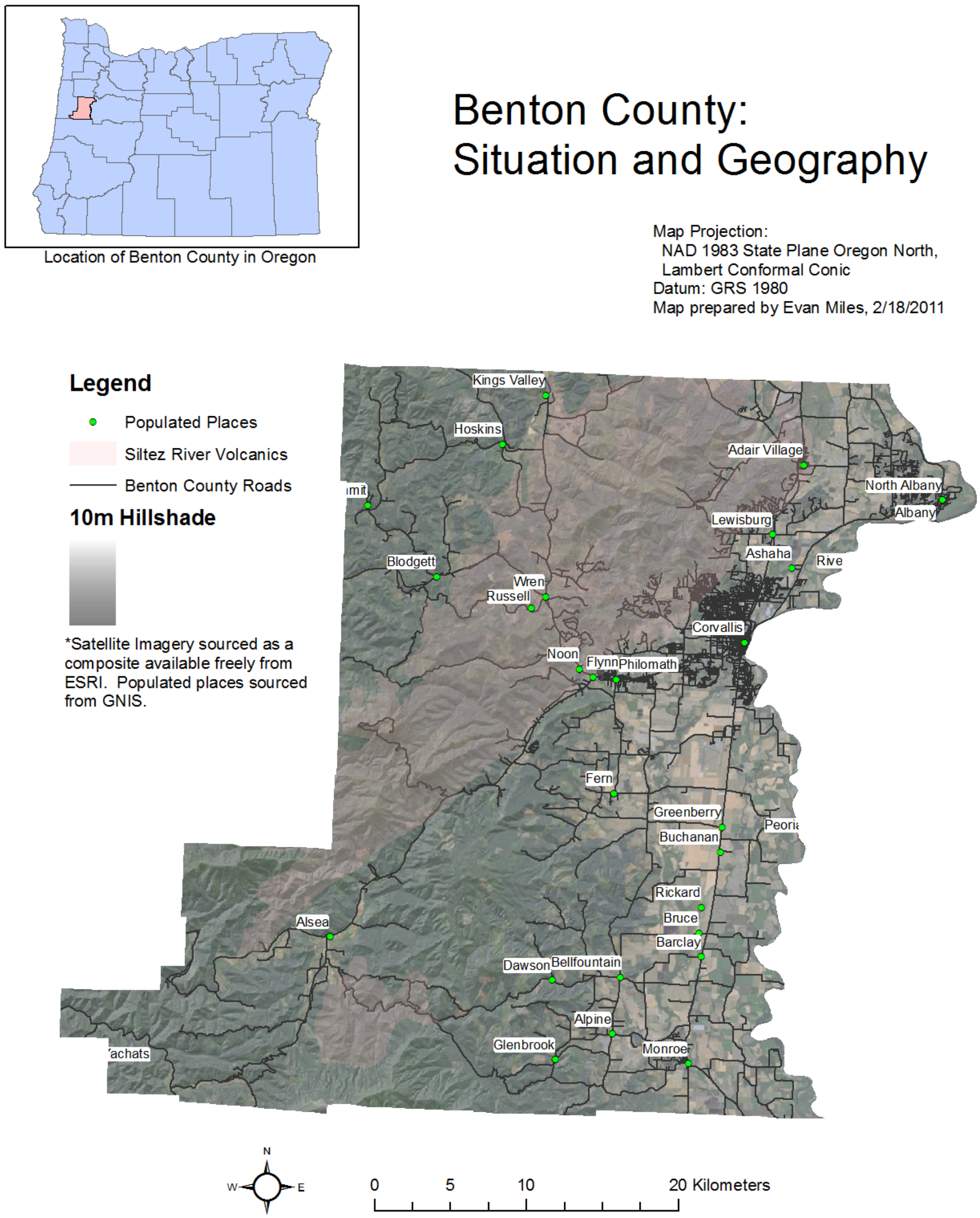


Figure 2.2 Topographic hillshade and satellite image of Benton County.

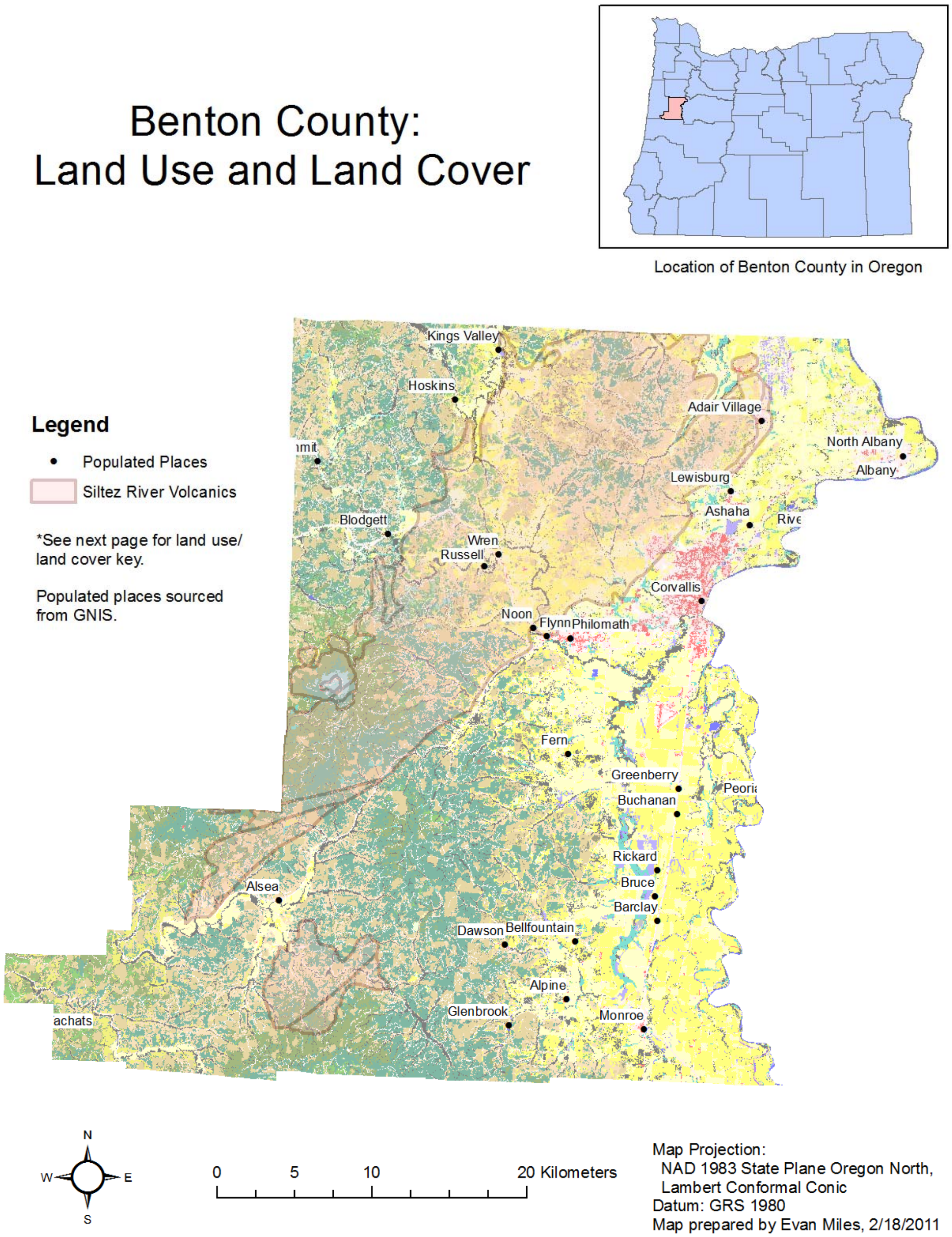


Figure 2.3 Land use and land cover within Benton County.

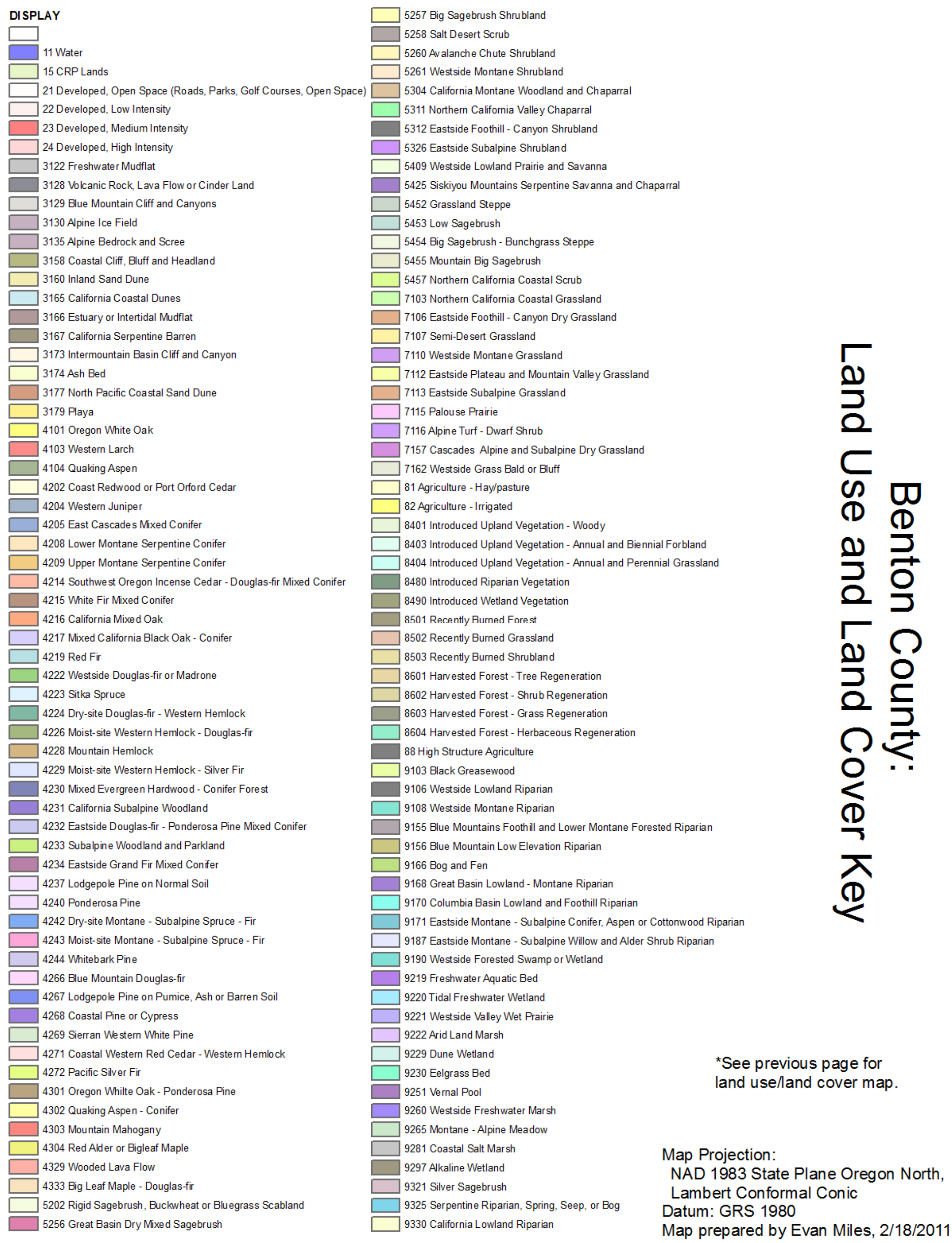


Figure 2.3 Cont'd. Land use and land cover within Benton County. Key.

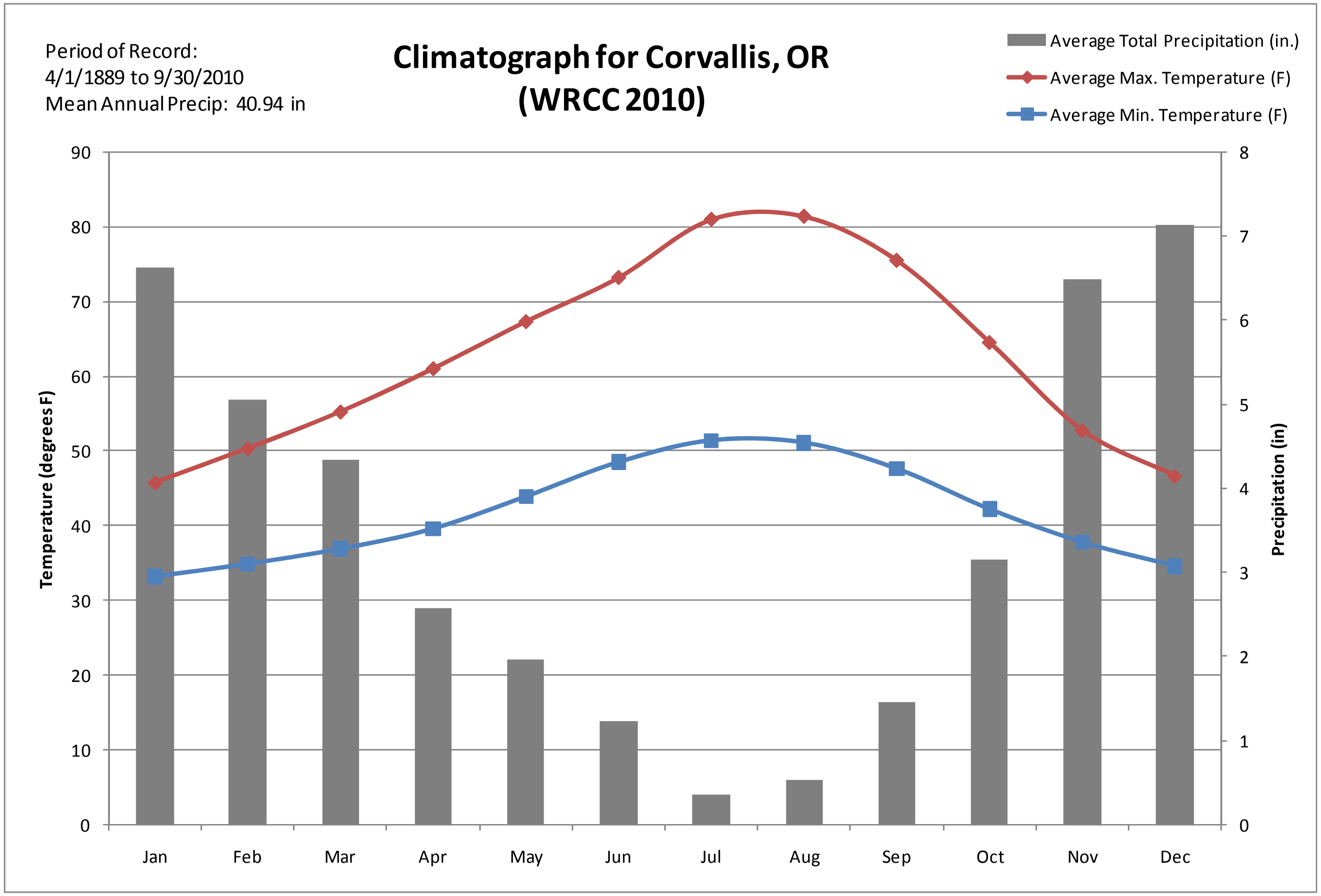


Figure 2.4 Climatograph of Corvallis, OR, prepared using WRCC 2010 data.

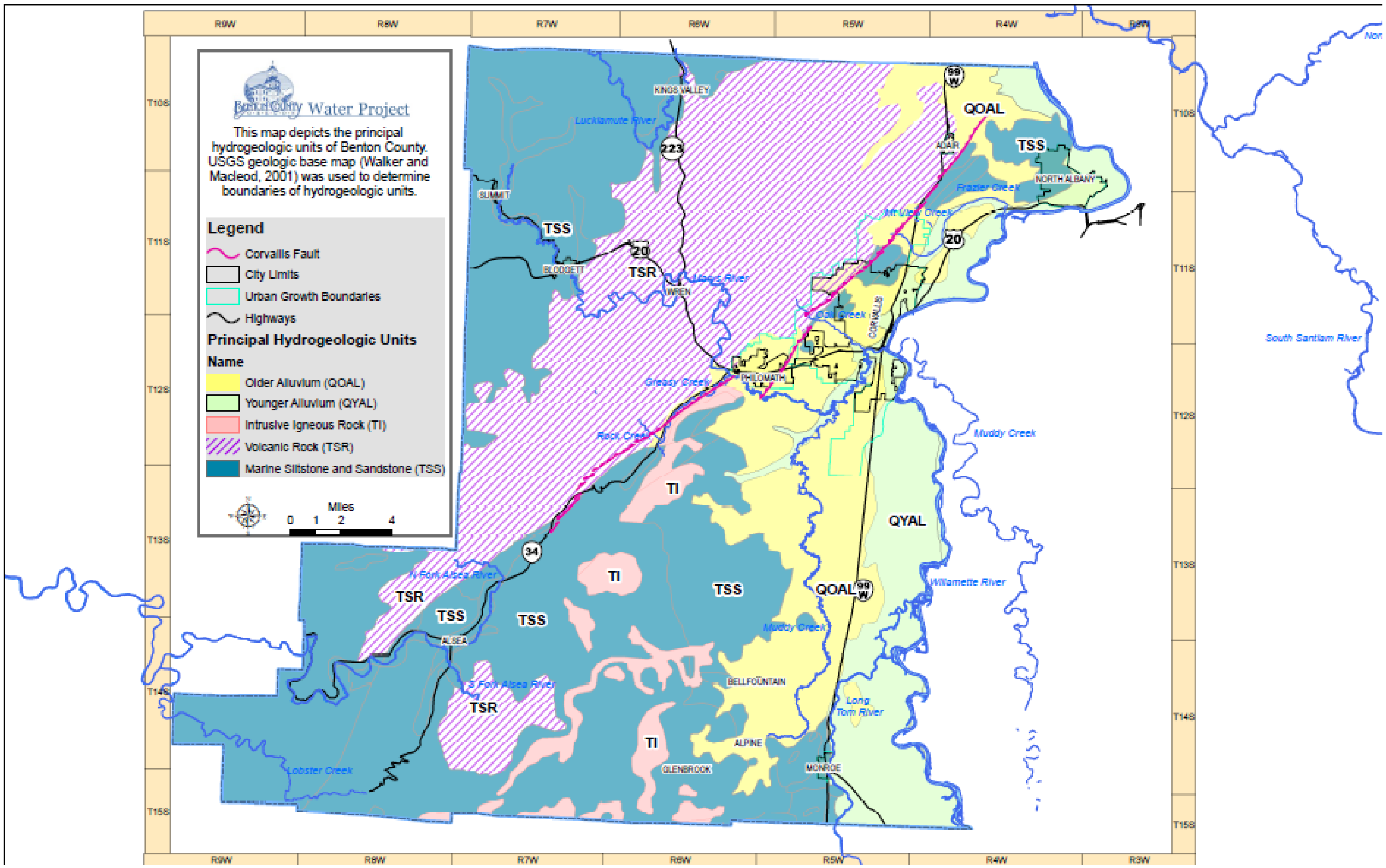


Figure 2.5 Hydrogeologic map, showing principal units. Courtesy Benton County.

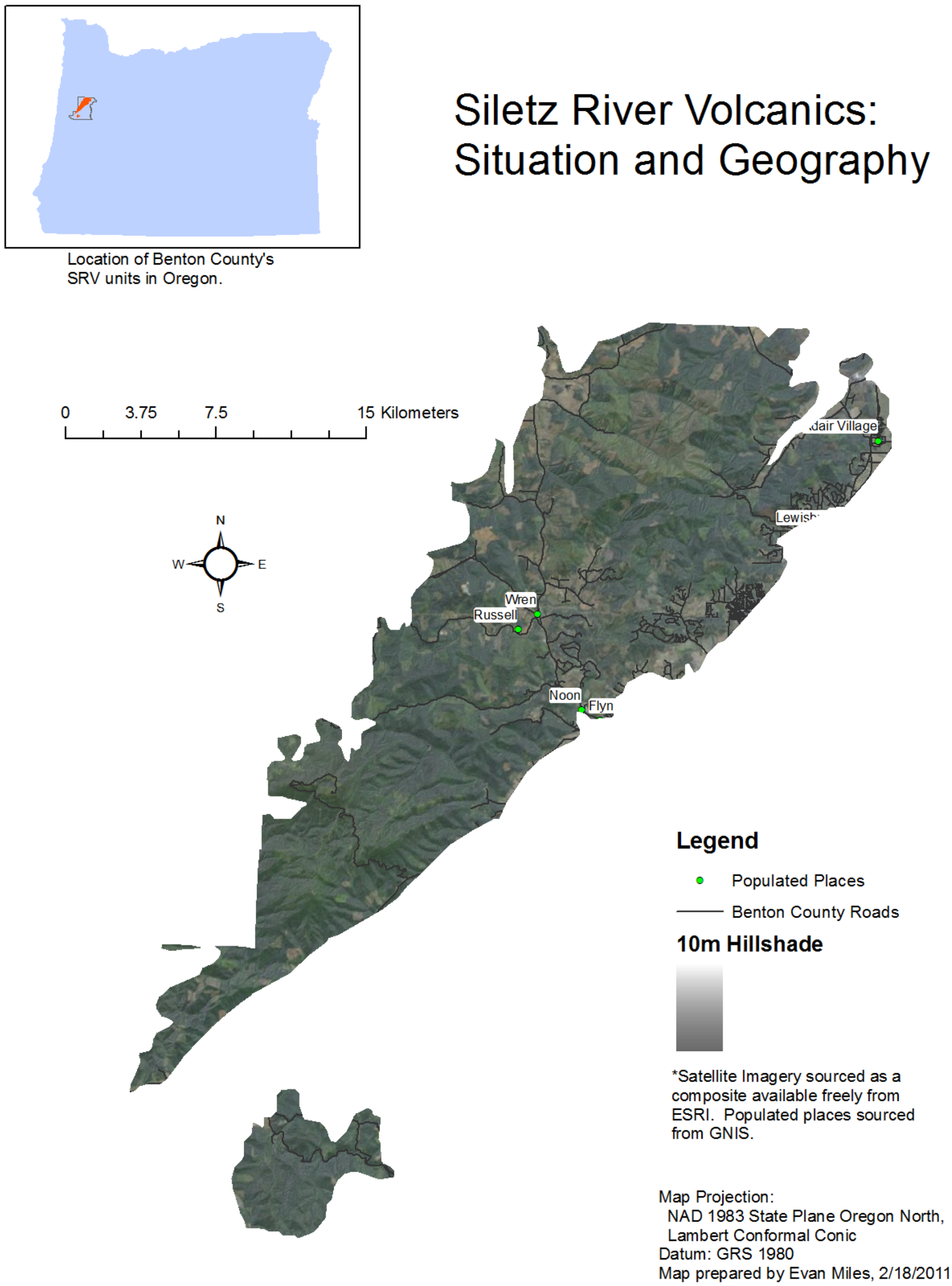


Figure 2.6 Topographic hillshade and satellite image of the Siletz River Volcanics.

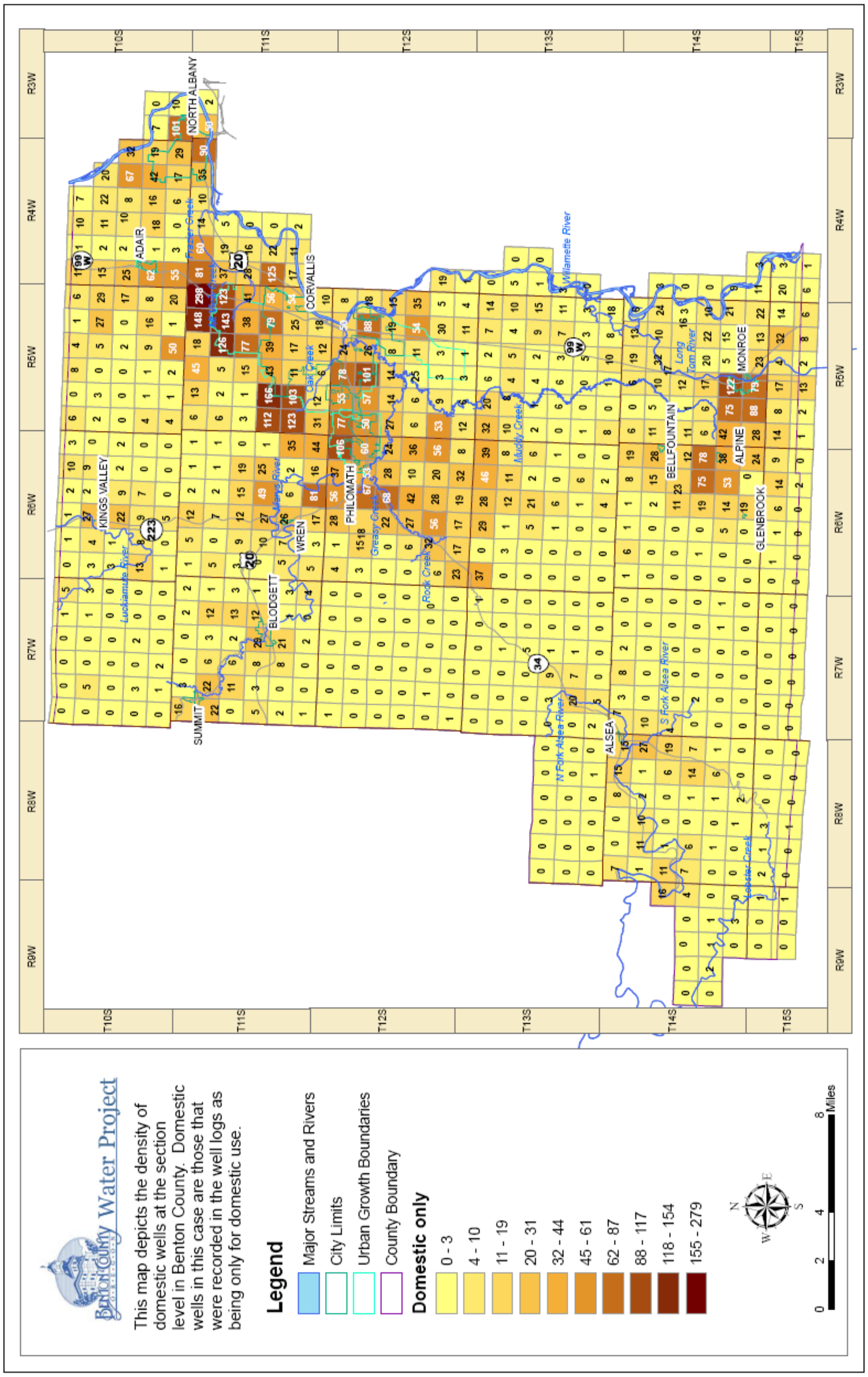


Figure 2.7 Domestic wells per PLSS Section. Courtesy of Benton County.

Figure 2.7 Domestic wells per PLSS Section. Courtesy of Benton County.

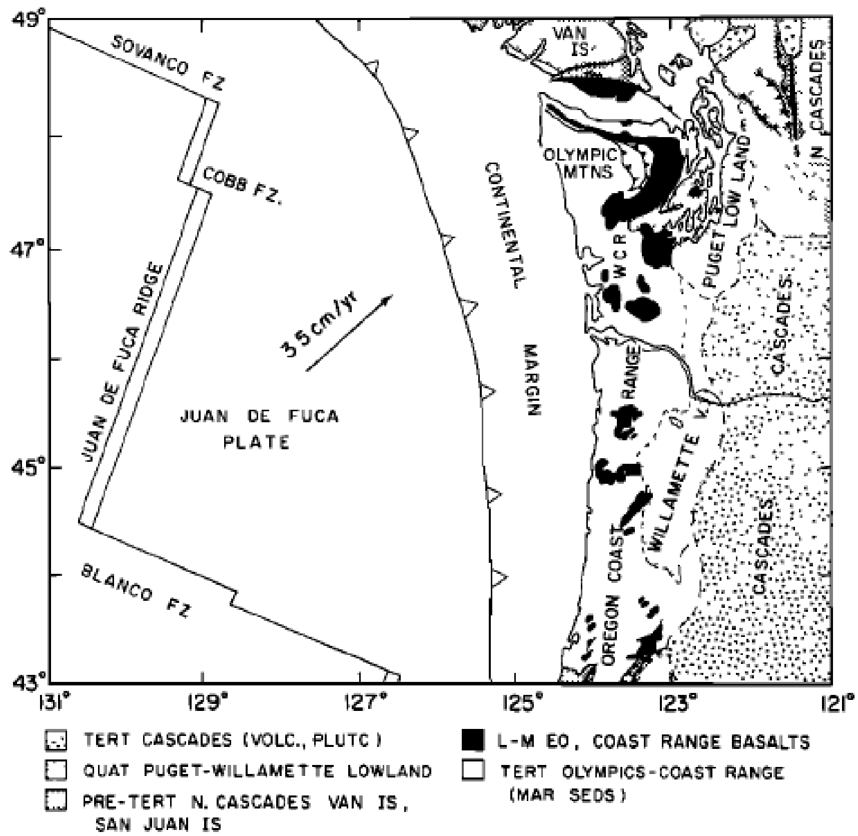


Figure 2.8 Units associated with the Siletz River Volcanics (Duncan 1982).

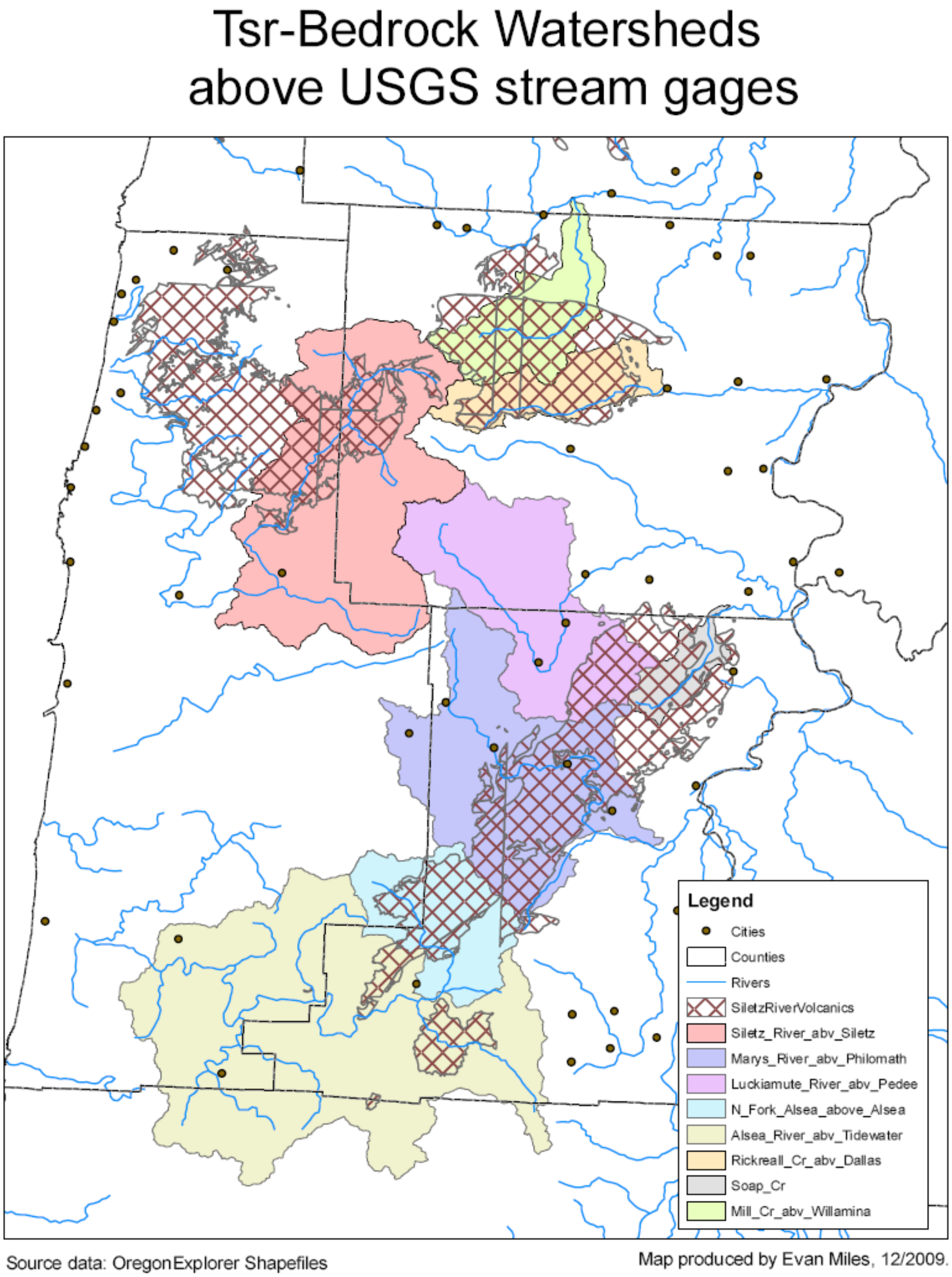


Figure 2.9 Gaged watersheds with SRV headwater source area in Benton, Lincoln, and Polk Counties.

Stream	USGS Gage #	Gage Location	Start Year	End Year	# Years	Mean Annual Flow (cfs)	Drainage Area (mi2)	%SRV above gage
Soap Creek	No Gage							77.85%
Rickreall Creek	14190700	Dallas	1958	1978	20	144.9	27.4	72.62%
Mill Creek	14193300	Willamina	1958	1973	15	139.5	27.4	68.63%
Alsea North Fork	14306100	Alsea	1957	1989	32	275.4	63	45.86%
Mary's River	14171000	Philomath	1940	2009	69	447.7	159	42.49%
Siletz River	14305500	Siletz	1905	2009	104	1499.8	202	22.38%
Luckiamute River	14190000	Pedee	1940	1970	30	458.3	115	15.41%
Alsea River	14306500	Tidewater	1939	2009	70	1456.4	334	13.31%

Table 2.10 USGS-gaged watersheds with SRV headwaters in Benton, Lincoln, and Polk Counties.

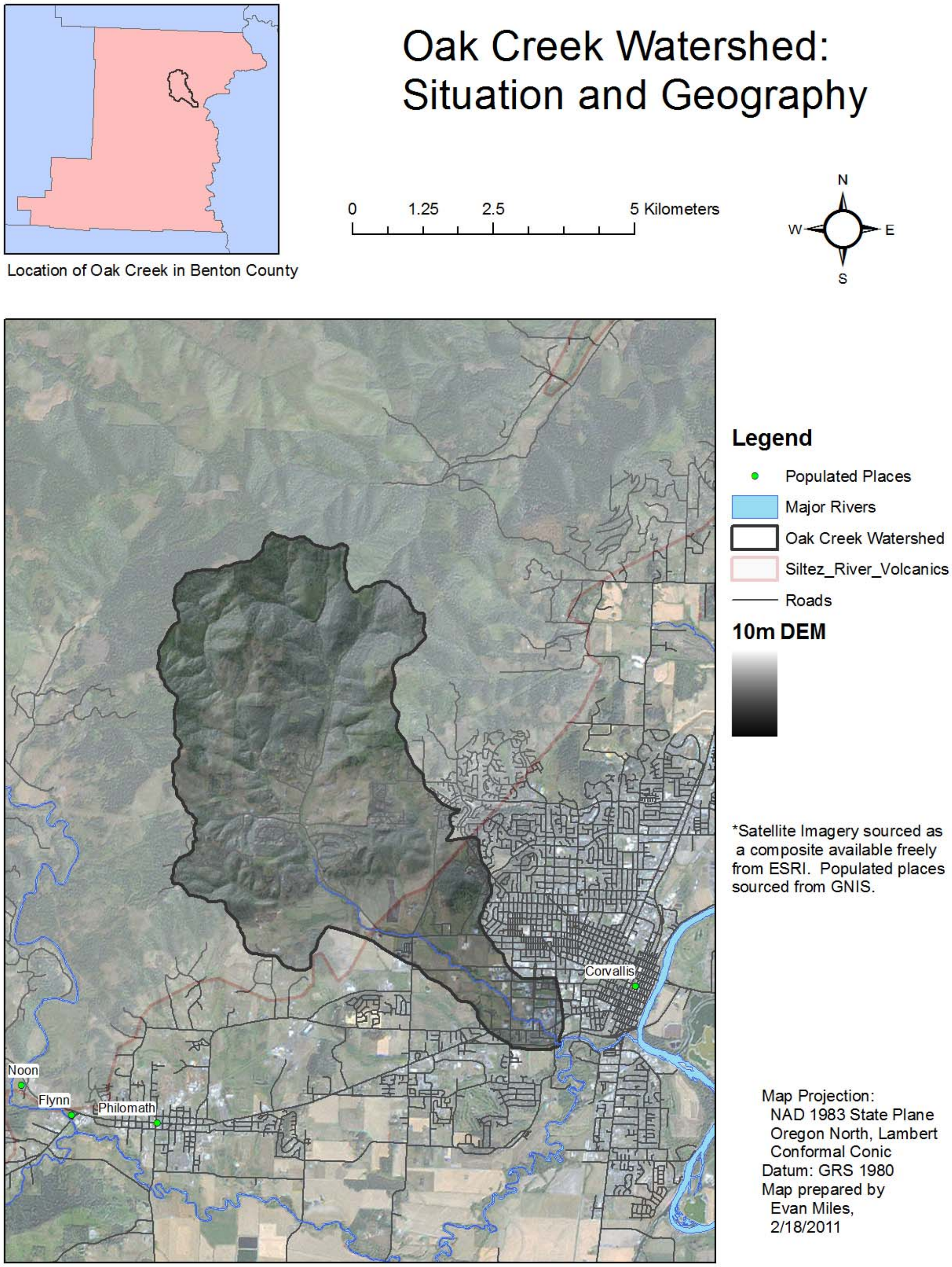


Figure 2.11 Location and extent of Oak Creek Watershed.

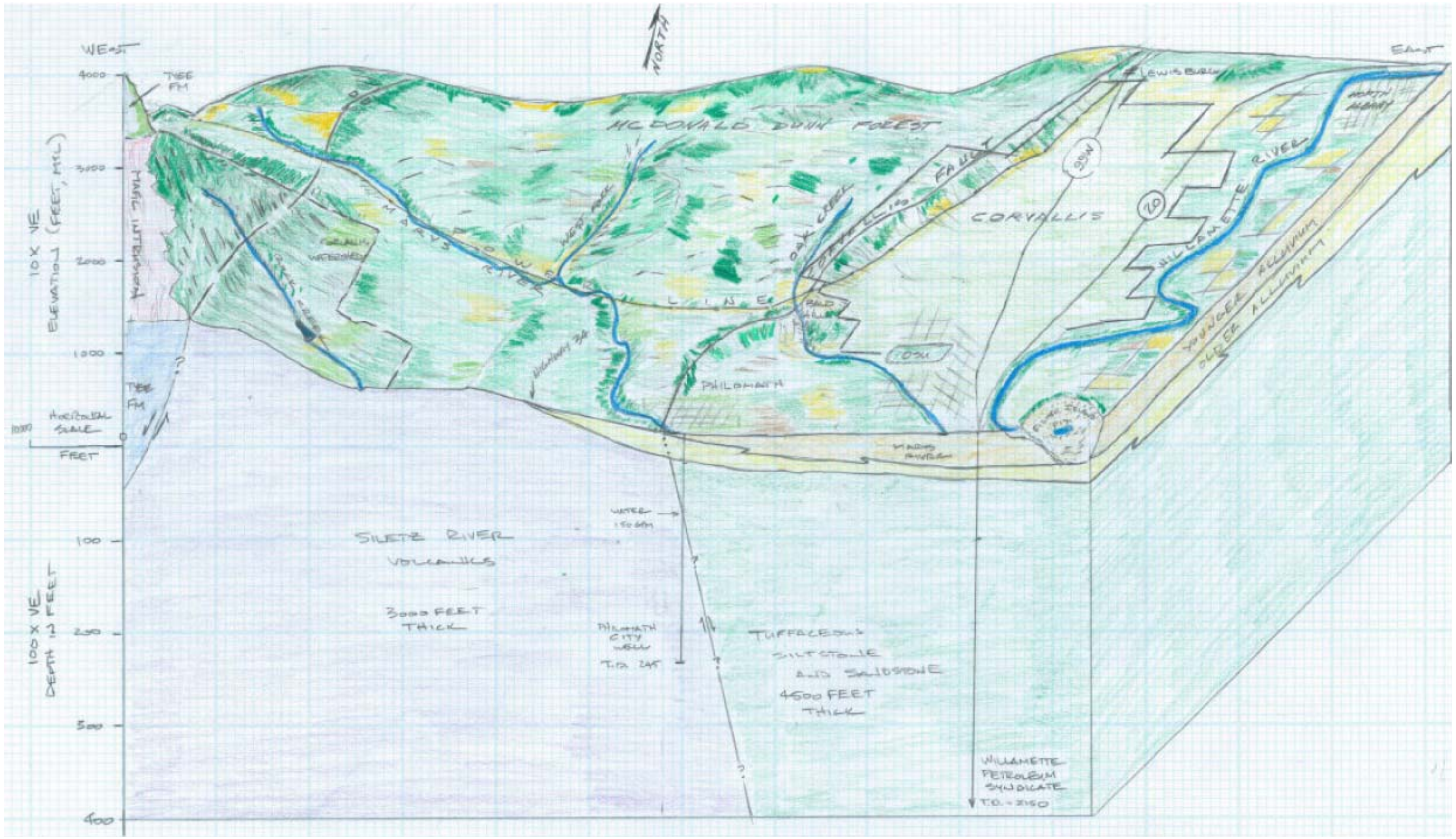


Figure 2.12 Benton County hydrogeology conceptual diagram, courtesy of Dr. Todd Jarvis, IWW, OSU.

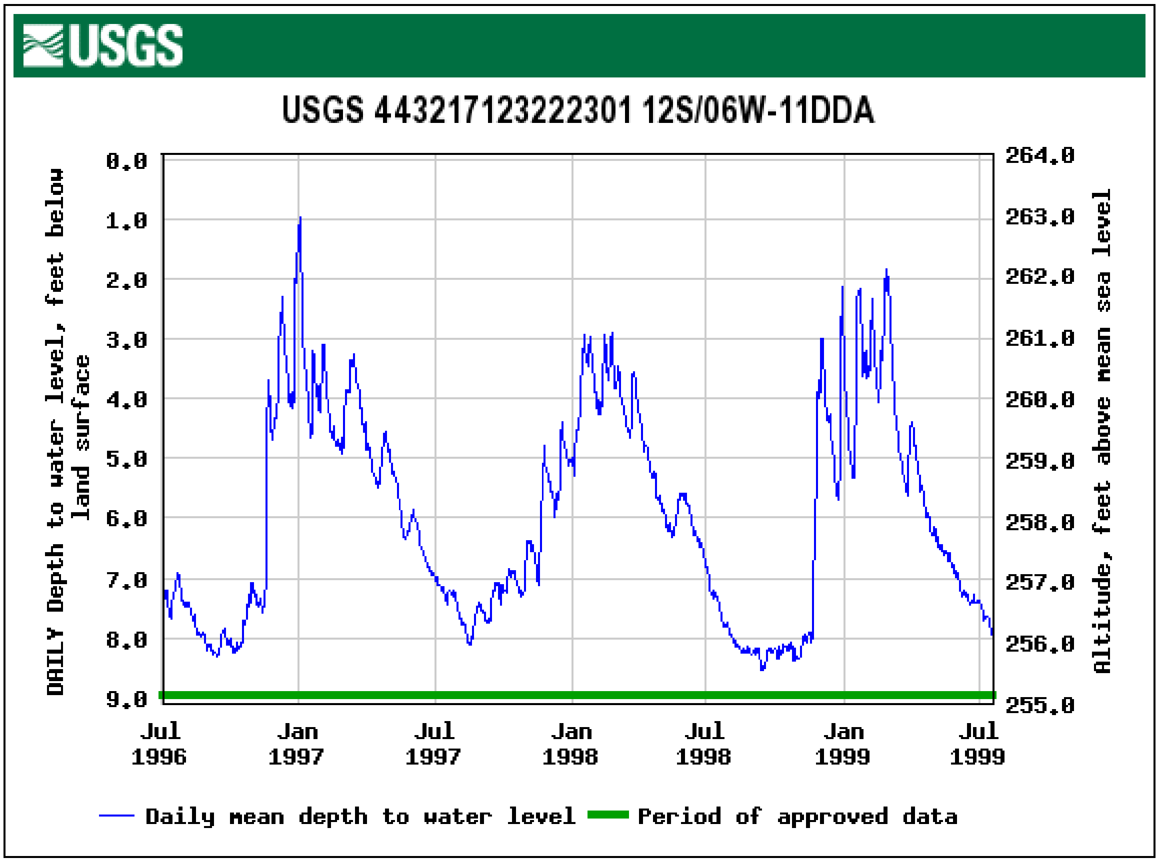


Figure 2.13 Chart of depth to water for a USGS monitoring well near Philomath. Courtesy of the USGS.

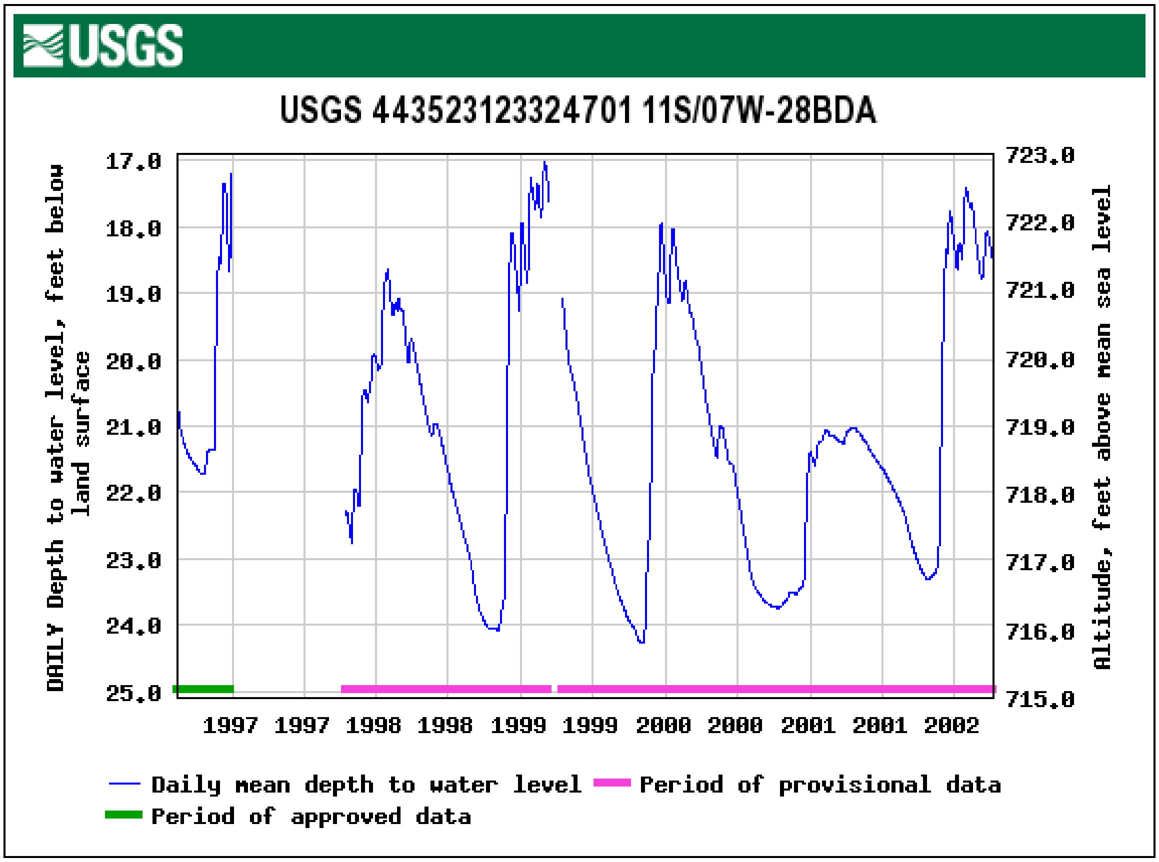


Figure 2.14 Chart of depth to water for a USGS monitoring well near Blodgett. Courtesy of the USGS.

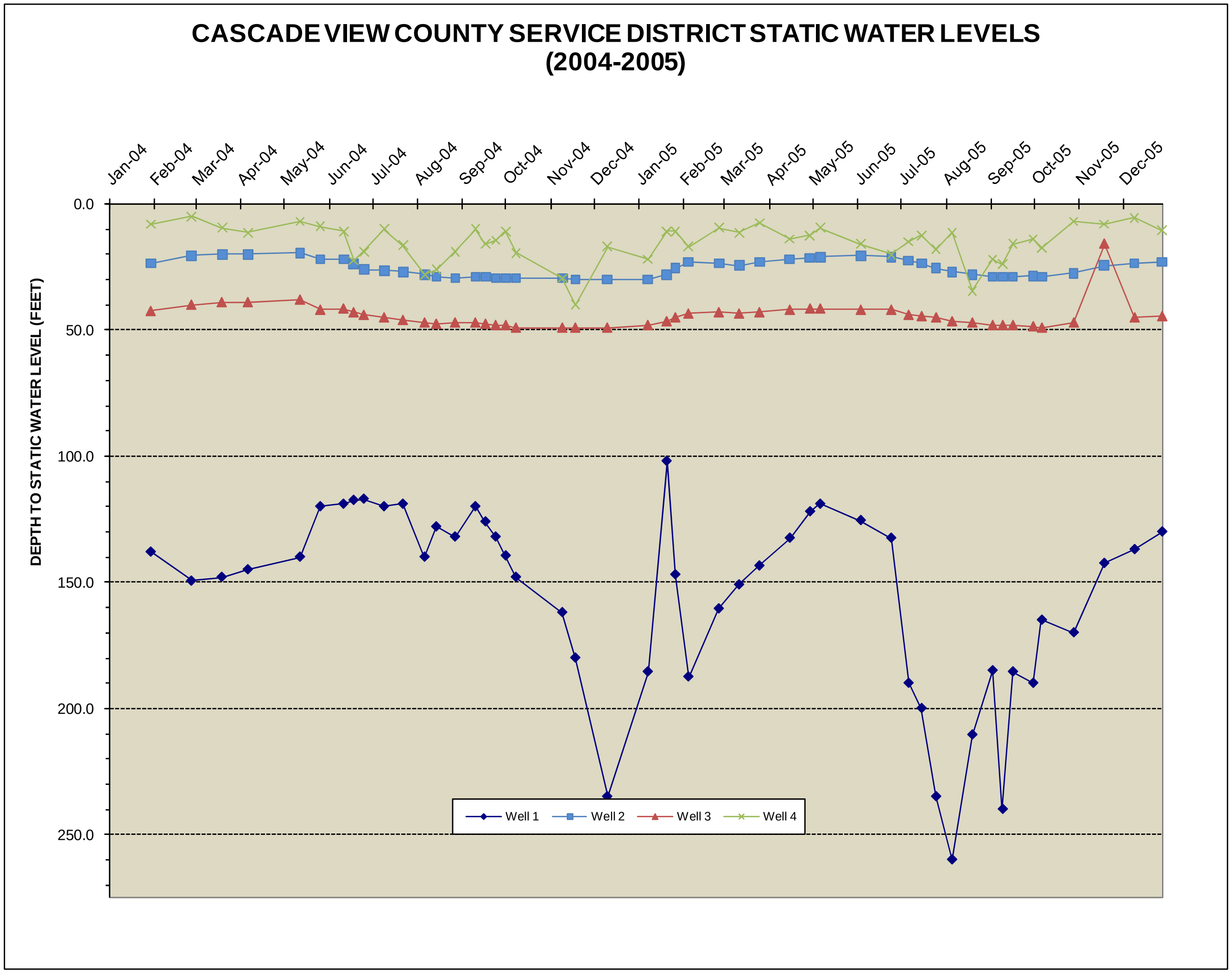


Figure 2.15 Chart of depth to water for a Cascade View wells near Blodgett. Courtesy of Benton County.

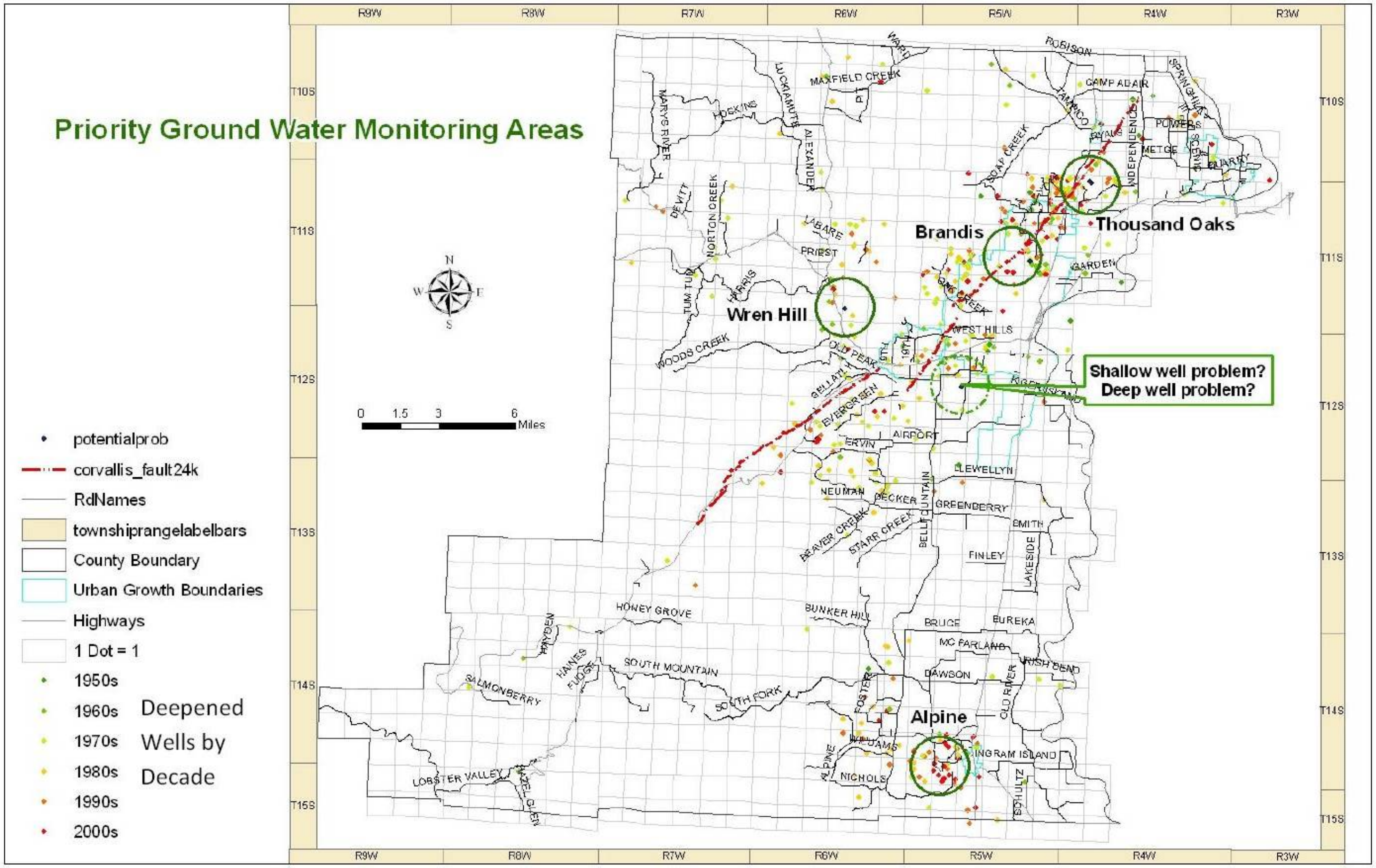


Figure 2.16 Priority Groundwater Monitoring Areas of Benton County. Courtesy of Lin et al. 2009.

3. METHODS

This thesis seeks to understand the spatial variability of several hydrogeologic parameters in Benton County and to specifically characterize the local Siletz River Volcanics formation as compared to the rest of the County using well log data. GIS analyses were performed to spatially distribute hydrogeologic parameters for Benton County and the Siletz River Volcanics. In addition, fieldwork was carried out within Oak Creek's watershed to identify late-summer spring emergence locations. This section of the thesis details the research activities carried out along each of these avenues.

3.1 GIS Analyses

The goal for this thesis' GIS analyses was to spatially interpolate common well parameters across Benton County, with emphasis on the Siletz River Volcanic Series. To accomplish this, three fundamental layers of analysis were performed using ESRI's ArcMap software, version 9.3.1. The base datasets used for this analysis are identified and described in section 3.1.1. Well georeferencing methods were selected and georeference datasets were prepared; see Section 3.1.2. Second, well logs extracted from the Oregon Water Resources Department Well Log Query tool were joined to each of the georeference datasets; see Section 3.1.3. Third, three interpolation methods were applied for each combination of parameter, extent, and georeference method; see Section 3.1.4. A flowchart summarizes the major process steps in Figure 3.1.

3.1.1 Base Datasets

The major datasets used in these analyses are summarized in Table 3.2. The primary dataset used in this project was a database of well log information, called the Well Log Query tool. Produced and maintained by the Oregon Water Resources Department (OWRD), this dataset captures owner, location, and borehole information from each well log for the State of Oregon. The Well Log Query system is used extensively by groundwater managers, scientists, and professionals, and provides well information in two forms. First, select information from each well log has been manually entered into an extractable database. Digitized data include the well characteristics, owner, well address, water yield, initial depth to water, and final static water level, among others. Users may query a specific well, owner, address, or region to interact with well records. Secondly, these database entries are dynamically linked to a scanned copy of the original well log, for end-user verification and to extract supplemental information such as screened intervals, descriptions of rock types encountered, or other purposes (OWRD 2011).

While the Well Log Query functions to great utility, data is not consistently geolocated. Attributes of longitude and latitude are specified for the very few of the data. However, nearly all data entries included location references according to the Public Land Survey System (PLSS) that specified the well location at the Township (36 square miles) and Section level (1 square mile), and often to the Quarter-Quarter Section level ($1/16^{th}$ square mile). In addition, nearly all wells have a postal address specified for the well owners, which may correspond to the physical location of the well.

A second crucial dataset was the digital set of geologic maps, called the Oregon Geologic Data Compilation (OGDC) that has been prepared by the Oregon Department of Geology and Mineral Industries (DOGAMI). This dataset contains layers of mapped geologic units (polygons), faults (polylines), and folds (polylines), and was derived from paper geologic maps for the entire State of Oregon. From the layer of geologic units, a shapefile was created showing the bounds of units associated with the Siletz River Volcanics (SRV). The scale of the original maps is variable, ranging from 1:12000 to 1:500000, so the data is subject to some linear error (DOGAMI 2006). This questionable accuracy was considered in this study by utilizing a buffer of 1000 ft when using the unit's boundary for analysis.

Several additional datasets were provided by Benton County to assist in the analysis. A shapefile of the surveyed polygons of Benton County's PLSS Sections contained necessary geographic referencing information at the 1-square-mile level. Shapefiles containing the extent of Benton County as a polyline and as a polygon were provided, and a point shapefile of physical addresses was made available for georeferencing. In addition, a LIDAR Bare-earth Digital Elevation Model (DEM) was provided for Oak Creek topography analyses (described in Section 3.2.2). Oregon State University's College of Forestry (COF) also made datasets available for the Oak Creek analyses, including LIDAR DEM data and a reference map of McDonald-Dunn Forest. The National Agriculture Imagery Program (NAIP) 2009 satellite imagery for Benton County was sourced through ArcGIS Online, an ESRI web mapping service that streams reference GIS data. The USGS Geographic Names Information System (GNIS) 2009 Populated Place Names point shapefile was downloaded from Oregon Explorer, a natural resources digital library that serves spatial data for Oregon. Oregon Explorer's data library was also used to source the 1999-2003 composite vegetation and land use land cover dataset. See Table 3.2 for geographic information for each of these datasets.

3.1.2 Formation of Quarter-Quarter Grid

The most accurate manner of georeferencing wells is via the well location description captured on the paper well log, which uses metes and bounds to reference wells to the nearest Quarter-Quarter corner. In conjunction with air photo and taxlot maps, this description can place wells to within several meters. A labor-intensive manual process is required to extract this information from each well log and accurately locate each well. This study instead sought to locate wells through three indirect methods. First, the PLSS Sections provide a very coarse grid covering Benton County; georeferencing wells to the Section they are within can allow basic examinations of the spatial distribution of well parameters. Second, wells could be georeferenced to the physical address of the domicile to which they provide water. This assumes that the well is in close proximity of the domicile of the owner, and requires that the physical address be successfully georeferenced. Finally, wells could be georeferenced to the nearest PLSS Quarter-Quarter Section Centroid as a 16x finer and consistent spatial approximation.

PLSS Section lines are available as a shapefile for Benton County, but Quarter-Quarter Sections have not been consistently surveyed or digitized for Benton County. Therefore the third georeference method required the derivation of a Quarter-Quarter

Section (aliquot) polygon grid from the Section polygon grid. It is important to note that the derived Quarter-Quarter Section polygon grid is approximate, and does not represent surveyed Quarter-Quarter Sections. Figure 3.3 shows the major processing steps required to form the Quarter-Quarter Sections grid.

In order to divide each Section polygon into a 4x4 grid of quadrilateral polygons, a midpoint grid method was utilized. A VBA script (Appendix A.1) for such gridding was located on the internet and modified to perform the necessary operations on the Benton County Sections shapefile. This gridding process required quadrilateral polygons, and unfortunately many of the Section polygons had more than 4 vertices, causing code errors (Figure 3.4.a). After simplification of the problematic Section polygons, the grid operation ran smoothly (Figure 3.4.b), producing a layer of polygons representing $1/16^{th}$ of a Section, but without the original Section attributes.

To assign identification attributes to the quarter-quarter grid, several operations were performed. First, the Zonal Geometry tool was applied to produce the centroids of each polygon. In parallel, the attribute table of the new quarter-quarter grid was exported to a database and merged to the Zonal Geometry, giving a full spatial description of each polygon. This merged database was then displayed as XY data using the calculated centroid locations, and exported as a shapefile. Visual assessment confirmed the accuracy of derived Quarter-Quarter centroids, which still had no PLSS attributes. Thus, a Quarter-Quarter Section Centroid file was created with identifiers to match the Quarter-Quarter Section polygon grid.

Next, in order to assign the complete PLSS location description to the quarter-quarter centroids and grid, several steps were required. First, a spatial join of the Sections shapefile to the quarter-quarter centroids shapefile assigned township, range, and section attributes to the quarter-quarter centroids. However, to create and assign quarter-quarter designations, a more convoluted approach was necessary, utilizing the original Benton County Sections shapefile once more.

First, a Section Centroids shapefile was created using the same method as above (calculate Zonal Geometry table, export attributes to .dbf and merge with geometry, display as XY data using centroid locations, and export to shapefile). From this shapefile, two 50ft-cell rasters were created depicting distance and direction to the nearest section centroid (Figures 3.5.a and b). This was performed using the Euclidean Distance and Euclidean Direction tools with the section centroids as sources for the calculations.

The quarter-quarter centroids shapefile was then used to sample both of these grids as new attributes. A complex reclassification scheme was employed in ArcMap's Field Calculator using a pre-logic VBA script (see Appendix A.2) to use the radial distance and direction from the nearest Section centroid to each Quarter-Quarter centroid to determine the Quarter-Quarter Section and apply a numerical identification of the same form as the wells would be prepared with (i.e., "102"). The numerical identifier employed a cartesian quadrant classification, zero to three, preceded by a 1 so that zeroes would be significant numbers. Therefore 102 refers to quadrant 2 (SW) of quadrant 0 (NE), or "SWNE" using the PLSS text notation.

Unfortunately it was clear upon visual inspection that the reclassification scheme produced many minor errors, which were corrected by hand for the nearly 15000 points. Finally, another pre-logic VBA script (Appendix A.3) was utilized to convert these numerical identifiers back into the common PLSS text notation (i.e., "NWNE"). Upon verification of the correct quarter-quarter assignment of all centroid points, a spatial join was performed with the quarter-quarter polygons layer to assign the location attributes to this file as well. Redundant attributes were then removed, leaving complete shapefiles of the Quarter-Quarter polygon grid and Centroids. These can be viewed in Appendix B.

3.1.3 Well Georeferencing

The OWRD Well Log Query tool was used to extract an Excel spreadsheet containing all wells within Benton County. In order to geo-reference the well data, the data was converted into a database format (.dbf). Some work went into preparing the well data attributes for a merge with each of the georeference datasets: PLSS Section, Address, and PLSS Quarter-Quarter Section.

While the well's address was captured as a single attribute in the database, its PLSS Section was identified by a combination of 5 attributes: Township Number, Township Text, Range Number, Range Text, and Section Number. Since all Townships in Benton County are South and West of the Willamette Meridian and Baseline, a unique numeric identifier was formed from the concatenation of Township, Range, and Section numbers (for example, Township 10 South, Range 5 West, Section 31 would be coded as "10 5 31"). This simple method only worked due to the size and situation of Benton County.

The Quarter-Quarter Section polygons were identified by a text attribute specifying within which Quarter-Quarter of the local Section a well was identified (for example, "NWNW"). In order to create a unique numeric identifier for each Quarter-Quarter polygon, two steps were required: conversion of the text identifiers to numeric identifiers, then concatenation of the unique Section identifier with the Quarter-Quarter numeric identifier, creating a unique numeric Quarter-Quarter Section identifier, which could match to the Quarter-Quarter Section polygon grid.

For the first task, a pre-logic VBA script was written into the field calculator to assign numerical attributes according to a Quarter-Quarter Case Select (See Appendix A.4). The numerical identifier utilized a cartesian quadrant classification, zero to three, preceded by a 1 so that zeroes would be significant numbers. Therefore 102 refers to quadrant 2 (SW) of quadrant 0 (NE), or "SWNE" using the PLSS text notation. For the second task, it was again noted that all Benton County Townships and Ranges are to the South and West of the Willamette Meridian and Baseline, meaning that the text identifiers could be dropped for purposes within the County. A field calculator operation was utilized to concatenate all the fields necessary to specify the location of each unique Quarter-Quarter.

At last, the well logs and georeference datasets contained fields that could be matched to one another. The PLSS Sections and Quarter-Quarter Sections each had a unique numeric identifiers which corresponded to attributes within the well log database table, and the well log table identified an Address that corresponded to the locations in

Benton County's address shapefile. Joins were performed to extract Oregon State Plane System coordinates (in Lambert Conformal Conic projection) from the georeference datasets for each well that could be identified. Table 3.6 summarizes the number of wells successfully georeferenced using each method. Many wells could not be georeferenced properly using some methods - this will be discussed further in Chapter 5. The resultant files of geo-referenced wells were exported as a shapefile for interpolation and further analysis, and are shown in Figures 4.1-4.8.

3.1.4 Interpolations

The georeferencing of wells (see Section 3.1.3) created spatial distributions of point values of several hydrogeologic parameters across Benton County for each georeference method. These parameters included depth to first water (ft), final static water depth (ft), and well yield (gpm). Since the study intended to examine parameters' spatial variability specifically within the Siletz River Volcanics in addition to the entirety of Benton County, the Siletz River Volcanics shapefile extracted from DOGAMI geology data (see Section 3.1.1) was used to create distinct spatial distributions for wells within a buffer of 1000ft from the mapped Siletz River Volcanics for each of the georeference method. Due to the poor spatial resolution of the PLSS Section grid, the PLSS Sctions dataset was not used for spatial interpolations. See Table 3.6 for a summary of the number of wells in each spatial distribution used for interpolations.

In addition to the parameters listed above, specific capacity and transmissivity were deemed particularly important parameters that can often be estimated from well logs. Specific capacity of a well is defined as the well's yield divided by the drawdown that occurs producing that quantity of water. In order to attach specific capacity to the new distribution of wells, it was necessary to manually digitize the drawdown that was captured on each paper well log. Due to the time consuming nature of this task, and the vast number of wells to be processed in this manner, this manual digitizing was performed for three georeferenced datasets: the Address-georeferenced wells within

Benton County, the Address-georeferenced wells within the Siletz River Volcanics, and the Quarter-Quarter-georeferenced wells within the Siletz River Volcanics.

From the specific capacity, transmissivity can be estimated according to Equations 3.1 and 3.2, developed by Driscoll (1986). Assuming that the groundwater extracted in the Siletz River Volcanics is confined, tranmissivity (T, gpd/ft) and specific capacity (Q/s, gpm/ft) should be related by Equation 3.1, while the relationship for unconfined aquifers estimates transmissivity as in Equation 3.2. Equations 3.1 and 3.2 only apply for US Customary units.

Equation 3.1: $T = 2000 \times Q / s$; Confined Aquifers

Equation 3.2: $T = 1500 \times Q / s$; Unconfined Aquifers

Equation 3.1 was therefore applied to the well data to estimate the transmissivity for georeferenced wells within the Siletz River Volcanics that included drawdown values. For ease of comparison between the two interpolation extents, this equation was applied in the same manner to the wells in all of Benton County that included drawdown.

Finally, it was deemed useful to consider the initial water elevation and the final static water elevation. To provide an approximation for these data, well elevations were sampled from a 10m Digital Elevation Model at the georeferenced well location. Then, these additional data were calculated by attribute mathematics using the depth to first water and post-drilling static water depth attributes, and appended to each dataset's shapefile.

Thus, numerous datasets were to be interpolated: 2 georeferencing methods (Address, Quarter-Quarter) by 2 data extents (Benton County, Siletz River Volcanics) for each of 7 hydrogeologic parameters extracted from the wells (depth to first water, final static water depth, initial water elevation, final static water elevation, well yield, specific capacity, transmissivity). To compound this, three interpolations were performed for each combination of georeferencing method, data extent, and hydrogeologic parameter.

A summary spreadsheet of interpolation methods performed, organized by interpolation method and hydrogeologic parameter, appears in Table 3.7.

The three interpolation methods were selected to complement each other visually, and computationally and were applied using ArcMap's Geostatistical Analyst extension. An Ordinary Kriging interpolation using 50 local data points (the maximum allowed by the tool) was used to display spatial trends and to emphasize areas that have consistently higher or lower values of a particular parameter – the Ordinary Kriging (OK) interpolation does a good job of removing spatial variability to look at trends between regions [Delhomme 1978]. Two Inverse Distance Weighting (IDW) interpolations were used: a 20-point nearest neighbor IDW interpolation and an IDW interpolation using all data points. Both IDW methods emphasize local highs or lows, and are heavily dependent on the distance to the nearest sample point (well location). The suitability and drawbacks of each method will be discussed in Chapter 5.

The interpolated surfaces produced appear in Figures 4.14-4.52, and are organized by hydrogeologic parameter. Each map shows a comparison of the three interpolated surfaces for each combination of georeference method and data extent.

3.2 Oak Creek Analyses

The county- and formation-wide well distribution studies were supplemented by a small watershed-scale survey of groundwater flow for the upper reach of Oak Creek, a watershed within the McDonald-Dunn Forest owned by Oregon State University. Upper Oak Creek's source area lies entirely within the Siletz River Volcanics, and potentially could inform groundwater scientists and professionals about the drainage of water within the formation. To this end, the study sought to develop maps of late-summer springs and of steady-state expected groundwater flowpaths.

3.2.1 Late-Summer Spring Locations

In mid-September 2010, the graduate student performed field work to accurately determine the emergence points of springs in the upper portion of Oak Creek watershed using a Trimble GeoXT GPS unit. These units' average accuracy is 10 ft when utilized properly (Bolstad et al. 2005). The field work was dependent on late-summer hydrologic conditions, so the student spent late August and early September vigilant of the first autumn rains before three days of trekking through McDonald Dunn Forest on September 16-18, 2010. Figure 3.8 shows a hydrograph for the Mary's River, gaged by the USGS near Philomath, for the three months preceding the field work. There is no stream gage on Oak Creek, although an attempt was made in 1980 to relate the Mary's River discharge to flow in Oak Creek (IWW 2008). Independent slug tracer tests performed by OSU student Ricardo González-Pinzón measured the flow of Oak Creek above the McDonald Dunn Forest gate as 20L/s on September 5, 2010, and 28L/s on September 11, 2010.

Over three days, the student was able to cover the portion of Oak Creek within the bounds of McDonald-Dunn Forest; Figure 3.9 shows the routes walked by the student and locations of notes. At each flowing stream encountered, the student would follow the stream's course uphill until the streambed was dry, and mark points of groundwater emergence using the GPS unit. At each stream identified on the publicly-available McDonald Dunn Forest map (COF 2011) that was found dry and for other obvious dry streambeds, the student would leave the trail and parallel the stream's incision downhill to the stream's emergence, or until the streambed's intersection of a tributary. At each groundwater emergence point, the student would determine the location with 30-60 samples using the Trimble unit. The Trimble unit uses repeated samples to improve its accuracy, and has been demonstrated to locate points within 10 feet (Bolstad et al. 2005, Oderwald and Boucher 2003). The student was able to locate the headwaters of all mapped and unmapped late-summer tributaries using this method. The locations of late-summer springs in Oak Creek are shown in Figures 4.53 – 4.55.

3.2.2 Development of Lidar Base Dataset

In addition to the late-summer spring mapping, the study hoped to develop steady-state groundwater flowpaths for the watershed, based on methods and MATLAB code developed by Lars Marklund and Anders Worman (Marklund 2009). While the method has been applied to varying extents and with various spatial resolutions, study sites have generally been larger than the Oak Creek watershed, and spatial resolutions greater than 10m (Marklund 2009). This study sought to apply Marklund's method and code at Oak Creek using LIDAR DEMs of 1m spatial resolution available covering the upper portion of the watershed. Since the MATLAB code required a rectangular DEM, some LIDAR preprocessing was required.

Oregon State University's College of Forestry contracted for LIDAR sampling of the McDonald Dunn Forest. Also, Benton County contracted for LIDAR sampling of the eastern portion of the county, surrounding Corvallis. The DEMs of these two datasets are the same resolution (1m) and abut one another. Portions of the Benton County LIDAR were merged to the McDonald Dunn Forest LIDAR to create a rectangular, continuous grid covering the Oak Creek Watershed. The upper-left hand corner missing elevation values, as it is not a part of the Forest and was discontinuous from the Benton County study. In order to complete the rectangle, a 10m DEM was resampled to 1m for these corners. As this portion of the rectangular grid was also distant from Oak Creek, a lower spatial resolution would not affect subsequent groundwater flowpath analysis substantially.

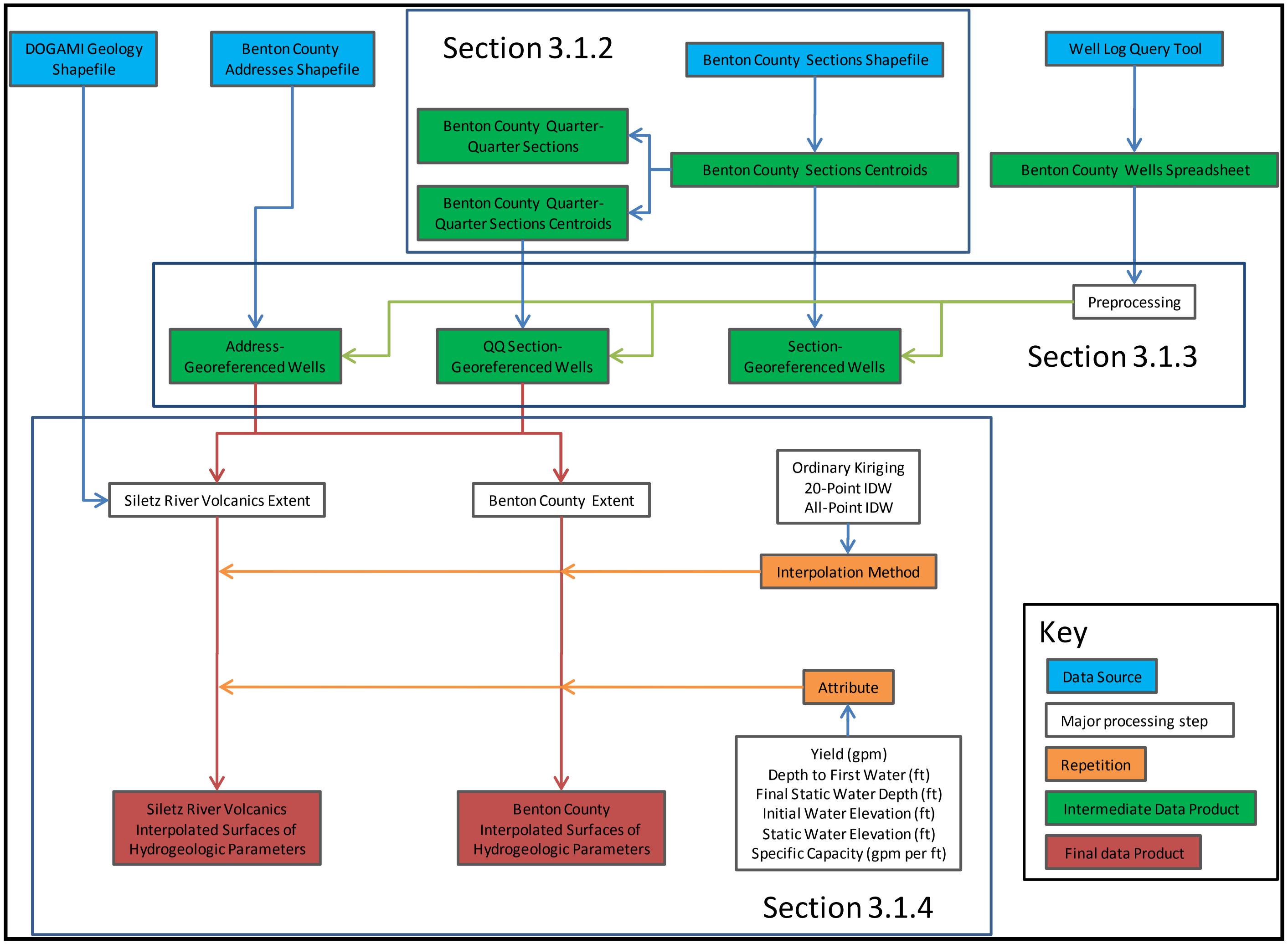


Figure 3.1. Flow chart of major GIS processing steps necessary for this project.

Description	Source	Vector/raster	Projection	Datum	Spheroid	Units	Scale/resolution	Attributes
Well log data digitized by OWRD for Benton County	OWRD Well Log Query	N/A: Table lacks consistent georeference information						township, range, section, sctn_ID, qtr160, qtr40, full_address, tal_lot, street_of_owner, longitude, latitude, bonded name, max yield, depth_to_water, completed_depth, final_water_level, use, startcard_no, complete_date
Shapefiles of surface geologic units, faults, and folds for Oregon	DOGAMI	Vector polygons and lines	NAD 1983 HARN Oregon SPC North	NAD 1983	GRS 1980	Int'l Feet	Variable, 1:12000 to 1:500000	Area, Perimeter, OrGeo#, OrGeo-ID, Map_Unit, Unit, Source_ID, Spatial_Obj_ID
Shapefile of surveyed section lines in Benton County	Benton County GIS	Vector polygons	NAD 1983 HARN Oregon SPC North	NAD 1983	GRS 1980	Int'l Feet	Unknown	Township, Range, Section, Full_Name, Length, Area
Shapefiles containing extent of Benton County as line and as polygon	Benton County GIS	Vector lines and polygons	NAD 1983 HARN Oregon SPC North	NAD 1983	GRS 1980	Int'l Feet	Unknown	--
Shapefile of point features with corresponding physical address	Benton County GIS	Vector points	NAD 1983 HARN Oregon SPC North	NAD 1983	GRS 1980	Int'l Feet	Unknown	Street, City, Zip, Old Mail Route Address
Bare-earth Digital Elevation Models	Benton County GIS	Raster	NAD 1983 UTM Zone 10N	NAD 1983	GRS 1980	meters	1m	Elevation (ft)
JPG of roads, trails, and streams in McDonald Dunn Forest	OSU College of Forestry	Raster	Unknown	--	--	--	--	--
Bare-earth Digital Elevation Models	OSU College of Forestry	Raster	NAD 1983 UTM Zone 10N	NAD 1983	GRS 1980	meters	1m	Elevation (m)
USDA NAIP 2009	ESRI ArcGIS Online	Raster	NAD 1983 UTM Zone 10N	NAD 1983	GRS 1980	meters	1m	Red, Green, Blue values
2009 USGS GNIS dataset for Oregon	Oregon Explorer	Vector points	NAD 1983 Oregon Statewide Lambert	NAD 1983	GRS 1980	Int'l Feet	1:24000	Name, LatLong, Elevation, Quad Map Name
2003 Composite vegetation coverage of Oregon; ORNHIC	Oregon Explorer	Raster	NAD 1983 Oregon Statewide Lambert	NAD 1983	GRS 1980	Int'l Feet	1:100000, 30m	Name, Landcover Name, Display Name, Landcover Code, Habitat Code, Habitat Name,

Table 3.2. Chart of major data sources, projection information, and attributes.

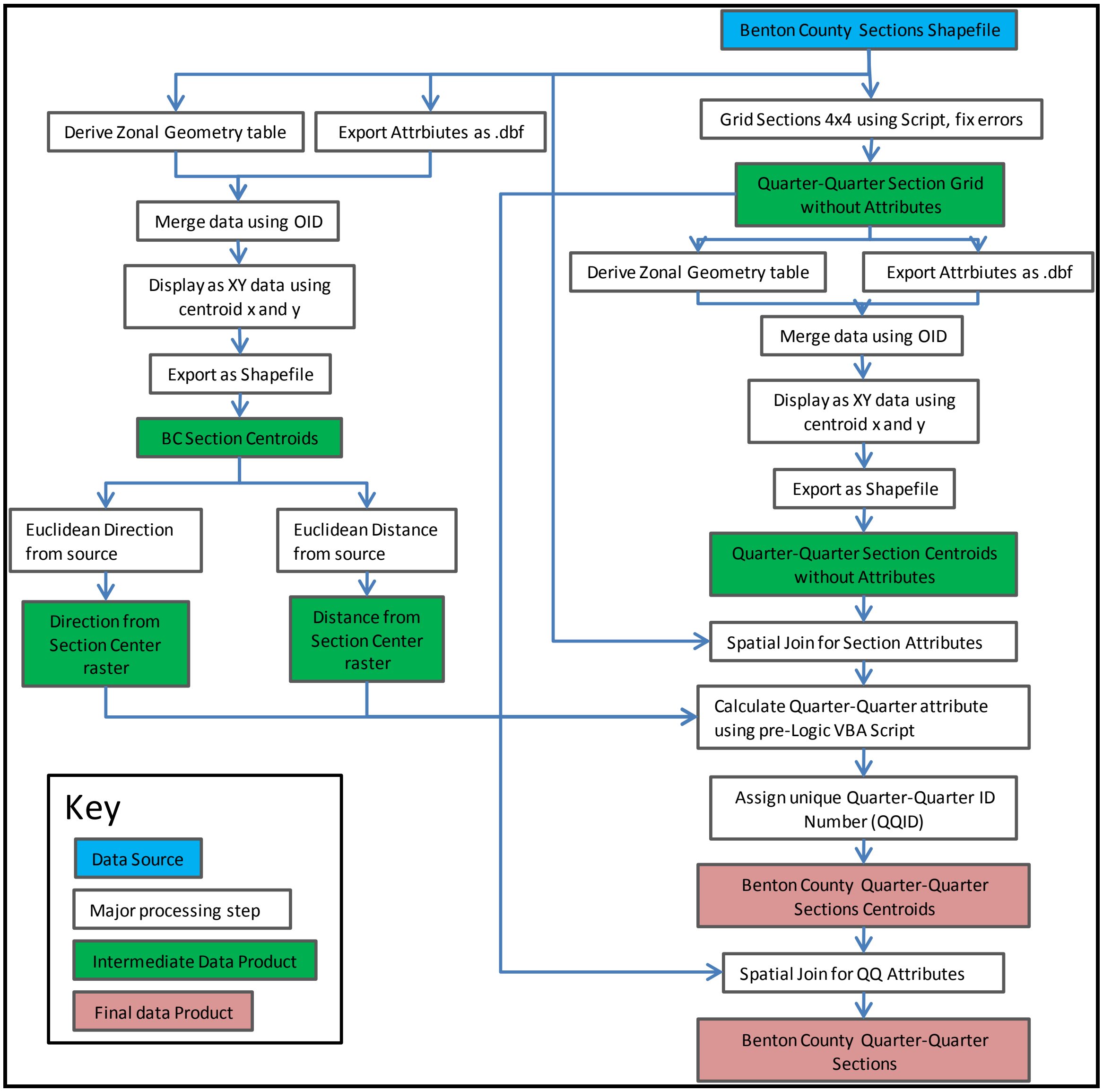
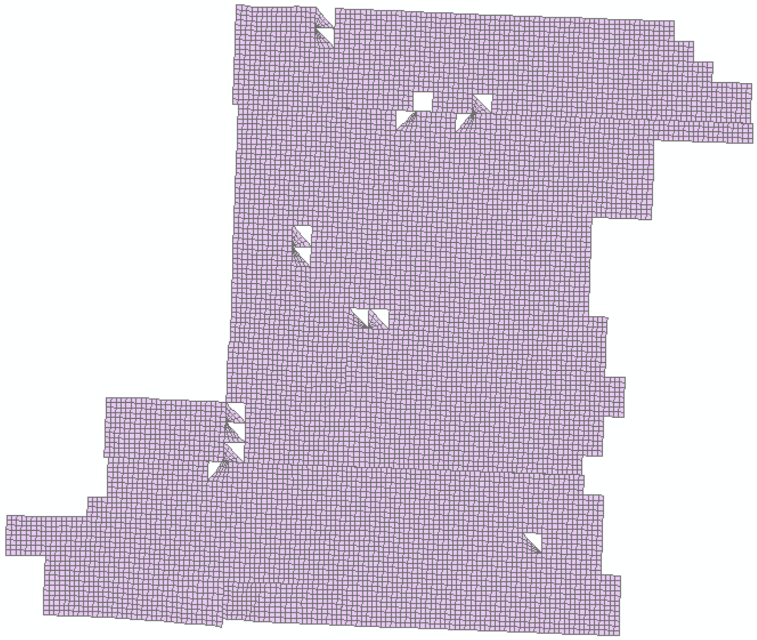
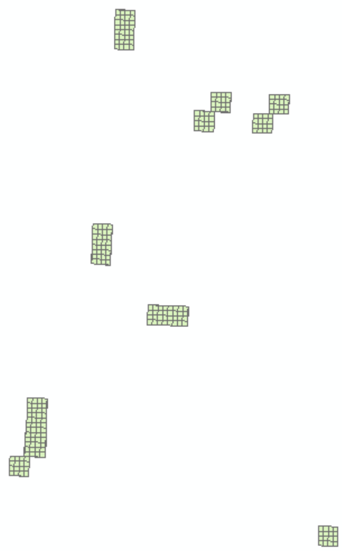


Figure 3.2. Flow chart of major processing steps for the formation of a Quarter-Quarter Section grid.

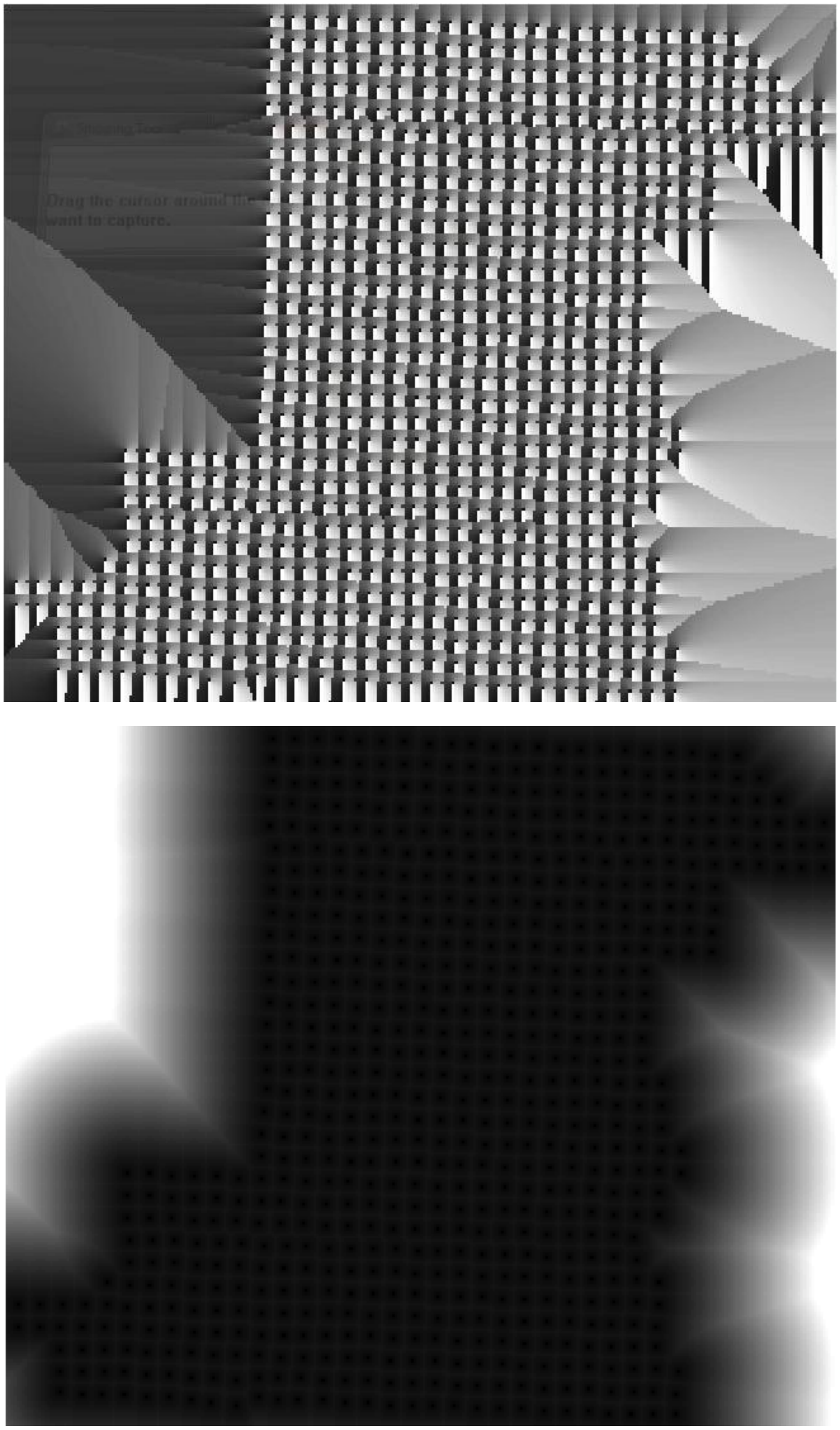


a.



b.

Figure 3.4. a. Errors in gridding the Section polygons due to non-quadrilateral data. b. Errant polygons were corrected and subsequently gridded, then merged with the rest of the data.



a.

b.

Figure 3.5. a. Euclidean Direction and b. Distance rasters for Benton County, using Section Centroids as sources.

Method	Extent	Wet Wells	"Dry" Wells
All Wells (not georeferenced)	Benton County	8435	3205
Section	Benton County	8209	3055
Address	Benton County	889	244
Address	Siletz River Volcanics	199	36
Quarter-Quarter	Benton County	2830	1218
Quarter-Quarter	Siletz River Volcanics	683	192

Table 3.6 Number of wells georeferenced by each method

Attribute	Interpolation Method	Extent, Georefernce Method			
		BC, Addresses	SRV, Addresses	BC, QQ	SRV, QQ
Specific Yield	All-Point IDW	x	x	x	x
Specific Yield	20-Point IDW	x	x	x	x
Specific Yield	Ordinary Kriging	x	x	x	x
Initial Depth to Water	All-Point IDW	x	x	x	x
Initial Depth to Water	20-Point IDW	x	x	x	x
Initial Depth to Water	Ordinary Kriging	x	x	x	x
Post-Drilling Static Water Depth	All-Point IDW	x	x	x	x
Post-Drilling Static Water Depth	20-Point IDW	x	x	x	x
Post-Drilling Static Water Depth	Ordinary Kriging	x	x	x	x
Initial Water Elevation	All-Point IDW	x	x	x	x
Initial Water Elevation	20-Point IDW	x	x	x	x
Initial Water Elevation	Ordinary Kriging	x	x	x	x
Post-Drilling Water Elevation	All-Point IDW	x	x	x	x
Post-Drilling Water Elevation	20-Point IDW	x	x	x	x
Post-Drilling Water Elevation	Ordinary Kriging	x	x	x	x
Specific Capacity	All-Point IDW	x	x		x
Specific Capacity	20-Point IDW	x	x		x
Specific Capacity	Ordinary Kriging	x	x		x
Transmissivity	All-Point IDW	x	x		x
Transmissivity	20-Point IDW	x	x		x
Transmissivity	Ordinary Kriging	x	x		x

Table 3.7 Interpolations performed: Combinations of Attribute, Extent, Georeference Method, and Interpolation Method. “x” indicates that the interpolation occurred. Specific capacity was not digitized for all wells in Benton County.

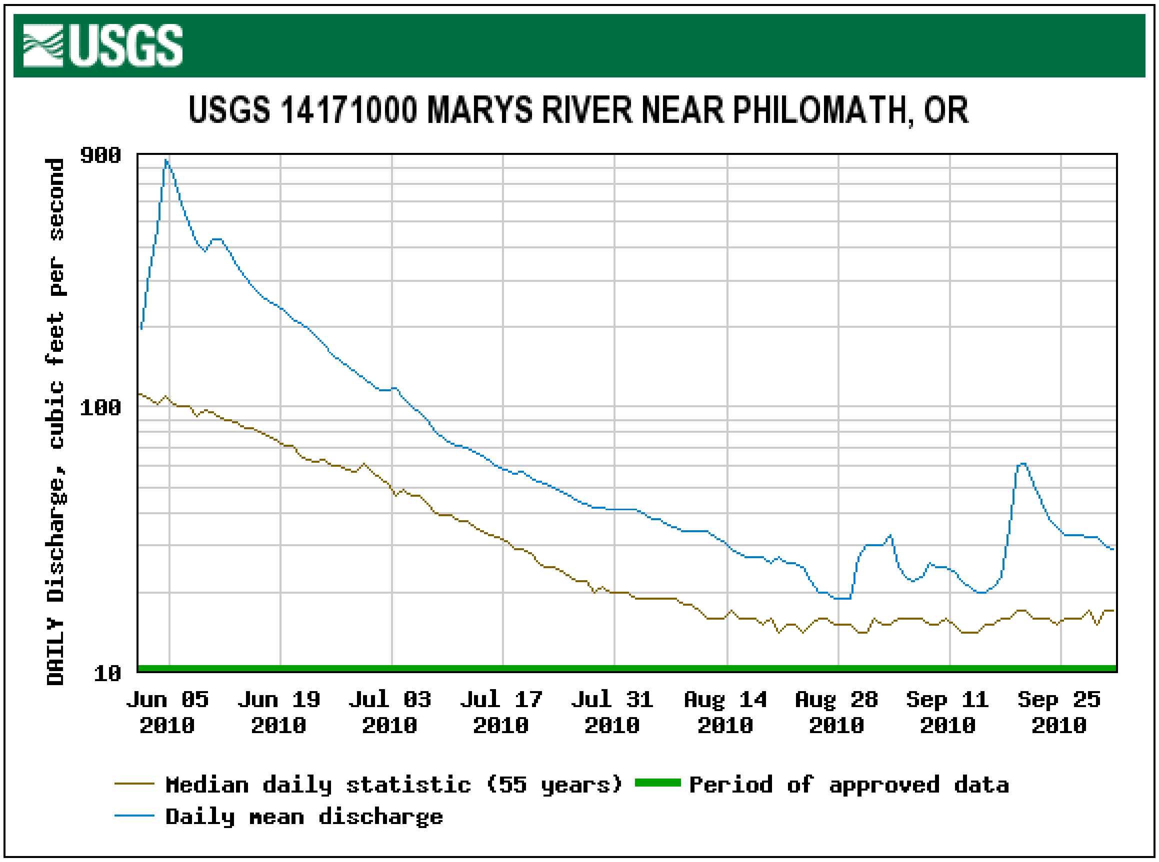


Figure 3.8 USGS hydrograph for Mary's River near Philomath, OR, on dates leading up to field work.

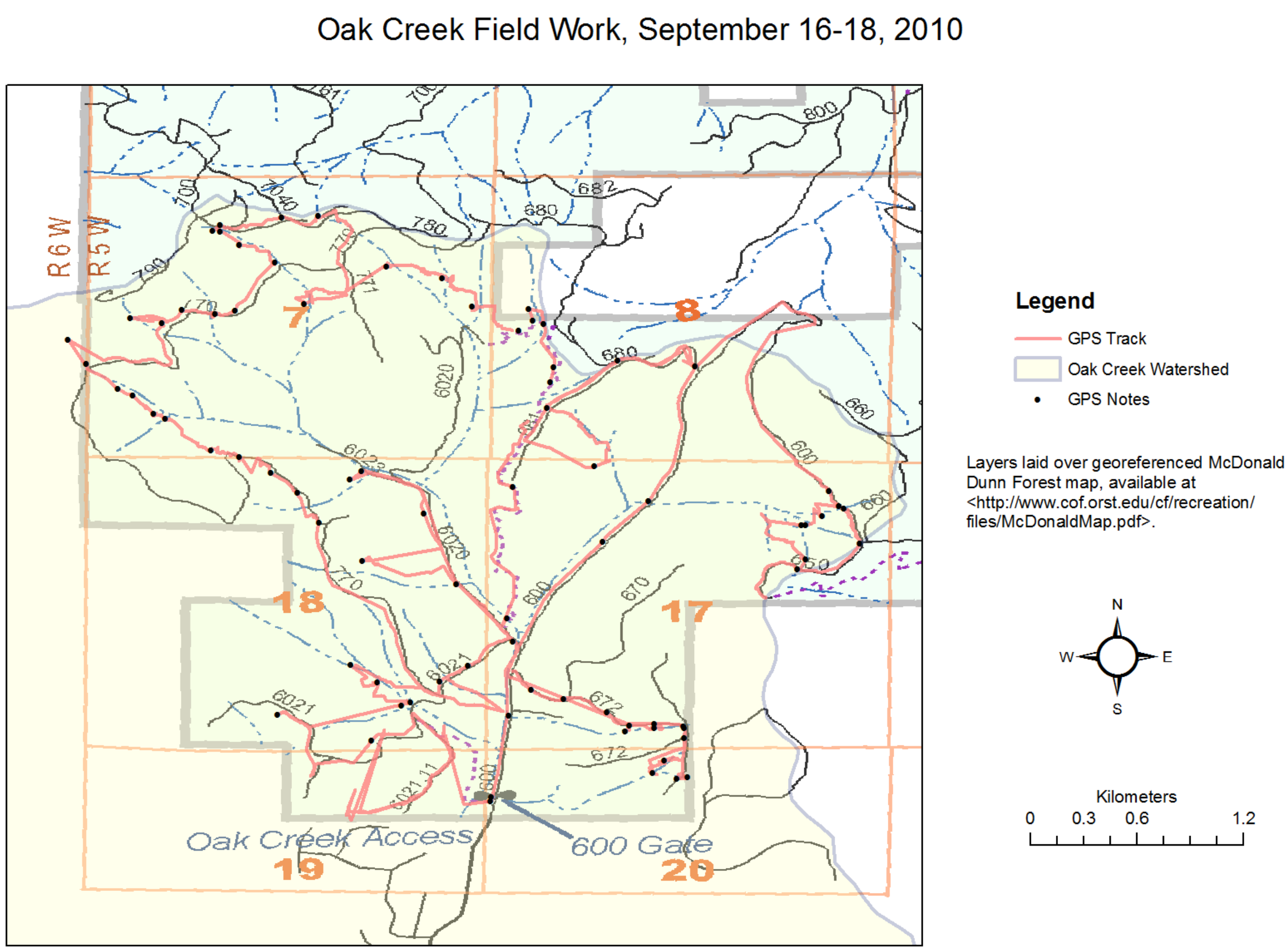


Figure 3.9 GPS Track and Notes from September 2010 field work.

4. RESULTS

4.1 Results of GIS Analyses

Maps showing the spatial distributions of wells can be found in Figures 4.1 – 4.8. Tables 4.9 and 4.10 break down the types of wells successfully georeferenced. Maps containing the interpolated surfaces of common hydrogeologic parameters can be found in Figures 4.14 – 4.52. Feature classes of the well spatial distributions and rasters of the raw interpolated surfaces can be found the geodatabase specified in Appendix D.

It is important to note that these interpolated surfaces should only be taken as estimates of average hydrogeologic parameters. Local values can vary substantially from the estimated values. Interpolated surface estimates should not be used for development or design purposes without a site characterization by an expert groundwater hydrologist.

4.1.1 Well Distributions

Figures 4.1 – 4.8 show the spatial distributions of wells successfully georeferenced, while Table 4.9 quantifies the wells in the original dataset downloaded from OWRD's Well Log Query tool and the number of wells successfully georeferenced by each method. Of the 11538 wells in the original OWRD dataset, georeferencing by PLSS Section was able to locate 11264 wells (97.6% of the original dataset), while locating by PLSS Quarter-Quarter Section was able to place 4048 wells (35%) and locating by Address only successfully located 1134 wells (9.8%). Figure 4.1 shows that the Section-georeferenced wells cover the majority of Benton County, but at a very coarse spatial resolution, with at least 1 mile between adjacent points. The spatial distribution of Quarter-Quarter-georeferenced wells in Figure 4.2 includes less than 40% of the wells in the county, but covers nearly the same area as the Section-georeferenced wells, and at a ¼-mile discretization. As can be seen in Figure 4.3, the Address-georeferenced wells sample a subset of the spatial coverage of the Section and Quarter-Quarter well datasets, and at variable spatial resolution. Figure 4.4 compares the well distributions of all 3 datasets for wells with reported yield greater than 0 gpm, which are considered “wet” wells in this study. Wells with a reported yield of 0 or no reported yield are considered dry.

Georeferencing by Section provided the most complete coverage of the county, locating by Quarter-Quarter provides an improved spatial distribution, and applying Addresses resulted in an inferior subset of the data. Nearly all wells (97.6%) were successfully located to the nearest PLSS Section centroid, corresponding to linear accuracy of 3733 ft at worst for the entirety of a grid with approximately 1-mile horizontal and vertical resolution (PLSS Sections are subject to large survey errors at corners). The resulting grid was not fine enough to distinguish between geological formations but provides a broad coverage of the county (see Figure 4.1) which utilizes nearly all well data available. Resultant distributions for all three georeference methods are shown in Figure 4.4.

A large portion of wells (35.1%) was successfully located to the nearst PLSS Quarter-Quarter Section centroid. While this does represent substantial data loss, the Quarter-Quarter wells are positioned on a finer grid (approximately 1320 ft between points) and points have a linear accuracy of 933 ft. Figure 4.11 compares the radius of accuracy for wells georeferenced by Section and Quarter-Quarter Section. The resulting set of Quarter-Quarter-located wells provides a good coverage of Benton County, while including over 1/3 of all of the wells in the County, and locating the wells with reasonable accuracy. Utilizing Addresses to georeference did not include a large portion of the wells and was subject to questionable accuracy, but distributed wells to unique locations across the landscape. Benton County’s Address shapefile contains more than 22000 records, most representing unique locations. In addition, Benton County recently endeavored to add information into the database to translate old postal addresses into a contemporary form. Thus, it was disappointing to only be able to locate 9.8% of Benton County’s wells by address. Nonetheless, Figure 4.3 shows that applying Addresses georeferenced about 10% of the wells to unique locations did cover the areas of highest well density while avoiding the problem of collocated wells.

Some regions of the county have very few wells. For example, a large area east of Alsea, a large area southwest of Wren and Russell, and a substantial tract between Kings Valley and Adair Village are all without wells at the Section level, and are shown increasingly unused by the Quarter-Quarter and Address well distributions. Comparing the well distributions with major river drainages (Figure 4.12) demonstrates that the majority of wells are drilled closer to the base of slopes rather than on ridge crests. Overlaying the Federally-owned lands and a DEM with the Quarter-Quarter well distribution provides some insight (Figure 4.13): most of these areas are publically-owned and at higher elevations. Both factors reduce the likelihood of well development. These data gaps played a confounding role for the interpolations of well parameters, especially for analyses of the Siletz River Volcanics.

Well coverage of the SRV (Figure 4.7) was good at the formation's east boundary, moderate near Wren and Noon, and fair or poor for much of the rest of the county. Large portions of the Siletz River Volcanics fall within Federal land or are at higher elevation, reducing the richness of well data in this formation substantially. Overall, the SRV has a lower density of wells than Benton County in general: for both Quarter-Quarter and Address georeference methods, only about 20% of the wells located in the County fell within 1000ft of the SRV while the SRV comprises 27.3% of the County's footprint (185 of 679 square miles). Overall the well coverage of the SRV was poor, possibly compromising the accuracy of interpolations.

In order to consider the sampling of well parameters performed in georeferencing with each method, cumulative probability distributions were formed for several of the hydrogeologic parameters investigated: well yield (Figure 4.15), initial depth to water (Figure 4.21), post-drilling static water depth (Figure 4.27), and specific capacity (Figure 4.40). The specific yield, initial depth to water, and final static water depth charts demonstrate general agreement between the distribution of all well logs in Benton County (the original dataset) and the georeferenced datasets covering Benton County, while specific capacity was not compiled for the original dataset (see Section 3.1.4). In particular, the Quarter-Quarter well dataset shows very close agreement with the original dataset for all three parameters, while the Address-georeferenced distribution of post-drilling depth to water differs somewhat from that of the original dataset.

Table 4.1 also shows that the three georeferencing methods sampled dry and wet wells in similar proportions to the original dataset. In the original dataset downloaded from OWRD's Well Log Query tool, 8435 of 11538 wells (73.1%) were wet, having a reported yield greater than 0 gpm. Georeferencing by Section yielded 8209 of 11264 wells (72.9%) as wet, by Quarter-Quarter yield 69.9% wet (2830 of 4048), and by Address yielded 78.4% wet (889 of 1134). Figure 4.5 compares the distributions of dry wells georeferenced by each method, showing that dry wells are distributed throughout the county. Figure 4.6, meanwhile, compares the locations of Quarter-Quarter-georeferenced abandoned wells, altered wells, and deepened wells with dry wells located by the same method. Table 4.10 summarizes the number of these types of wells located by each georeference method.

Tables 4.9 and 4.10 also show the numbers of particular well types located within the Siletz River Volcanics for Quarter-Quarter and Address georeference methods. For both methods, a higher percent of wells were wet (with reported yield greater than zero) than for the entire extent of Benton County. For Address-georeferencing, 84.3% of wells located within the SRV had positive yield, compared to 78.4% for the entirety of Benton County. For Quarter-Quarter wells, 69.9% were wet in Benton County, but 78.0% of the wells located in the SRV were wet.

4.1.2 Well Yield

Figures 4.14 – 4.17 show the interpolations performed for well yield data. All surfaces are in gallons per minute (gpm), and raw data are included in the geodatabase specified in Appendix D. Well yield values ranged from 0 gpm (dry) to 2000 gpm across Benton County for Quarter-Quarter georeferenced wells and 0 gpm (dry) to 910 gpm for Address-georeferenced wells. The mean yield values were 53.4 gpm and 28.2 gpm for

Quarter-Quarter and Address georeference methods, respectively. Standard deviations of yield for all of Benton County were 122.3 gpm and 60.3 gpm for Quarter-Quarter and Address, respectively. Interpolations of yield across Benton County are displayed for wells georeferenced by Quarter-Quarter in Figure 4.14 and by Address in Figure 4.15.

Well yields in Benton County are generally highest close to the Willamette River (eastern bound of the County), and decreasing to the West in the Coast Range. Well yield values are estimated up to 2000 gpm close to the Willamette River, while potential well yields are generally 10-100 gpm for the majority of the county. The three surfaces interpolated from Quarter-Quarter-georeferenced wells are in good agreement, highlighting similar areas of higher and lower yield for both inverse-distance-weighted surfaces as well as the ordinary kriging surface. In particular, zones of particularly high mean yield are identified along the Willamette River in the NE tip of the County (E of North Albany), 5 miles NE of Corvallis (SE of Lewisburg), 7 miles SSE of Corvallis (7 miles NE of Bellfountain), and in the SE portion of the County (E of Monroe). Additionally, a zone of very high yield is identified 5 miles WSW of Corvallis (4 miles SE of Wren). Low yield values are estimated for a large area of the NW and SW portions of the county, as well as several small areas W and SW of Corvallis.

Interpolations of the sparser Address-georeferenced wells exhibit similar trends and generally emulate one anothers' areas of high or low well yields. The trend of yields decreasing to the W of the Willamette River is evident in all three surfaces, although well yields are not estimated above 450 gpm. The Address-based interpolated surface additionally predicts a zone of higher well yields just W of Wren and in the SW corner of the County (10 miles SW of Alsea). It is clear from comparing the two sets of surfaces that the influence of outlier data (evident in the address-based surfaces) is minimized by the quarter-quarter interpolations; in many cases an island of high or low yield is centered on a single well, and the improved coverage of the quarter-quarter-based surface shows the point to be an outlier.

Within the Siletz River Volcanics, well yield values ranged from 0 gpm (dry) to 800 gpm for Quarter-Quarter-georeferenced wells, and 0 gpm (dry) to 75 gpm for Address-georeferenced wells. The mean yield values were 21.8 gpm and 18.9 gpm for Quarter-Quarter and Address georeference methods, respectively. The standard deviations of yield for wells within the Siletz River Volcanics were 41.5 gpm and 15.8 gpm for Quarter-Quarter and Address georeference methods, respectively. Interpolations of yield for wells within the Siletz River Volcanics are shown Figures 4.16 and 4.17 for Quarter-Quarter and Address georeference methods, respectively.

For the interpolation surfaces of well yield limited to the extent of the Siletz River Volcanics, few trends are identifiable and consistent across the datasets and interpolation methods. A broad band of higher predicted conductivity (20-50 gpm) seems to cross the southern portion of the formation (3-9 miles south of Blodgett) in an East-West direction. A narrower band of high conductivity seems to trend West from 2 miles N of Corvallis towards Wren and Blodgett, containing islands of relatively high conductivity up to 100 gpm. Overall, the interpolations are patchy, with yields common in the 0-15 gpm range, with the occasional zone of higher well yield. This patchy character and range of yield values is also exhibited for the interpolations of all of Benton County, which also take into account data outside the SRV.

Figure 4.18 shows the cumulative distribution of georeferenced yield values for both extents and both interpolation methods. Table 4.9 summarizes the number of wet and dry wells in the original dataset and georeferenced well datasets. Table 4.19 summarizes the yield statistics (not including dry wells) in the original dataset and georeferenced well datasets. Figures 4.5 and 4.8 map the wells interpreted as dry for each interpolation extent.

Examining Table 4.19, the numerical distribution of well yield values is fundamentally different for the SRV as compared to Benton County. For the address and quarter-quarter georeference methods, the mean yield value is significantly different at the 95% confidence level, with well yield lower in the SRV than in Benton County for both cases. Interestingly, the medians are comparable for all data sets, but the range and standard deviations for wells in the SRV are substantially lower than for the entirety of Benton County, indicating substantially higher variability relative to the mean yield. Additionally the percentages of wet wells and number of problematic wells (Tables 4.9, 4.10, and 4.20) indicate that the Siletz River Volcanics contains a lower density of dry and deepened wells than Benton County in general. This is important because the fracture-flow that is expected to occur usually results in extremely variable well yields – some wells are supplied with seemingly inexhaustible water while others yield virtually none (Berkowitz 2002).

Frank (1972) considered 29 wells in the SRV and found that the well yields ranged from 4 to 55 gpm. The mean well yield from his set of wells was 16.3 gpm, while the results of this study indicate a mean value between 18.9 and 21.8 gpm for the Siletz River Volcanics, with median values of 13 and 15 gpm. Frank's values indicate similar well yields for the other consolidated rocks within the county, and much higher yield values (means of 84.3 [30 wells] and 355gpm [28 wells]) for the older and younger alluvium, respectively, within the Willamette Valley. A consultant's study of 155 wells in the SRV estimated a mean yield of 18 gpm, with a standard deviation of 14 gpm (EGR 1998).

The results of this study indicate yields than comparable to those from Frank's report, but the location of wells examined in his report should be considered. Figure 4.21 displays Frank's data by Township (his aggregation) and compares the resulting layer to the interpolated surface from this study. The agreement is very good: the QYAL units of high yield are highlighted by both spatial distributions, and intermediate values seem to match. Unfortunately, Frank's study only included wells covering the Northeast portion of Benton County.

Finally, a comparison of dry, abandoned, altered, and deepened wells with the interpolated surfaces of well yield show that high yield generally does not occur in the areas of higher density of problematic wells (Figure 4.22). Of course, dry wells do occur in locations of high estimated yield, and low yields are estimated for areas with no dry wells. In addition, an examination of the identified areas of groundwater concern (Section 2.2.4), shows that the areas identified by Benton County as Priority Groundwater Monitoring locations all have clusters of problematic wells. However, additional areas of dense problematic wells are evident in Figure 4.22.

4.1.3 Depth to First Water

Figures 4.23 – 4.26 show the interpolations performed for depth to first water. All surfaces are in feet (ft), and raw data are included in the geodatabase specified in Appendix D. Figure 4.27 shows the cumulative distribution of depth to first water values for both extents and both interpolation methods. Table 4.28 summarizes the statistics of depth to first water for wet wells in the original dataset and the georeferenced datasets.
Initial depth to water values ranged from 0 ft (artesian) to 594 ft across Benton County for Quarter-Quarter georeferenced wells and 0 ft to 618 ft for Address-georeferenced wells. The mean depths to first water were 84.5 ft and 109.4 ft for Quarter-Quarter and Address georeference methods, respectively. The standard deviations of depth to first water for wells in Benton County were 94.0 ft and 99.1 ft Quarter-Quarter and Address georeference methods. Interpolations of depth to first water across Benton County are displayed for wells georeferenced by Quarter-Quarter in Figure 4.23 and by Address in Figure 4.24.

Values of depth to first water (ft) are estimated to 600 ft deep within the Coast Range, while initial depths to water in the Willamette Valley are generally less than 20 ft (Figures 4.23 – 4.27). The three surfaces interpolated from Quarter-Quarter-georeferenced wells are in very good agreement. They highlight similar areas of shallow and deep water tables for both inverse-distance-weighted surfaces as well as the ordinary kriging surface. Especially consistent is the transition from a shallow water table (less than 20 ft depths) to initial water-bearing formations of depths greater than 50 ft. In addition, numerous pockets of deeper water are evident in the Willamette Valley, potentially indicating small topographic rises. Notably, the depths to water within the Coast Range are variable, but generally on the order of hundreds of feet (rather than tens of feet in the Valley). Lastly, the surfaces predict shallow water tables in the NW and SW corners of the county.

Interpolations of the sparser Address-georeferenced wells show the same patterns of shallow water tables within the Willamette Valley and deeper water tables in the Coast Range. The inverse-distance-weighted surfaces oddly predict an increase in depth closer to the Willamette River in southern Benton County, a likely example of a well-known phenomenon: IDW interpolations return to a mean value far from the interpolation points. Again, numerous pockets of greater initial depth to water appear in the foothills of the Coast Range, in approximately the same locations as predicted by the quarter-quarter-based interpolations.

Within the Siletz River Volcanics, well depth to first water ranged from 0 ft (artesian) to 594 ft for both methods. The mean depth to first water values were 123.2 ft and 131.4 ft for Quarter-Quarter and Address georeference methods, respectively. The standard deviation of depth to first water for wells within the Siletz River Volcanics was 108.0 ft and 102.1 ft for Quarter-Quarter and Address georeference methods, respectively. Interpolations of depth to first water for wells in the Siletz River Volcanics are shown Figures 4.25 and 4.26 for Quarter-Quarter and Address georeference methods, respectively.

The initial depth to water surfaces predicted for the Siletz River Volcanics are very consistent with the surfaces predicted by the county-wide datasets. A few areas of shallow first water are notable: NE of Wren by 5 miles, a region of depths expected under 50 ft extend NW to Kings Valley. Additionally, a zone 4 miles S of Wren is expected to have water table depths on the order of 50 ft. For a few notable areas, profound depths to the water table are expected by the interpolations: NW of Lewisburg by 2 miles in the Soap Creek drainage, initial depths to water of around 300ft are expected, while NE of

Wren by 1 mile, values of depth to first water may approach 400 and 500 ft, according to the interpolated surface.

Examining Table 4.28, the numerical distribution of depths to first water differs greatly between the two extents considered in this study. For both georeference methods, the mean values of depth to first water for the two extents are significantly different at the 95% confidence level, with the depth to first water much greater for the Siletz River Volcanics. The mean depths to first water within the Siletz River Volcanics are 123.2 ft (Quarter-Quarter wells) and 131.4 ft (Address wells), while these values for the extent of Benton County are 84.5 ft and 109.4 ft, respectively. However, the greatest depth to first water successfully georeferenced was located outside of the Siletz River Volcanics.

4.1.4 Final Static Water Depth

Figures 4.29 – 4.32 show the interpolations performed for final depth to water, the reported depth to water after completion of the well. All surfaces are in feet (ft), and raw data are included in the geodatabase specified in Appendix D. Figure 4.33 shows the cumulative distribution of final depth to water values for both extents and both interpolation methods. Table 4.34 summarizes the statistics of final depth to water for wet wells in the original dataset and the georeferenced datasets.

Values of post-drilling depth to water ranged from -155 ft (either an error or positive pressure) to 439 ft across Benton County for Quarter-Quarter georeferenced wells and -25 ft to 412 ft for Address-georeferenced wells. The mean final depth to water values were 36.6 ft and 39.9 ft for Quarter-Quarter and Address georeference methods, respectively. The standard deviations of depth to first water for wells in Benton County were 42.8 ft for Quarter-Quarter wells and 44.1 ft for Address wells. Interpolations of final depth to water across Benton County are displayed for wells georeferenced by Quarter-Quarter in Figure 4.29 and by Address in Figure 4.30.

Figure 4.29 through 4.32 show the interpolated surfaces of final depth to water, or the depth to the equipotential surface after drilling. The ordinary kriging interpolations demonstrate that there is no simple, consistent trend in the equipotential surface, as they present a nearly uniform surface with final static water depths of 50-100 ft. The inverse-distance-weighted surfaces for Address and Quarter-Quarter georeference methods demonstrate substantial variability across Benton County, with adjacent shallow and deep equipotential surfaces.

IDW interpolations based on both spatial datasets demonstrate consistently shallow equipotential surfaces near the Willamette River (correlated to the shallow unconfined aquifer) while numerous small areas in the Coast Range have moderately deep equipotential surfaces, seemingly independent of elevation. In particular, three zones in Benton County are identified by the IDW interpolations as generally being associated with deeper equipotential surfaces: the south-central portion of the county (from Bellfountain and Monroe to the W about 6 miles), a zone 5 miles WSW of Corvallis (4 miles SE of Wren) extending towards Philomath that also exhibits high well yields, and a zone 4 miles NW of Corvallis that extends N and W for a few miles.

Within the Siletz River Volcanics, well final depth to water ranged from -14 ft to 439 ft for Quarter-Quarter-georeferenced wells, and -25 ft to 272 ft for Address-georeferenced wells. The mean final depth to water values were 45.4 ft and 41.8 ft for Quarter-Quarter and Address georeference methods, respectively. The standard deviation final depth to water for wells within the Siletz River Volcanics was 51.8 ft and 43.7 ft for Quarter-Quarter and Address georeference methods, respectively. Interpolations of final depth to water for wells within the Siletz River Volcanics are shown in Figures 4.31 and 4.32 for Quarter-Quarter and Address georeference methods, respectively.

Limiting the extent to the Siletz River Volcanics, the same patterns are evident as in Benton County, and nearly the same trends are displayed for both georeference methods. Most notable is the zone of deep equipotential surface 4 miles NW of Corvallis that extends N and W for a few miles. Another zone of profound final depth to water is located 4 miles S of Wren. It is fascinating that much of the Siletz River Volcanics is estimated to have very shallow equipotential surfaces, indicating the presence of confined groundwater. This is general agreement with local hydrogeologic consultant reports that indicate confined groundwater in the SRV (Braun Intertec Northwest 1995, EGR 1994, EGR 1998, among others).

Table 4.34 shows the numerical distribution of post-drilling depths to water. The table shows that while final water levels in the Siletz River Volcanics may be deeper than the general levels in Benton County, the datesets are not different at the 95% confidence level. The cumulative distribution of final depths to water (Figure 4.33) also indicates that the distribution of values is not substantially different. The 19 SRV wells considered in Frank (1972) ranged in completion depth from 53 to 498 ft, with an average complete depth of 190.9 ft. Given an unconfined aquifer, the mean final depth to water should be bounded by this value as a floor and the mean initial depth to water as a ceiling. For the Siletz River Volcanics, this study measured a mean initial depth to water of 123.2 to 131.4 ft and a mean final depth to water of 41.8 to 45.5 ft. This strongly indicates the presence of confined groundwater in the Siletz River Volcanics.

Along this avenue of analysis, a map of Quarter-Quarter wells under confined and unconfined conditions was prepared (Figure 4.35). A well is considered to be penetrating only a water table if the equipotential surface after drilling is the same or slightly deeper than the depth to first water, while a well must penetrate a confined layer if the equipotential surface rises above the initial depth to water. Unfortunately, Figure 4.35 does not show a clear trend or spatial correlation. This may indicate a flaw in the simplistic characterization of confined and unconfined aquifers, or maybe indicate that confined bodies of groundwater generally occur on scales smaller than 933 ft.

4.1.5 Initial Water Elevation

Figures 4.36 – 4.39 show the interpolations performed for initial static water elevation. All surfaces are in feet (ft), and raw data are included in the geodatabase specified in Appendix D. Values of initial static water elevation ranged from -263.3 ft (263.3 ft below MSL) to 1469.7 ft across Benton County for Quarter-Quarter georeferenced wells and -134 ft to 787 ft for Address-georeferenced wells. Interpolations of initial static water elevation across Benton County are displayed for wells georeferenced by Quarter-Quarter in Figure 4.36 and by Address in Figure 4.37. Within the Siletz River Volcanics, well initial static water elevation ranged from -13.3 ft to 1469.7 ft for both georeferencing methods. Interpolations of initial static water elevation for wells within the Siletz River Volcanics are shown Figures 4.38 and 4.39 for Quarter-Quarter and Address georeference methods, respectively.

Both sets of interpolations across Benton County show several clear trends. First, the initial water table elevation exhibits a proportional relationship with local topography. Topographic highs also exhibit the higher water table elevations. As importantly, topographic lows have the lowest water table elevations. Second, the drainage pattern of the Mary's River is relatively evident as a local topographic low (W and SW of Corvallis), just as the Willamette River is clearly the groundwater sink for much of the valley. Third, a minor gradient in static water elevation exists to the North within the Willamette Valley, suggesting groundwater flows the same direction as the Willamette River. Finally, a few locally low areas of water table exist near the western extent of the Willamette Valley: one slightly W of Corvallis, one near Monroe, and one 3 miles N of Bellfountain.

The interpolations of SRV wells resulted in nearly identical estimated surfaces of initial water elevation, and exhibit the same relationship with elevation as do the Benton County data. The highest point for which there is well data, on McCulloch Peak in the McDonald-Dunn Forest, also corresponds with the highest elevation of initial water. These interpolated datasets are very consistent between interpolation methods, extents, and georeference methods.

4.1.6 Final Static Water Elevation

Figures 4.40 – 4.43 show the interpolations performed for post-drilling (final) static water elevation. All surfaces are in feet (ft), and raw data are included in the geodatabase specified in Appendix D. Values of final static water elevation ranged from 4.5 ft to 1489.7 ft across Benton County for Quarter-Quarter georeferenced wells and -77 ft to 848 ft for Address-georeferenced. Interpolations of final static water elevation across Benton County are displayed for wells georeferenced by Quarter-Quarter in Figure 4.40 and by Address in Figure 4.41. Within the Siletz River Volcanics, well final static water elevation ranged from 166.1 ft to 1489.7 ft for both georeferencing methods. Interpolations of final static water elevation for wells located within the Siletz River Volcanics are shown Figures 4.42 and 4.43 for Quarter-Quarter and Address georeference methods, respectively.

These interpolated surfaces show a very strong relationship between topography and equipotential, with higher topographic elevations corresponding to a higher equipotential surface. It is important to note that minor topographic features do not appear to impact the interpolated surface greatly even in areas with well coverage – substantial relief may be needed to impact the groundwater surface. In addition, two depressions in the interpolated equipotential surface may be fascinating areas for further study: Kings Valley and the Alsea Valley both appear to have post-drilling static water tables of relatively low potential. Within the SRV, the interpolations resulted in surfaces also exhibiting the positive correlation with elevation. The highest point for which there is well data, on McCulloch Peak in the McDonald-Dunn Forest, also corresponds with the highest elevation of initial water. In general, the SRV correspond to equipotential surfaces several hundred feet higher elevation than the adjacent Willamette Valley.

Figures 4.40 and 4.41 may be compared to the map of estimated water elevations included in the USGS Water-Supply Paper published in 1972 (Frank 1972). The Ordinary Kriging interpolations seem to mimic the groundwater trends on Frank's map most closely. In particular, the Ordinary Kriging interpolation of Quarter-Quarter-georeferenced wells matches Frank's surface most closely. These surfaces appear similar to the simulated hydraulic head contours modeled by Jeremy Craner (Craner 2006).

4.1.7 Specific Capacity

Figures 4.44 – 4.46 show the interpolations performed for specific capacity. All surfaces are in gallons per minute per foot (gpm/ft), and raw data are included in the geodatabase specified in Appendix D. Figure 4.47 shows the cumulative distribution of specific capacity values for all three resultant datasets. Table 4.48 summarizes the statistics of specific capacity for wet wells in the original dataset and the georeferenced datasets.

Specific capacity values ranged from 0 gpm/ft (for a nearly dry well) to 40 gpm/ft across Benton County for Address-georeferenced wells. The mean specific capacity was 0.962 gpm/ft for Address-georeferenced wells. The standard deviation of specific capacity for wells in Benton County was 3.96 gpm/ft. Interpolations of specific capacity across Benton County are displayed for wells georeferenced by Address in Figure 4.44. Much of the county falls into the range of 0.1 - 1.0 gpm/ft, according to the interpolated surfaces. Locally high values of specific capacity fall in the NE portion of the county, between Corvallis, North Albany, and Adair Village, and in a band 2-10 miles S of Corvallis stretching W for 8 miles, with specific capacities estimated greater than 1 gpm/ft. The placement of the lowest values of specific capacity was not consistent between interpolation types.

Within the Siletz River Volcanics, well specific capacity ranged from 0 gpm/ft (nearly dry well) to 0.0685 gpm/ft for Quarter-Quarter-georeferenced wells, and 0 gpm/ft to 2.78 gpm/ft for Address-georeferenced wells. The mean specific capacity values were 0.0252 gpm/ft and 0.324 gpm/ft for Quarter-Quarter and Address georeference methods, respectively. The standard deviation of specific capacity for wells within the Siletz River Volcanics was 0.0199 gpm/ft and 0.477 gpm/ft for Quarter-Quarter and Address georeference methods, respectively. Interpolations of specific capacity for wells lcoated within the Siletz River Volcanics are shown Figures 4.45 and 4.46 for Quarter-Quarter and Address georeference methods, respectively.

The agreement of the Benton County interpolation and the SRV interpolations was moderate. Interpolations of specific capacity within the Siletz River Volcanics consistently delineated zones of low specific capacity from very low specific capacity. Relatively higher specific capacity values of above 0.2 gpm/ft were estimated in the NE portion of the formation (N of Corvallis and W of Adair Village) and in a band stretching W across the formation several miles S of Wren, which has been noted to have high specific capacities. These two zones could not be distinguished in the interpolations with an extent of Benton County, but directly abut recognizable zones of higher specific capacity within the County.

Table 4.48 characterizes the numerical distributions of specific capacity values for the three datasets, showing that the SRV exhibits much lower specific capacity values, although the difference between extents is not significant at the 95% confidence level. While there is not a significant difference between extents for the Address-georeferenced wells, these data are both significantly different from the Quarter-Quarter data at the 95% level, so little can be said about specific capacity within the SRV as compared to Benton County.

In the USGS Water-Supply Paper, Frank (1972) considered the specific capacity for wells in the SRV and found that values ranged from 0.03 to 5.5 gpm/ft. The mean specific capacity from his set of wells was 0.51 gpm/ft, while the results of this study indicate a mean value between 0.025 and 0.324 gpm/ft for the Siletz River Volcanics, with median values of 0.026 and 0.125 gpm/ft. While the values reported in this study are lower, they are of comparable magnitude. Similarly, the range of specific capacity values in this study was 0 to 2.78 gpm/ft which is again lower but comparable to Frank's data.

Frank's data indicates similar specific capacity values for the other consolidated rocks within the county, and much higher mean specific capacity values (means of 4.8 [30 wells] and 72.6 gpm/ft [28 wells]) for the older and younger alluvium, respectively, within the Willamette Valley. This study's data for the entirety of Benton County indicates a mean specific capacity of 0.96 gpm/ft (Table 4.41), again much lower than Frank's report estimates. The results of this study indicate generally lower specific capacity than would be expected from Frank's report.

The well data examined by Frank are spatially distributed by Township in Figure 4.49, showing moderate agreement with an Ordinary Kriging interpolation of Specific Capacity. The limitation here is likely the few georeferenced wells that could have specific capacity data appended, resulting in a poorer interpolation. Nonetheless, the highest specific capacities are strongly correlated (QYAL), while both datasets exhibit a decline in specific capacity moving to the Northwest and into the SRV.

4.1.8 Transmissivity

Figures 4.50 – 4.52 show the interpolations performed for transmissivity. All surfaces are in gallons per day per foot (gpd/ft), and raw data are included in the geodatabase specified in Appendix D. Values of transmissivity ranged from 0 gpd/ft to 80000 gpd/ft for Address-georeferenced wells. Interpolations of transmissivity across Benton County are displayed for wells georeferenced by Address in Figure 4.50. Within the Siletz River Volcanics, well transmissivity ranged from 0 gpd/ft to 6132.5 gpd/ft for Quarter-Quarter wells and 4.5 gpd/ft to 5555.5 gpd/ft for Address-georeferenced wells. Interpolations of transmissivity for wells within the Siletz River Volcanics are shown Figures 4.51 and 4.52 for Quarter-Quarter and Address georeference methods, respectively.

Figures 4.50 – 4.52 were directly derived from the specific capacity data whose interpolations are shown in Figures 4.44 – 4.46. As such, the transmissivity surfaces exactly follow the specific capacity surfaces, amplified by a factor of 2000. EGR reports SRV transmissivities between 11 and 2640 gpd/ft, with a mean near 700 gpd/ft, which looks comparable to the surfaces in Figures 4.51 and 4.52. Braun Intertec Northwest's study of Madrona Estates estimated transmissivity between 1358 and 1822 gpm/ft (Braun 1995), which corresponds to the interpolated values at the Northeast extent of the SRV.

4.2 Results of Oak Creek Studies

The analyses of upper reaches in Oak Creek Watershed produced and compiled several new data products. As these datasets were produced to enrich resources for future studies, and not substantially analyzed as within the context of the GIS studies, they will not be discussed in Chapter 5.

The majority of springs within the upper portion of the watershed (that which is within McDonald-Dunn Forest) were located under late-summer conditions; see Section 4.2.1. In addition, a composite LIDAR bare-earth DEM (1m spatial resolution) was formed from several components, encompassing the entire watershed above the Mary's River. This was additionally subset to encompass only the upper portion of the watershed within McDonald-Dunn Forest; see Section 4.2.2. Finally, this subset of the LIDAR dataset was analyzed with a MATLAB code that applies Fourier series to determine steady-state groundwater Flowpaths; see Section 4.2.3.

Figure 3.9 shows the paths taken by the student and locations of notes taken within McDonald-Dunn Forest. Figure 4.53 shows the locations of springs discovered on these paths, also overlaid on a georeferenced map of the Forest. Unfortunately this figure shows that a few potentially important channels were not visited during the field work. In addition, the spring locations do not always match the stream channels precisely. This is due to errors mapping the streams or more likely, errors georeferencing the map. Figures 4.54 and 4.55 show these datasets draped over the hillshade of a 10m DEM. These data, collected during early September 2010, are taken to approximate the perennial emergence points of groundwater in the upper reaches of the watershed.

ArcHydro was used to calculate the contributing area for land surface flowpaths through each spring, and these values were sampled in conjunction with the spring elevation. Figure 4.56 summarizes the estimated elevations of springs, while Figure 5.57 summarizes the sampled contributing areas of springs. Note that due to the 10m precision of the DEM used in this analysis, it is assumed that accumulated surface flowpaths do not always pass through the spring sample point. Furthermore, springs do not always emerge at locations of high surface flow accumulation. Rather, local hydrogeologic structure plays a fundamental role collecting and directing groundwater to a discharge point. Nonetheless, upslope surface area has a proportional relationship with upslope substrate volume. Still, Figure 5.58 demonstrates that spring elevation and upslope contributing area do not demonstrate a significant relationship for Oak Creek.

Additionally, the LIDAR composite datasets prepared in this study are shown in Figures 4.59-4.61. Unfortunately this study was not able to pursue analyses applying these datasets. They are included as data products for future studies, and included in the geodatabase specified in Appendix D.

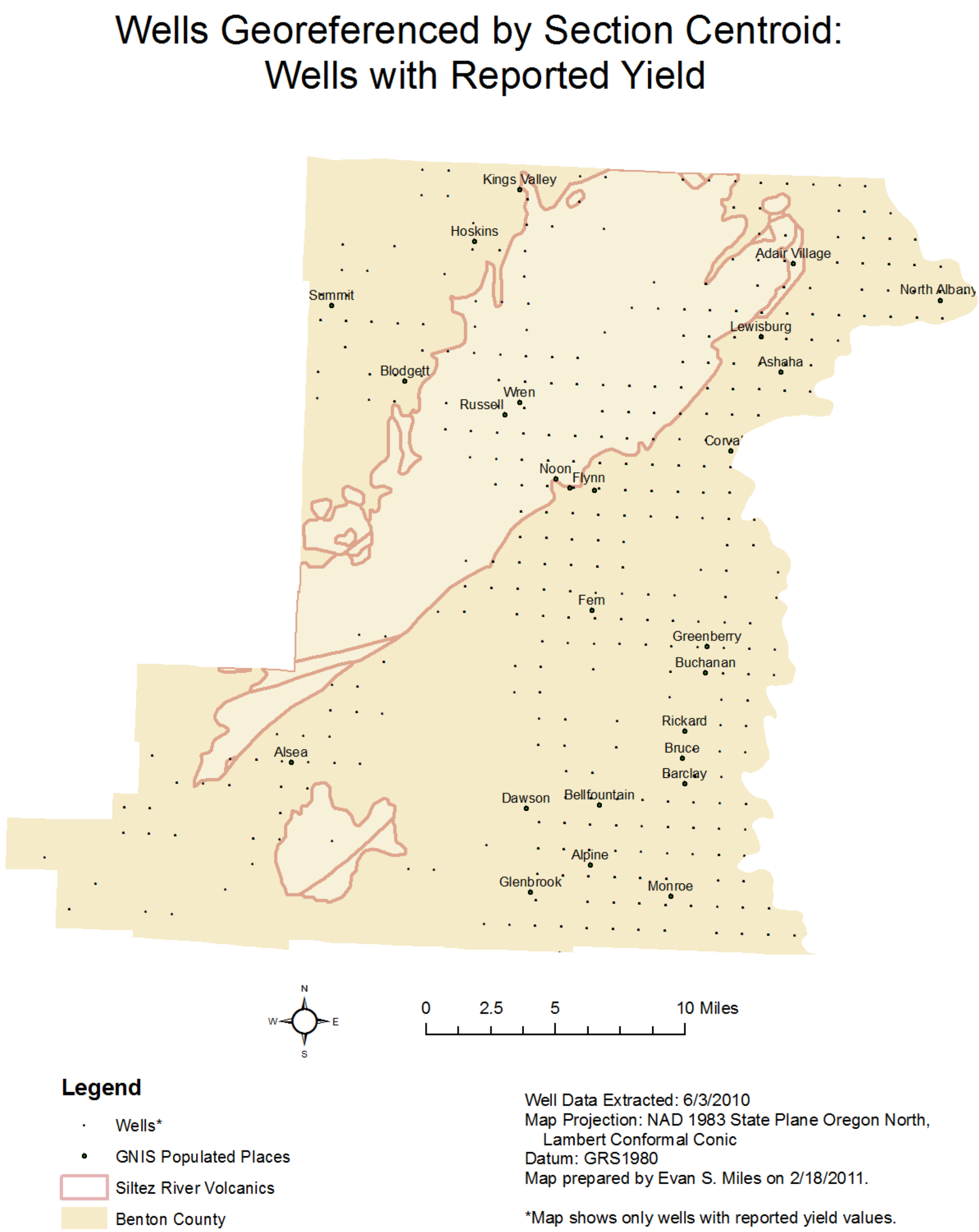


Figure 4.1 Wells with reported yield georeferenced by PLSS Section.

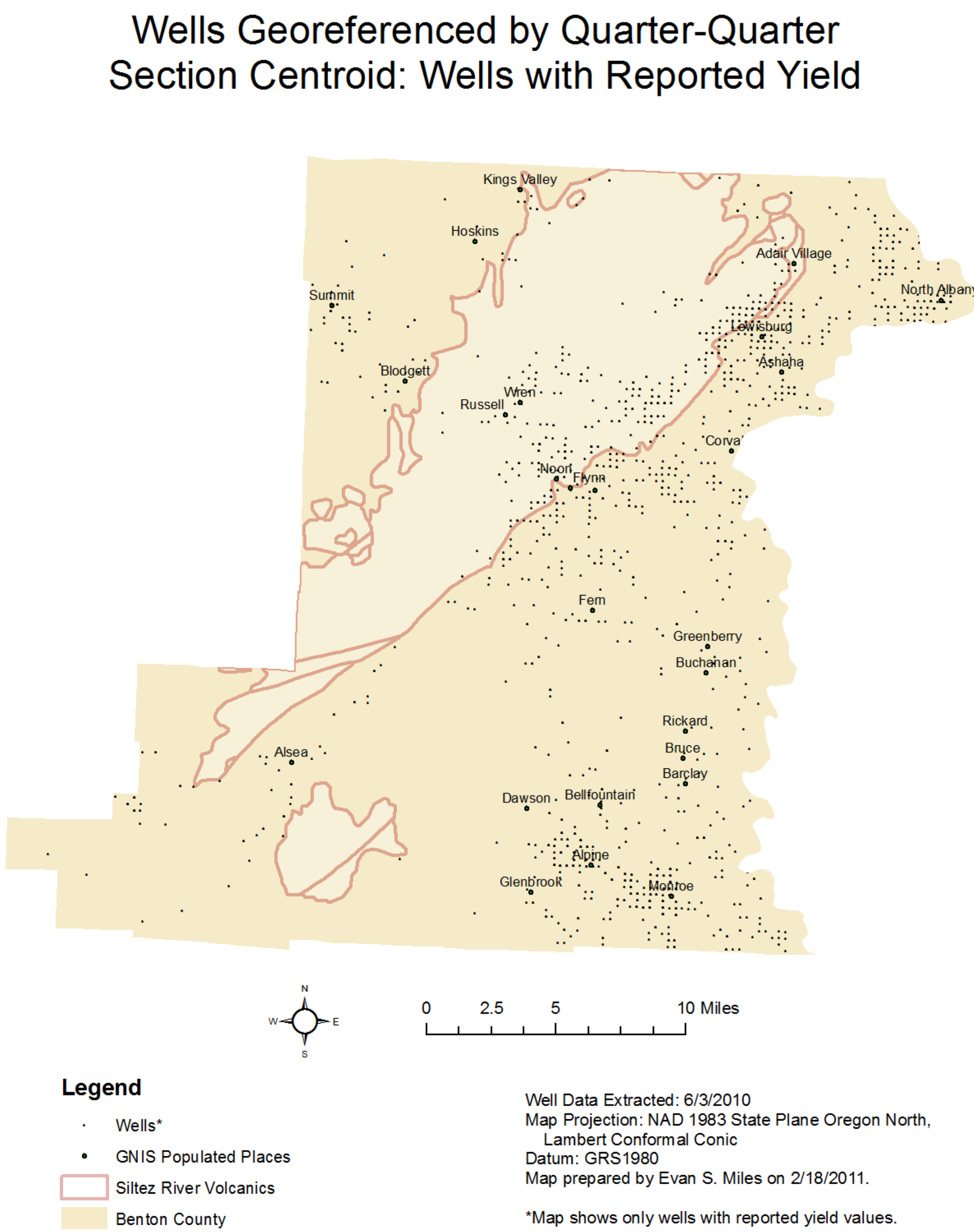


Figure 4.2 Wells with reported yield georeferenced by PLSS Quarter-Quarter Section.

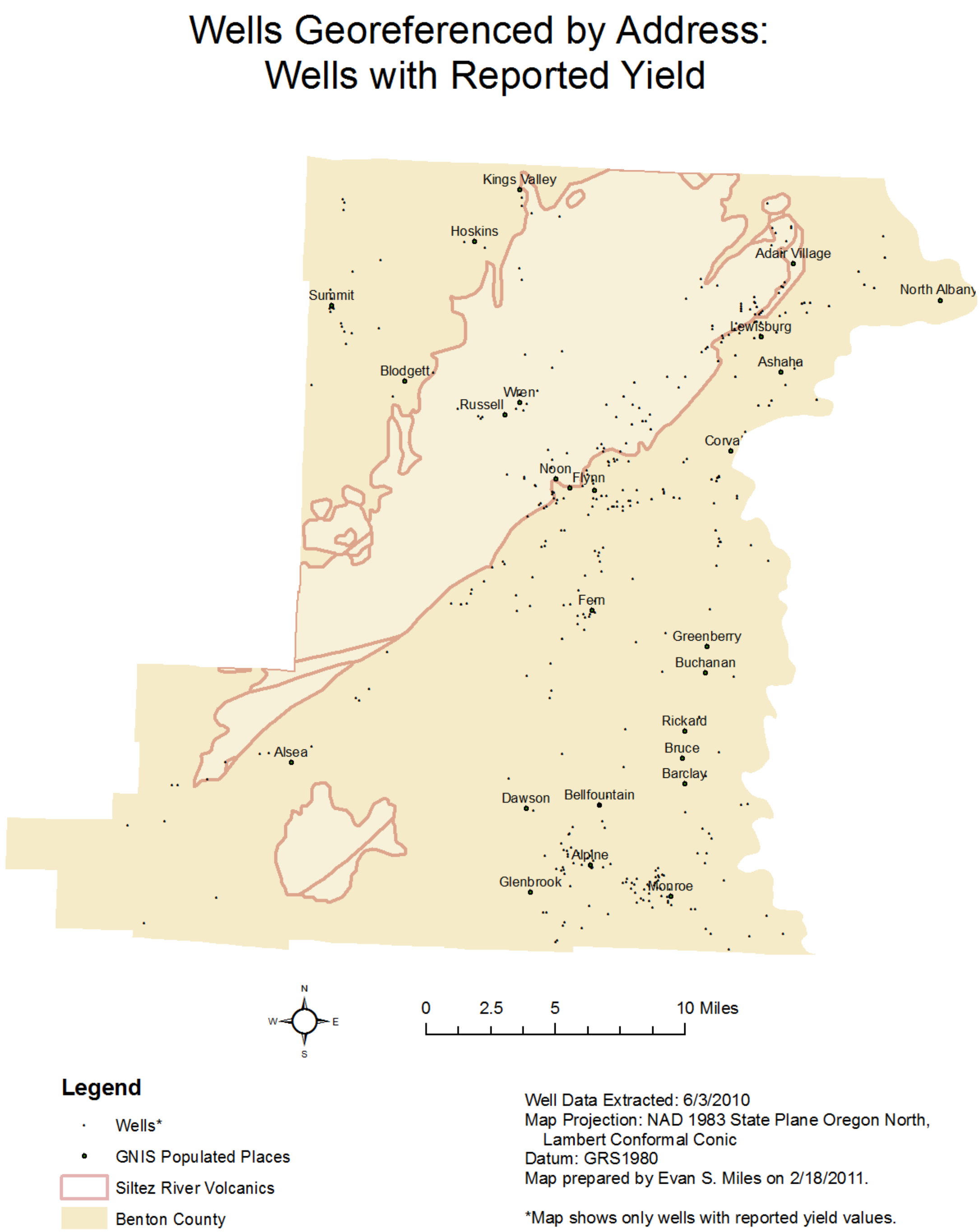


Figure 4.3 Wells with reported yield georeferenced by Address.

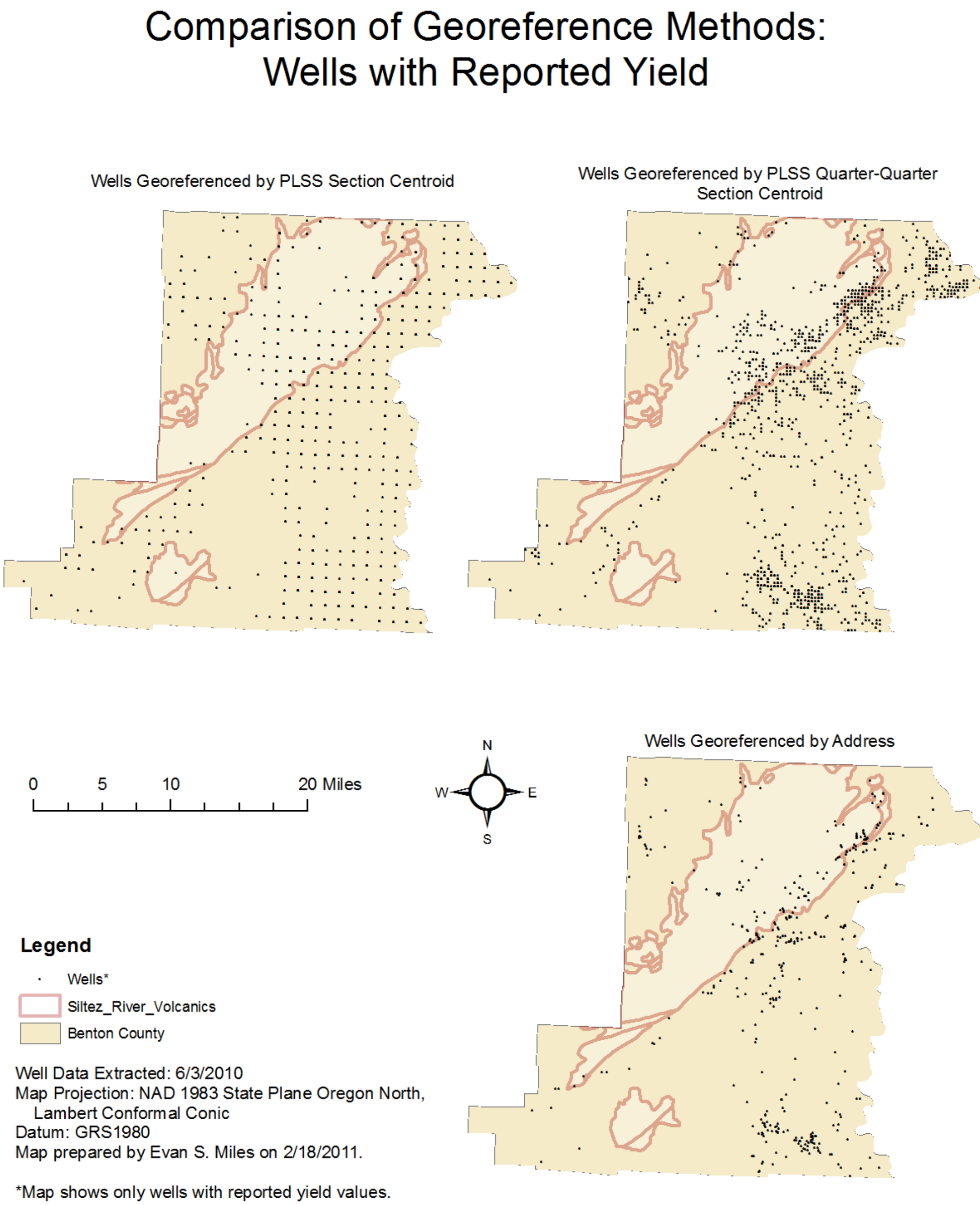


Figure 4.4 Comparison of distributions of wells with reported yield by georeference method.

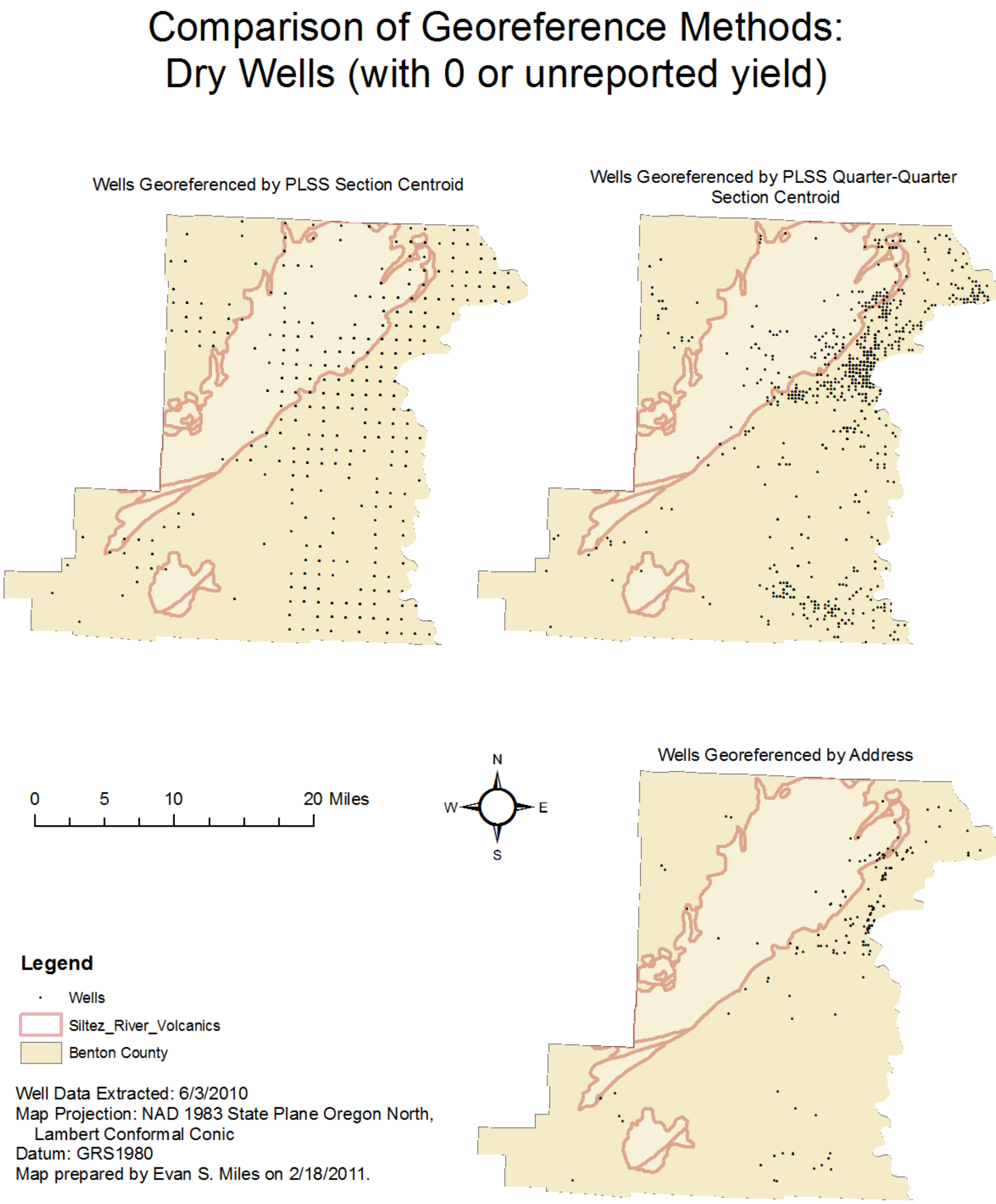


Figure 4.5 Comparison of distributions of dry wells (0 gpm or unreported yield) by georeference method.

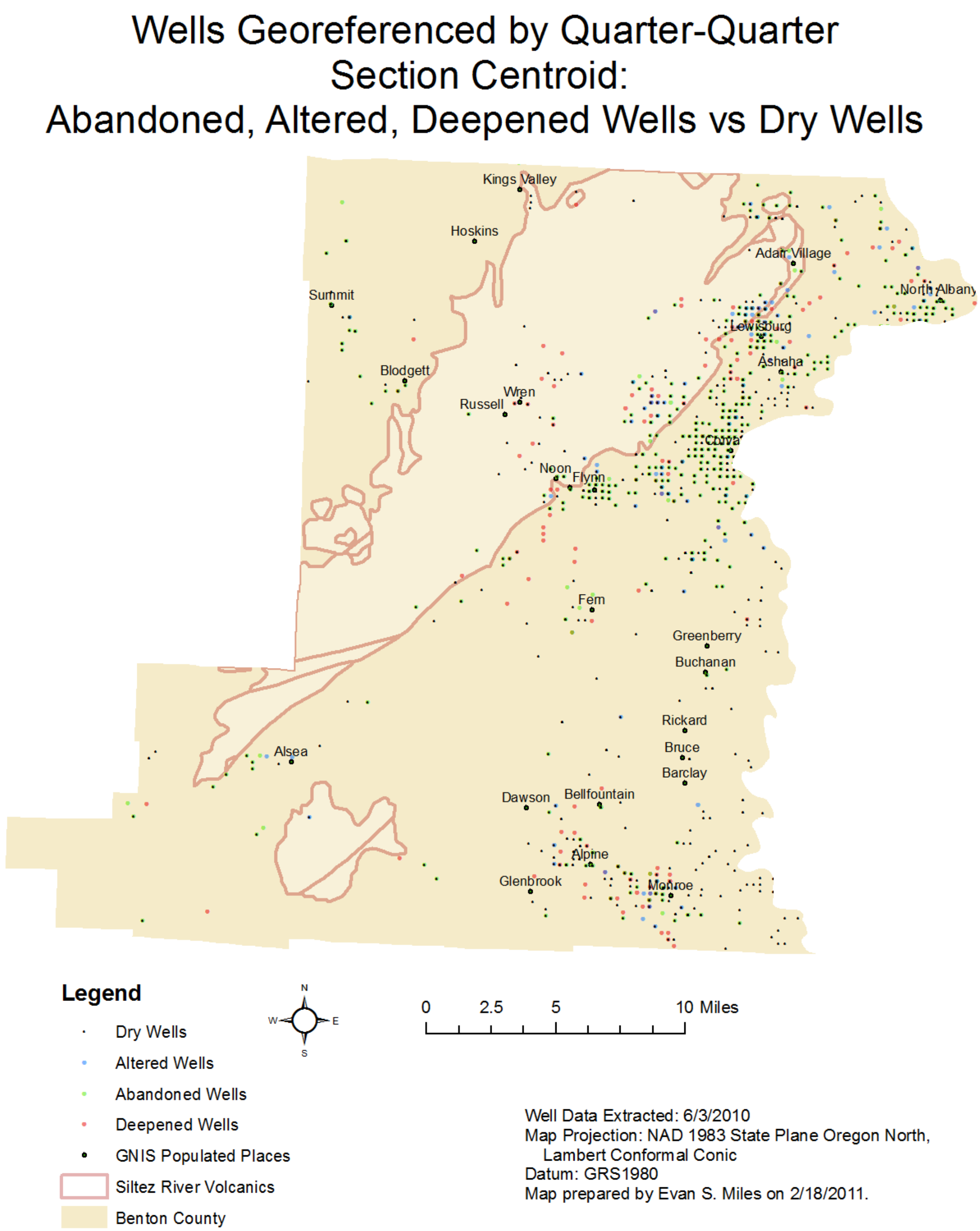


Figure 4.6 Distributions of altered and deepened wells georeferenced by Quarter-Quarter.

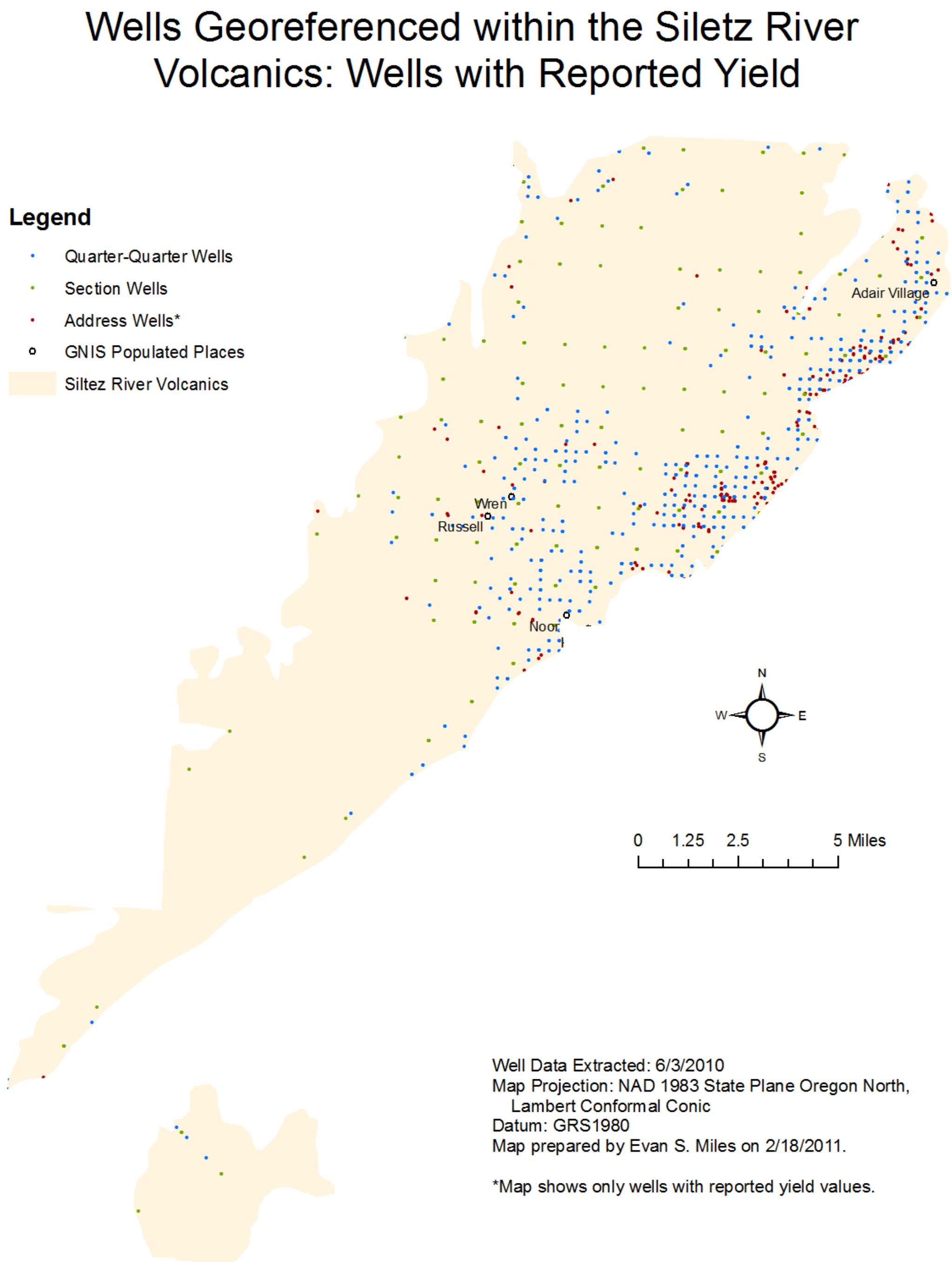


Figure 4.7 Distributions of wells with reported yield within the Siletz River Volcanics.

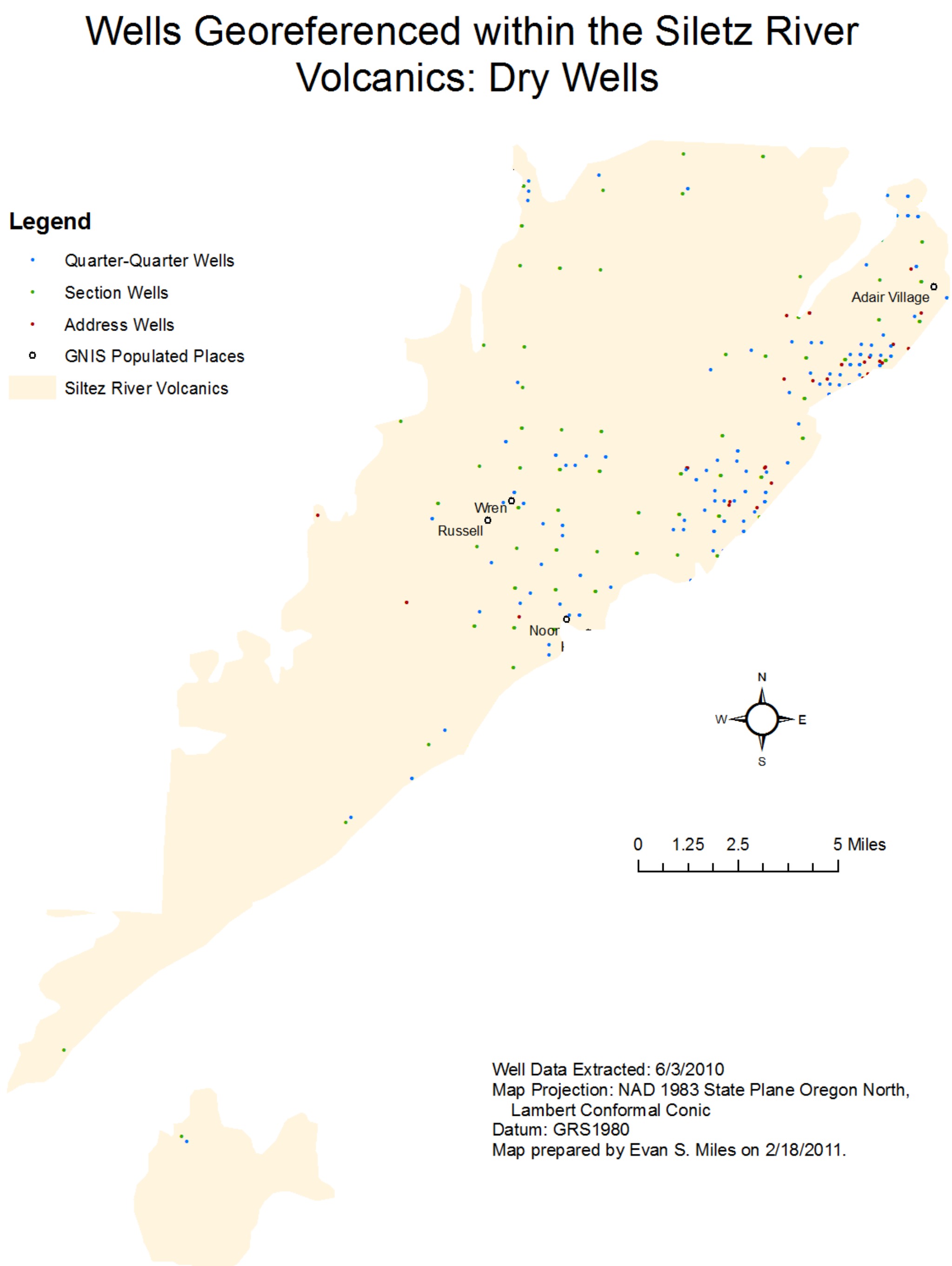


Figure 4.8 Distributions of dry wells (0 or unreported yield) within the Siletz River Volcanics.

Method	Extent	Total Number of Wells	Percent Georeferenced	Wet Wells	Percent Wet
All Wells (not georeferenced)	Benton County	11538	NA	8435	73.10625758
Section	Benton County	11264	97.62523834	8209	72.87819602
Address	Benton County	1134	9.828393136	889	78.39506173
Address	Siletz River Volcanics	236	2.04541515	199	84.3220339
Quarter-Quarter	Benton County	4048	35.08407003	2830	69.91106719
Quarter-Quarter	Siletz River Volcanics	876	7.592303692	683	77.96803653

Table 4.9 Total number of wells georeferenced by each method.

Method	Extent	New Wells	Abandoned Wells	Deepened Wells	Altered Wells
All Wells (not georeferenced)	Benton County	10078	1828	452	198
Section	Benton County	9859	1727	448	194
Address	Benton County	1002	117	52	34
Address	Siletz River Volcanics	196	18	17	13
Quarter-Quarter	Benton County	3530	771	156	102
Quarter-Quarter	Siletz River Volcanics	753	84	45	35

Table 4.10 Numerical distribution of well construction methods for each georeferenced dataset.

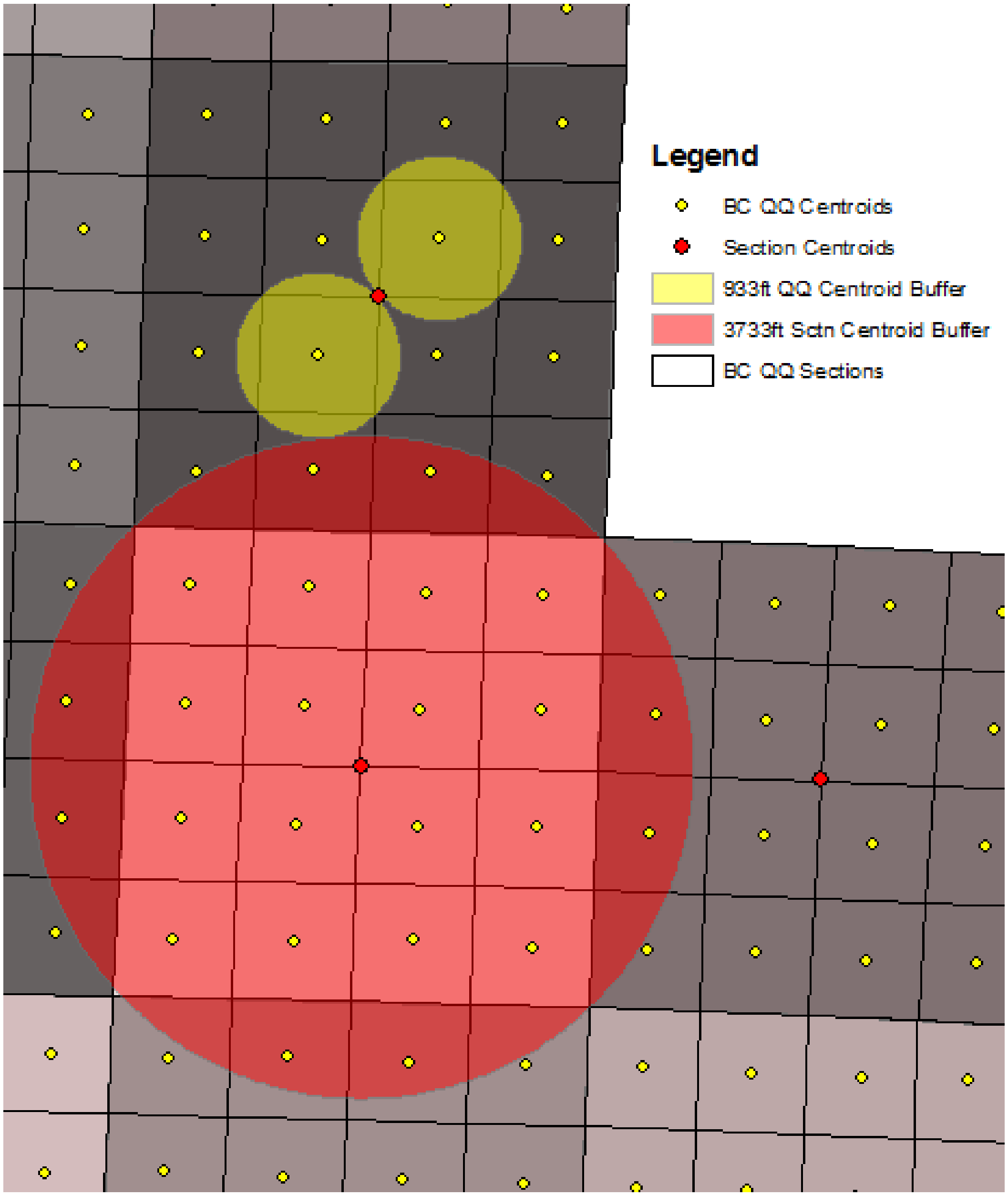


Figure 4.11 Sections and Quarter-Quarter Sections with centroids and well accuracy displayed for each.

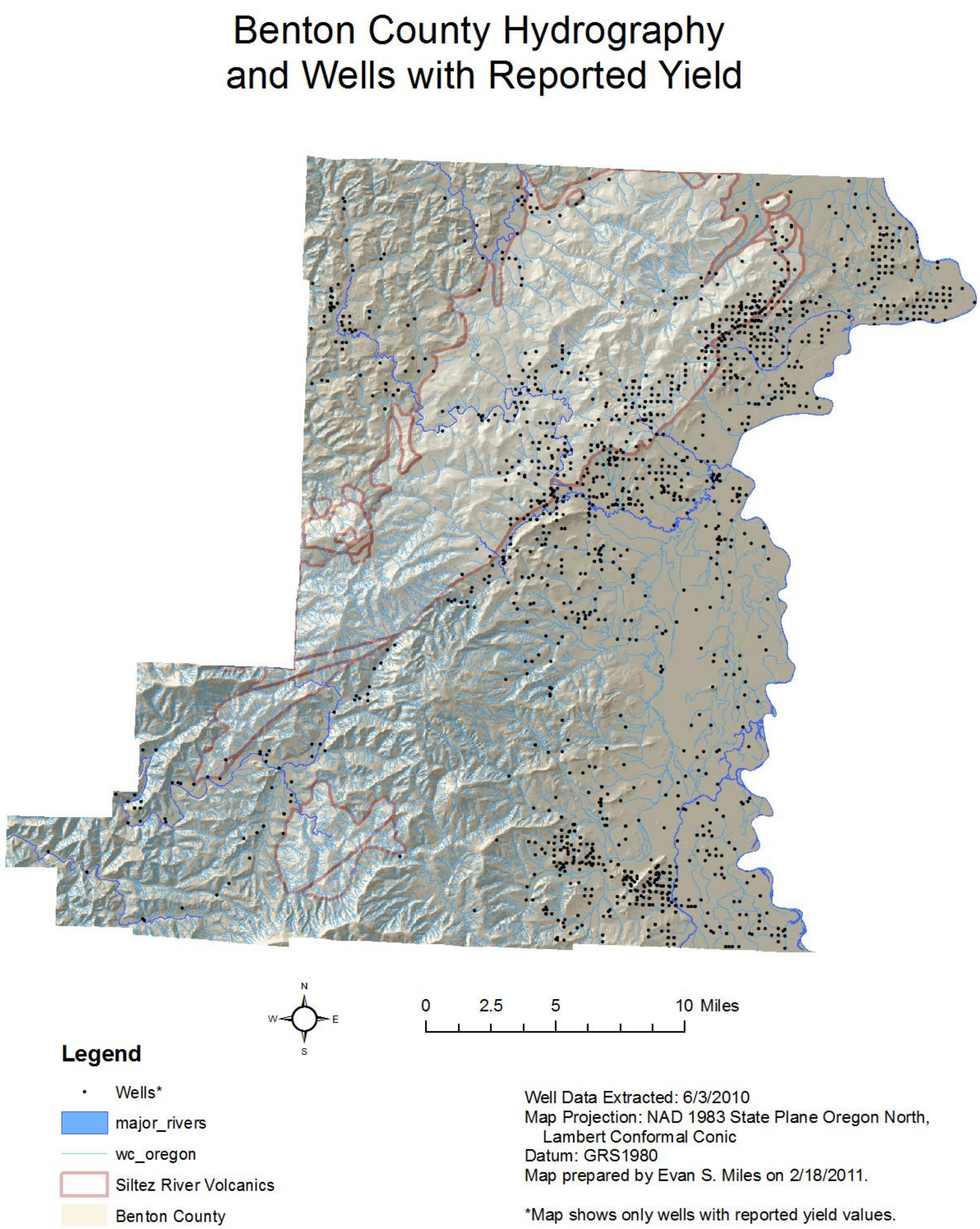


Figure 4.12 Streams of Benton County compared to Quarter-Quarter wells.

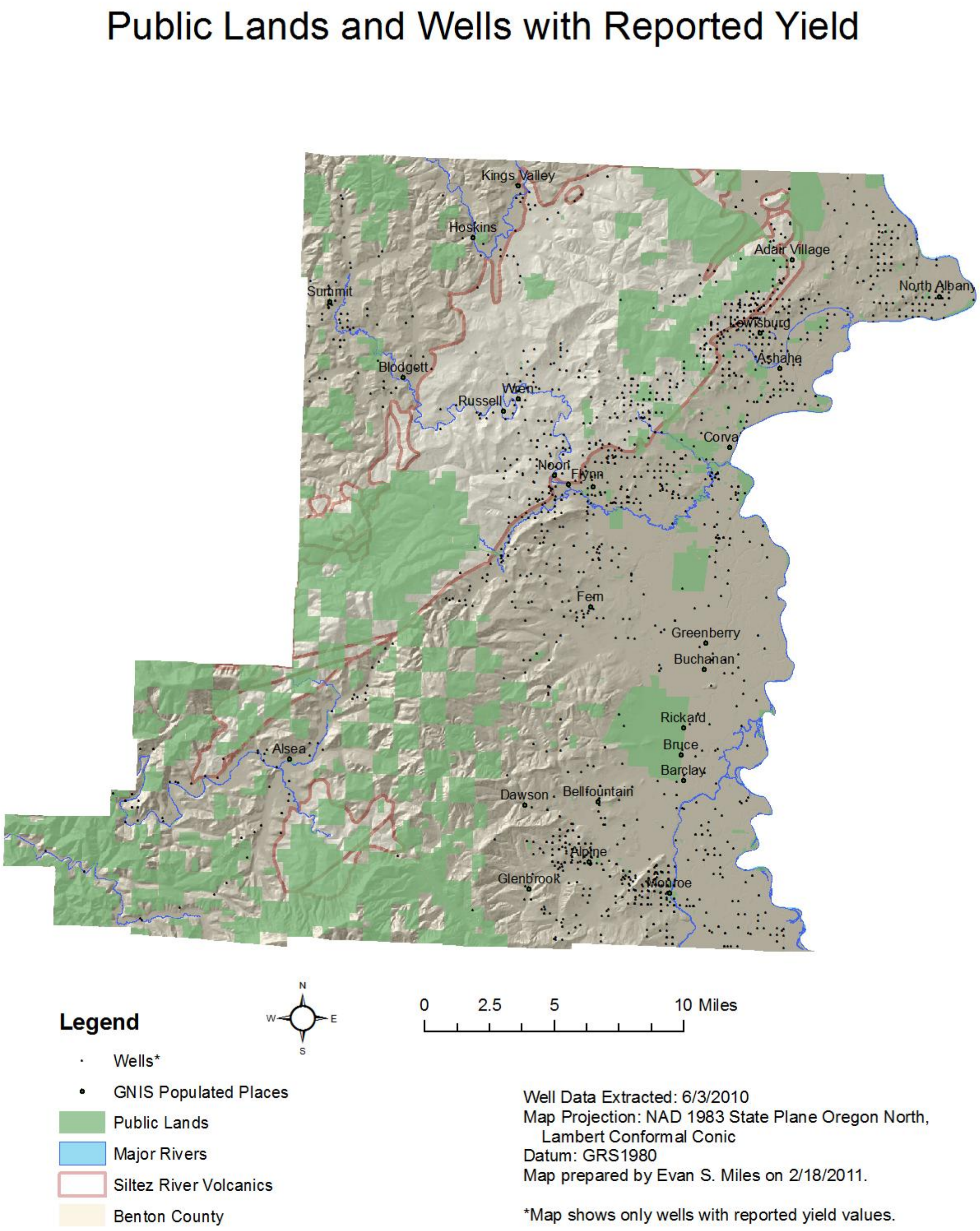


Figure 4.13 Public Lands compared with Quarter-Quarter well distribution.

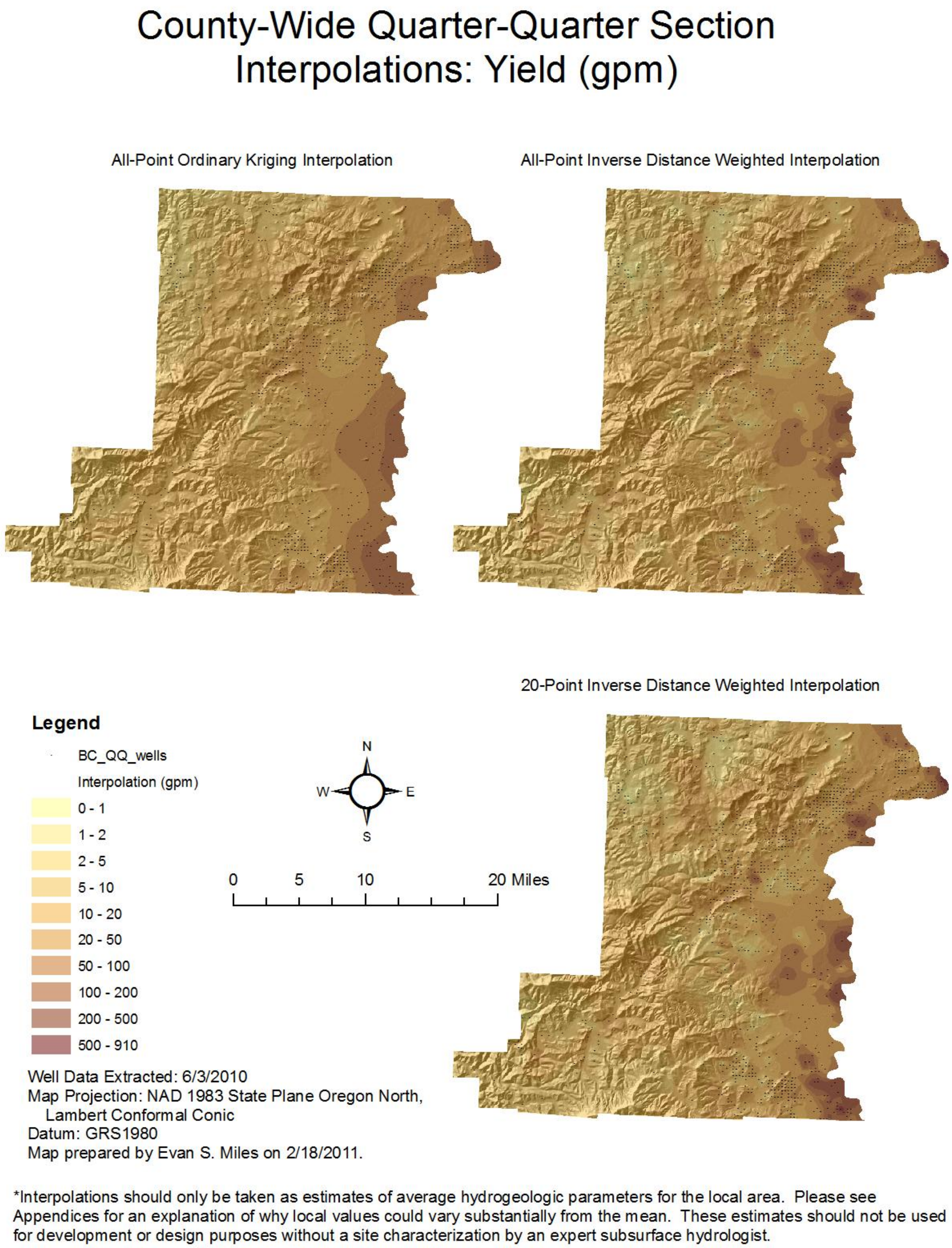


Figure 4.14 Well yield estimates (gpm) across Benton County for Quarter-Quarter-georeferenced wells.

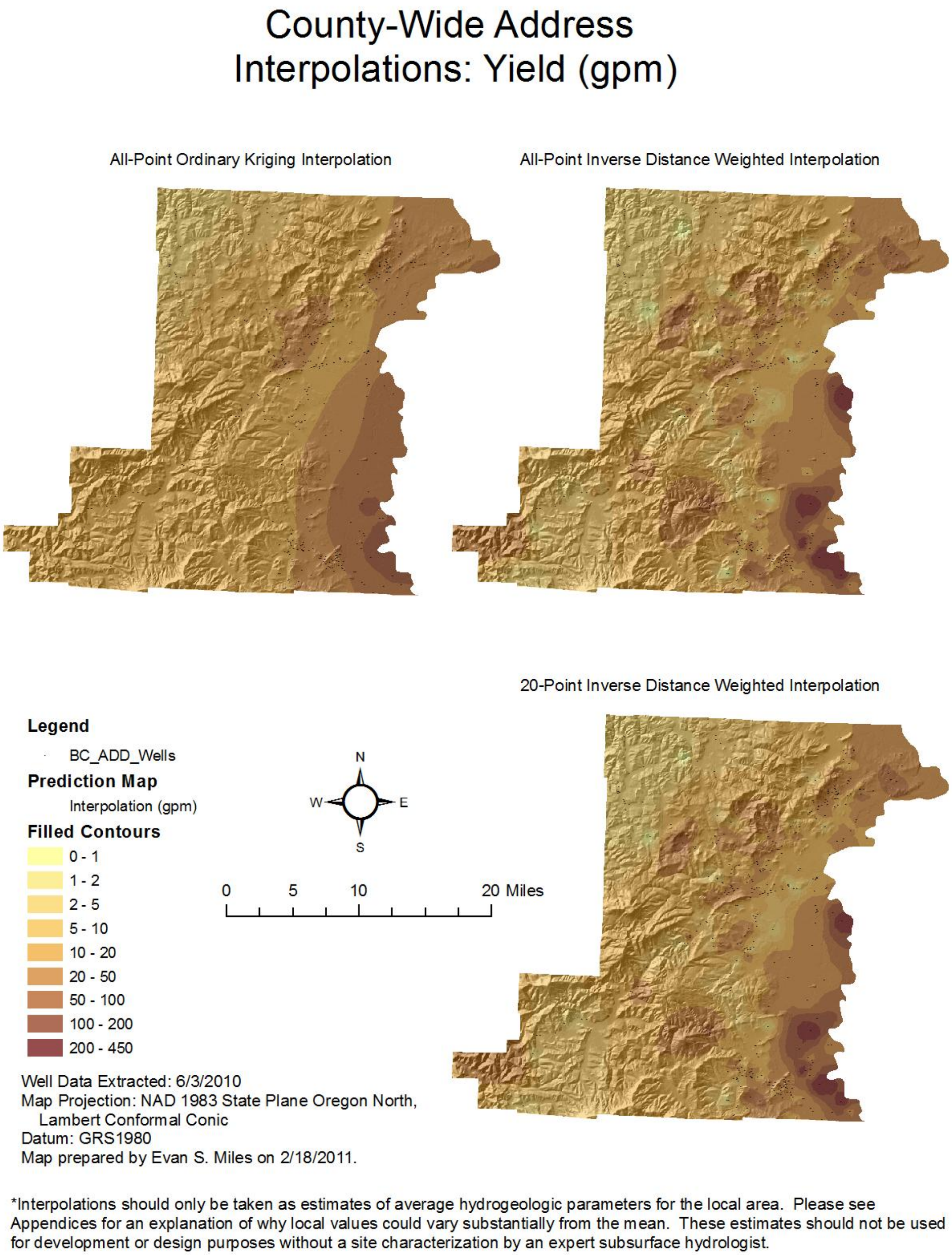


Figure 4.15 Well yield estimates (gpm) across Benton County for Address-georeferenced wells

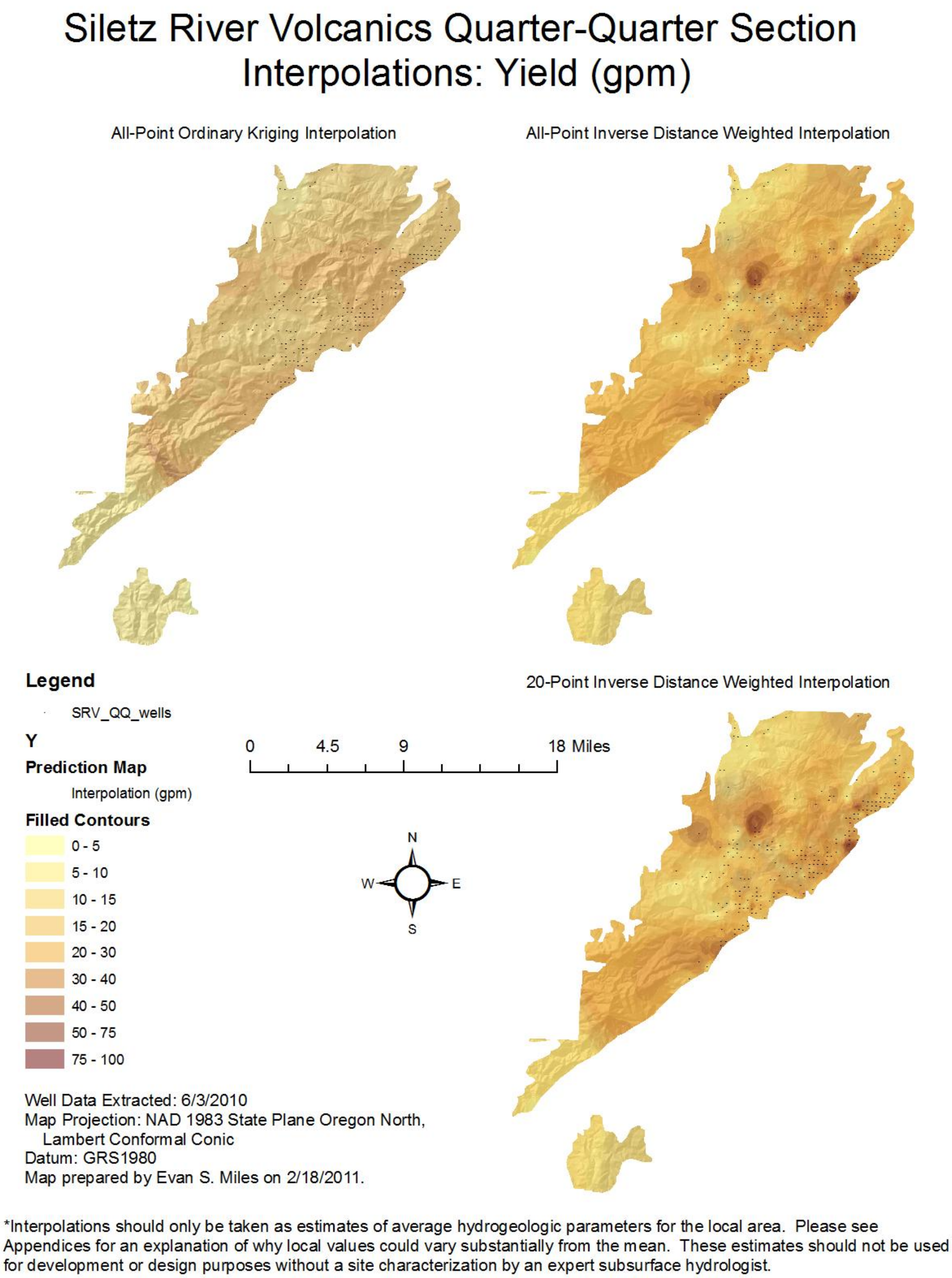


Figure 4.16 Well yield estimates (gpm) in the SRV for Quarter-Quarter-georeferenced wells.

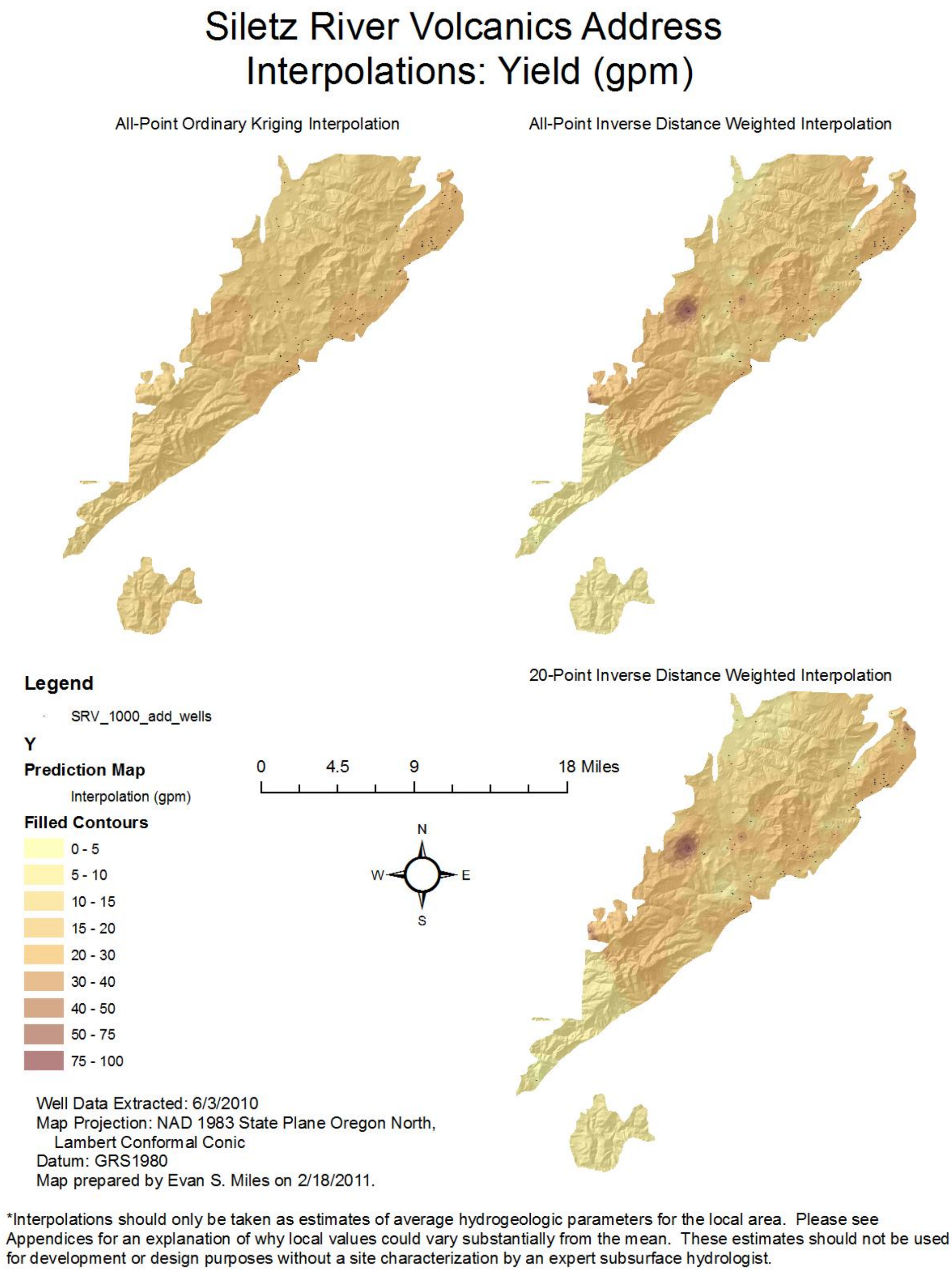


Figure 4.17 Well yield estimates (gpm) within the SRV for Address-georeferenced wells.

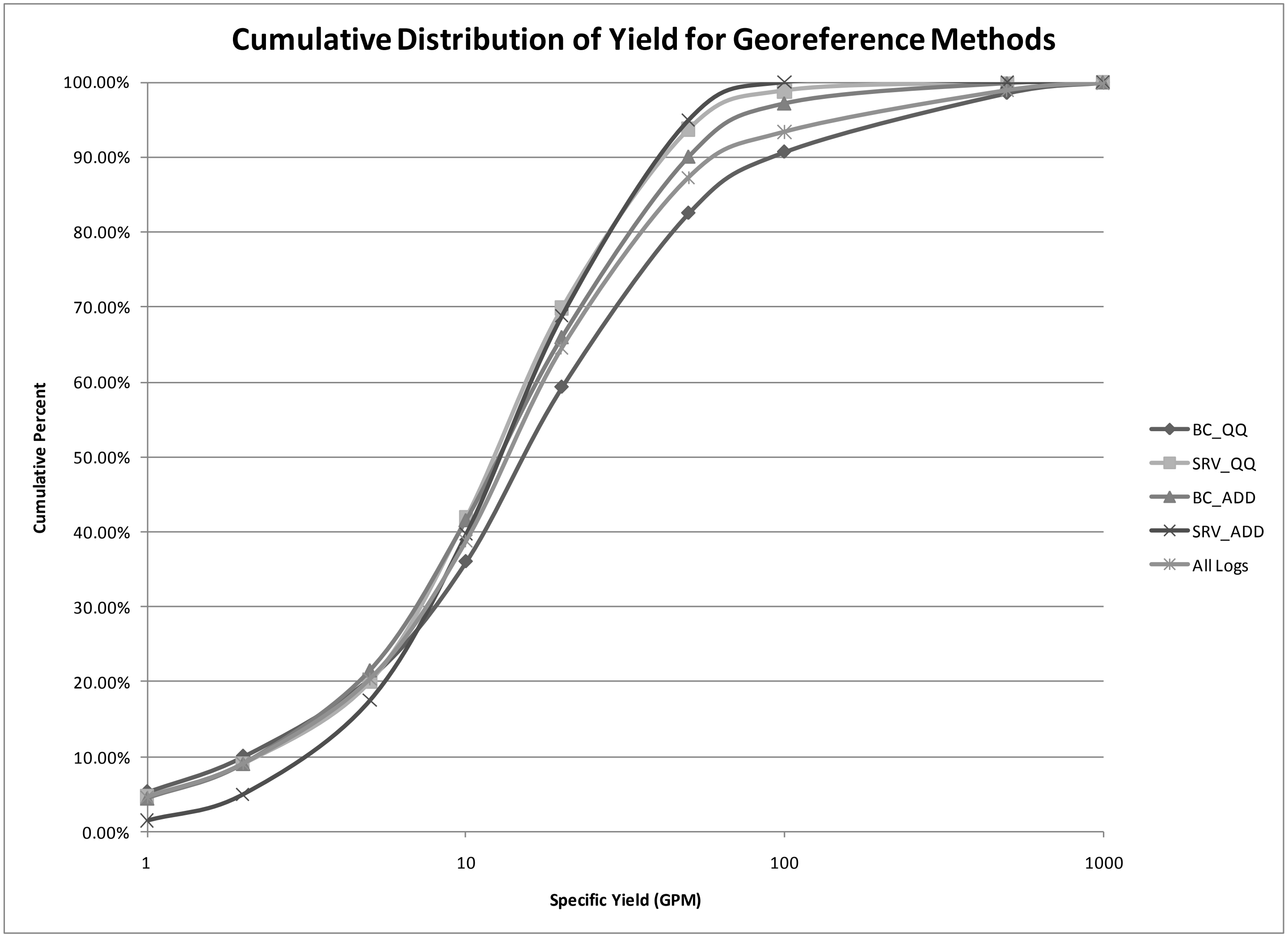


Figure 4.18 Cumulative distributions of well yield (gpm) values for georeference methods and extents.

	BC_QQ	SRV_QQ	BC_ADD	SRV_ADD	All Wells
Mean	53.36275618	21.80585652	28.17097863	18.90954774	45.16918277
Standard Error	2.299732275	1.587776753	2.021092005	1.117714688	1.689432766
Median	18	13	15	15	15
Mode	20	20	30	20	20
Standard Deviation	122.3405696	41.49538427	60.26108746	15.76730601	154.2203213
Sample Variance	14967.21496	1721.866916	3631.398661	248.6079387	23783.90752
Kurtosis	40.58081097	200.6428457	78.39472937	1.882106464	855.5420564
Skewness	5.20217567	12.16779334	7.708962719	1.439717018	22.26334982
Range	1999.9	799.7	909	74	7199.9
Minimum	0.1	0.3	1	1	0.1
Maximum	2000	800	910	75	7200
Sum	151016.6	14893.4	25044	3763	376394.8
Count	2830	683	889	199	8333
Confidence Level(95.0%)	4.509321577	3.117517763	3.966673993	2.204152849	3.311708363

Table 4.19 Statistics of well yield (gpm) for georeference methods and extents.

Method	Extent	% New Wells	% Abandoned Wells	% Deepened Wells	% Altered Wells
All Wells (not georeferenced)	Benton County	87.34616051	15.8433004	3.917490033	1.716068643
Section	Benton County	87.52663352	15.33203125	3.977272727	1.722301136
Address	Benton County	88.35978836	10.31746032	4.585537919	2.998236332
Address	Siletz River Volcanics	83.05084746	7.627118644	7.203389831	5.508474576
Quarter-Quarter	Benton County	87.20355731	19.04644269	3.853754941	2.519762846
Quarter-Quarter	Siletz River Volcanics	85.95890411	9.589041096	5.136986301	3.99543379

Table 4.20 Percentages of problematic wells for each georeferenced dataset.

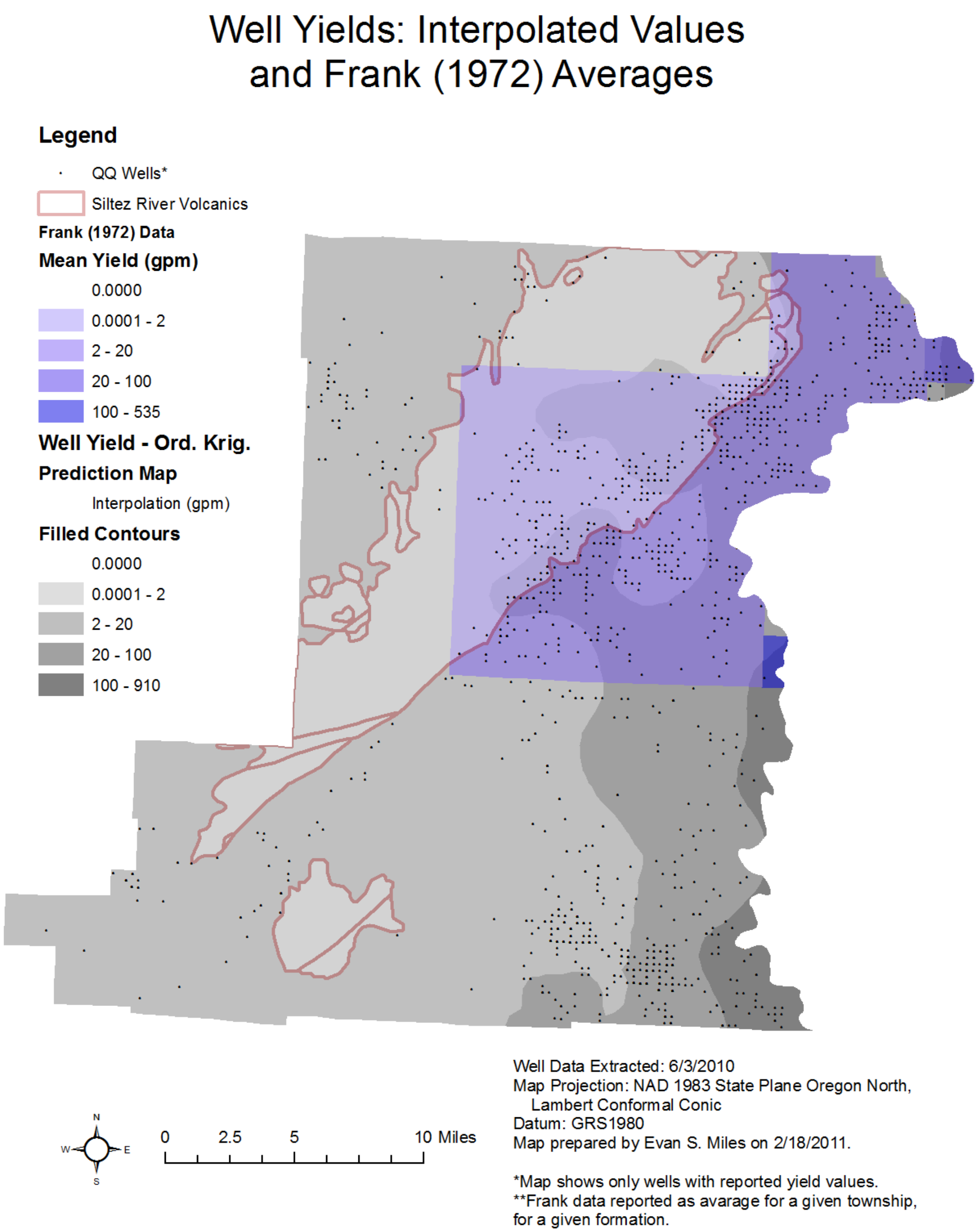


Figure 4.21 Comparison of yield values reported by Frank (1972) and this study.

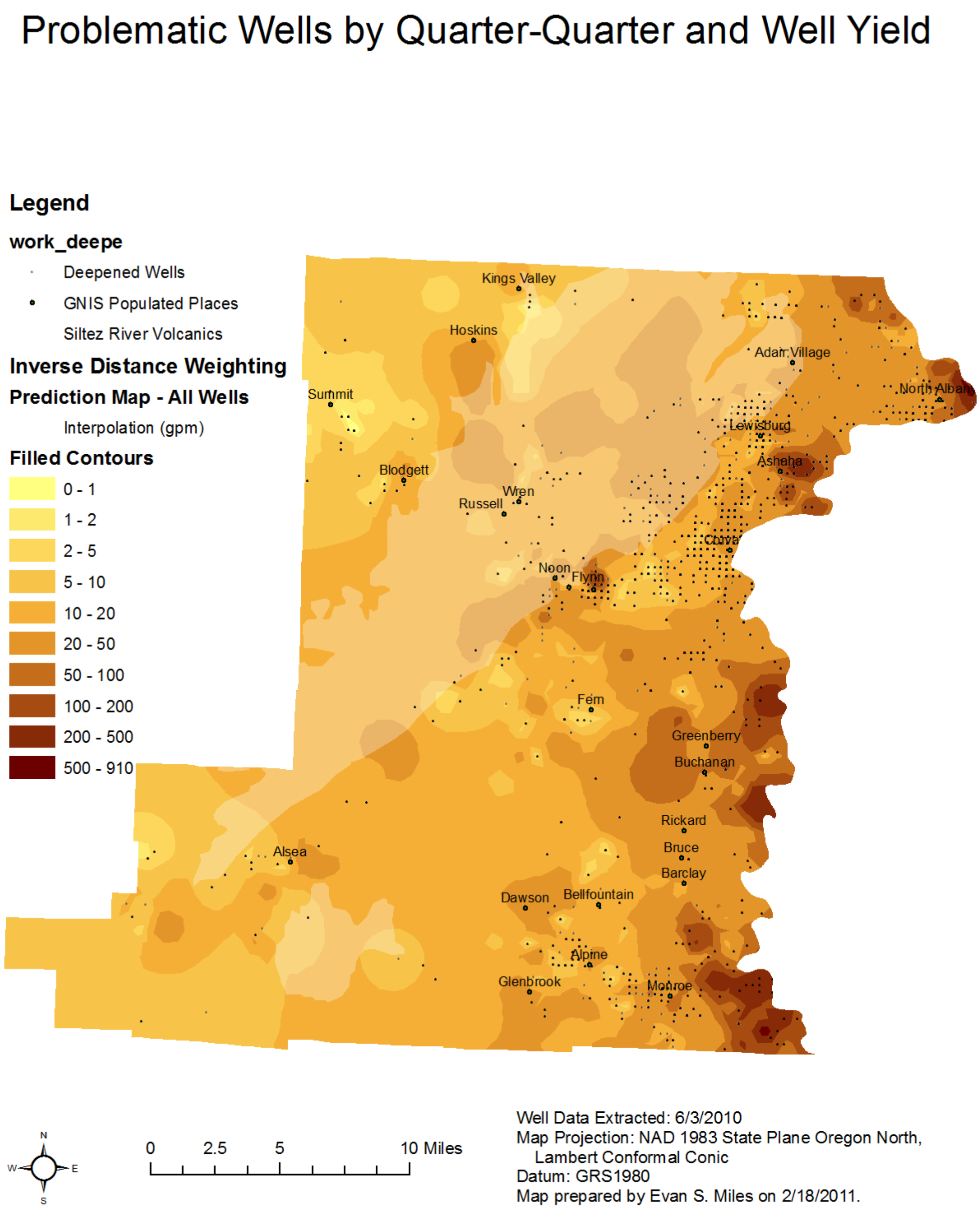


Figure 4.22 Locations of abandoned, altered, deepened, and dry wells compared with yield.

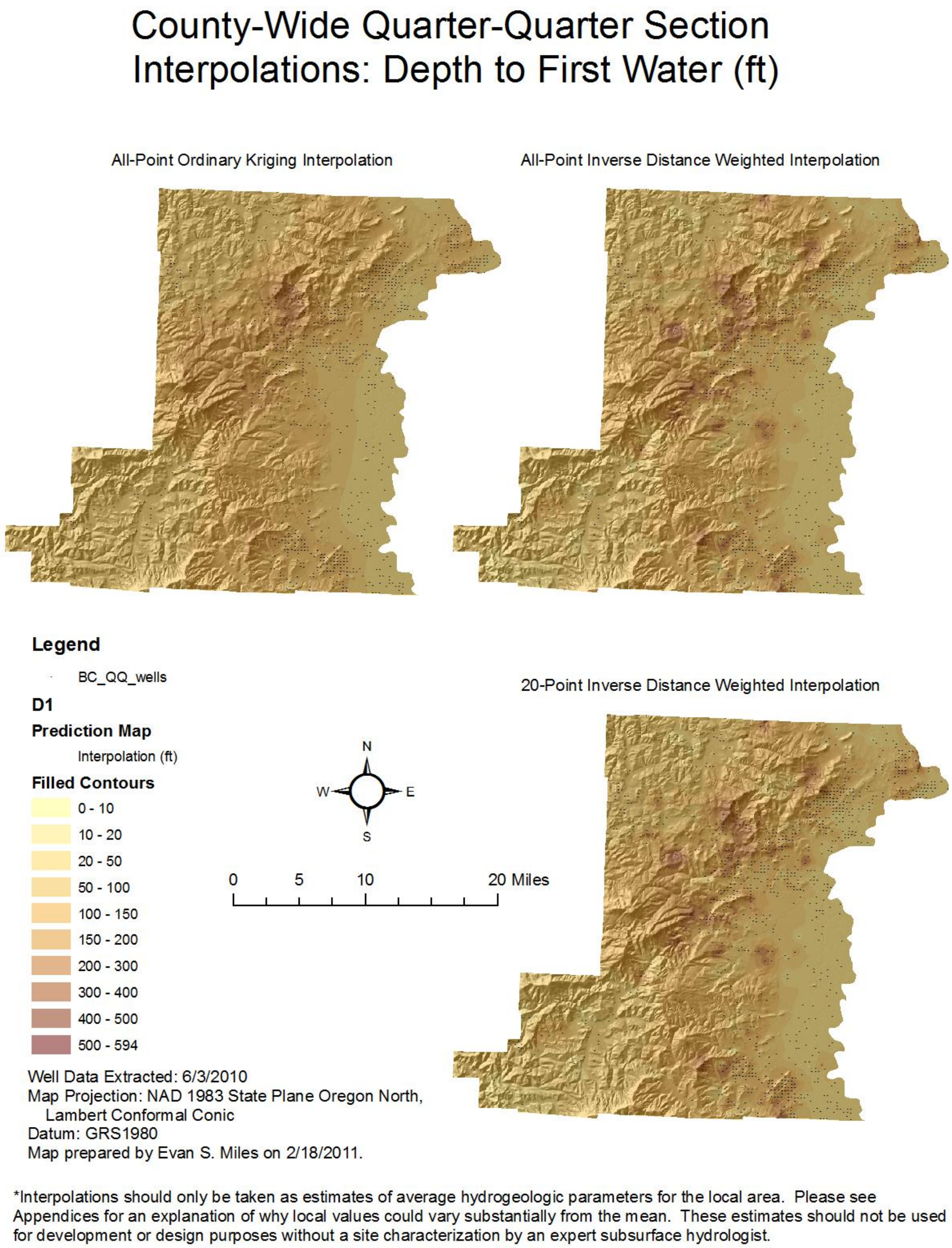


Figure 4.23 Interpolations of depth to first water (ft) across Benton County for QQ-georeferenced wells.

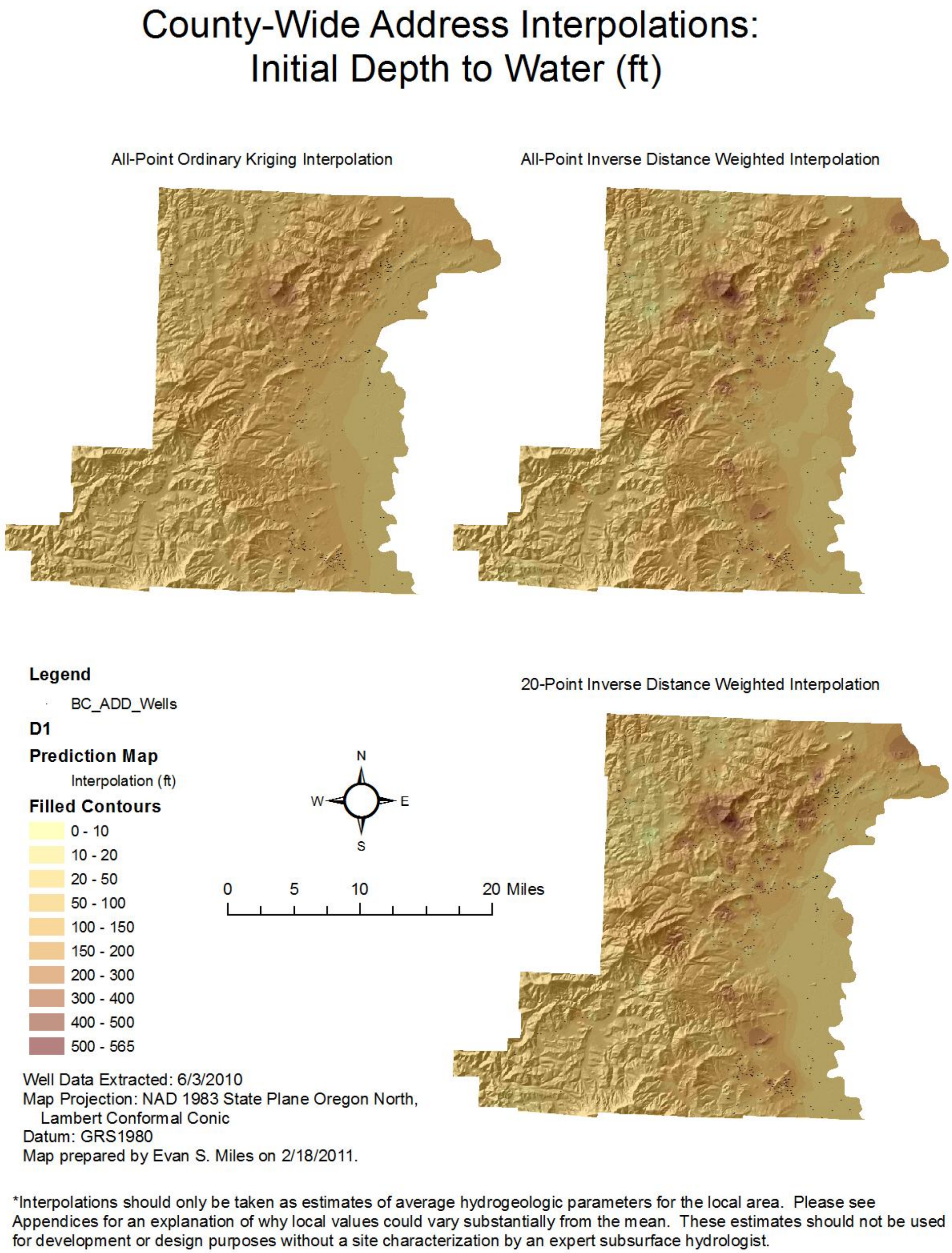


Figure 4.24 Estimates of depth to first water (ft) across Benton County for Address-georeferenced wells.

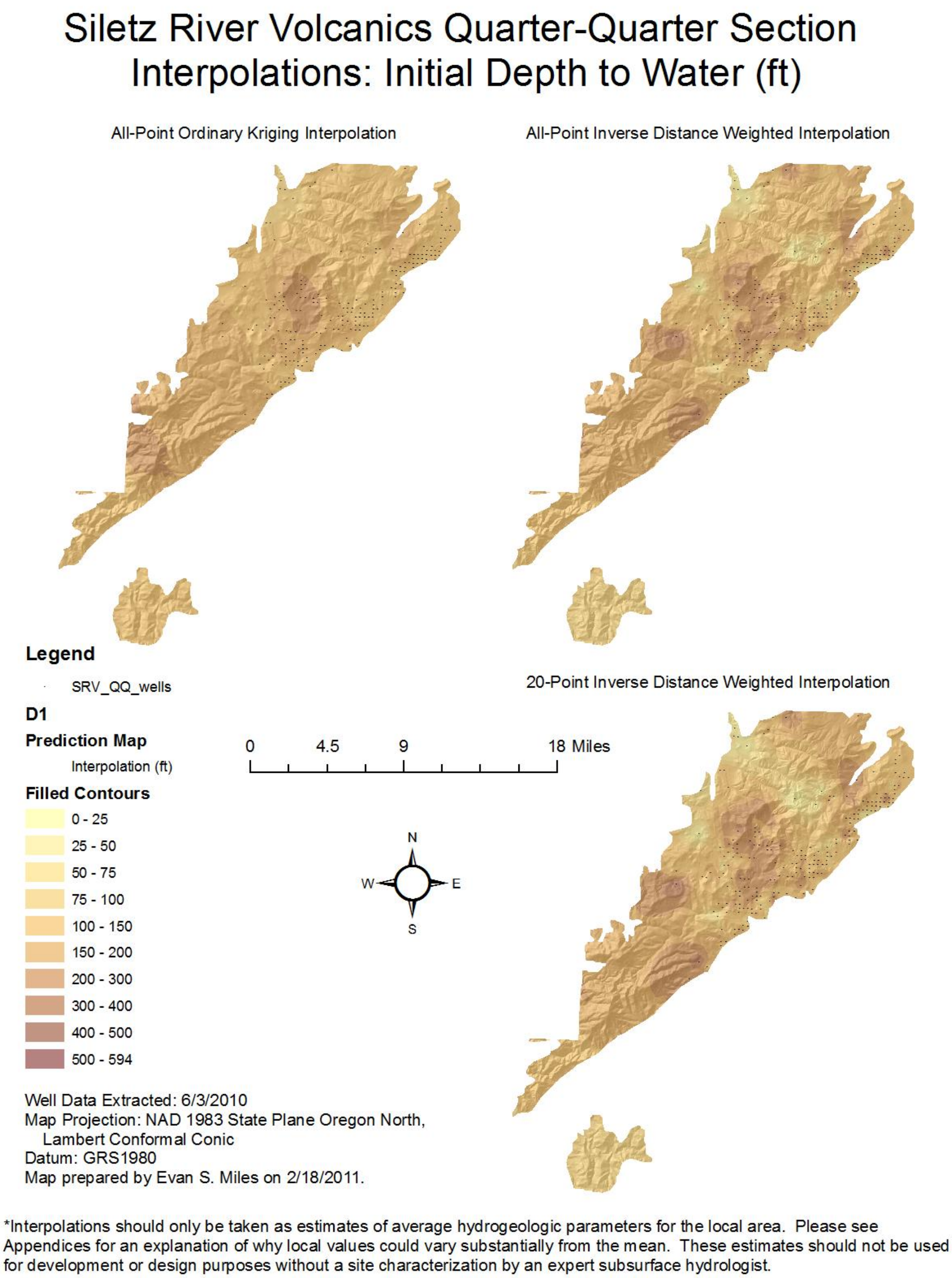


Figure 4.25 Interpolations of depth to first water (ft) in the SRV for QQ-georeferenced wells.

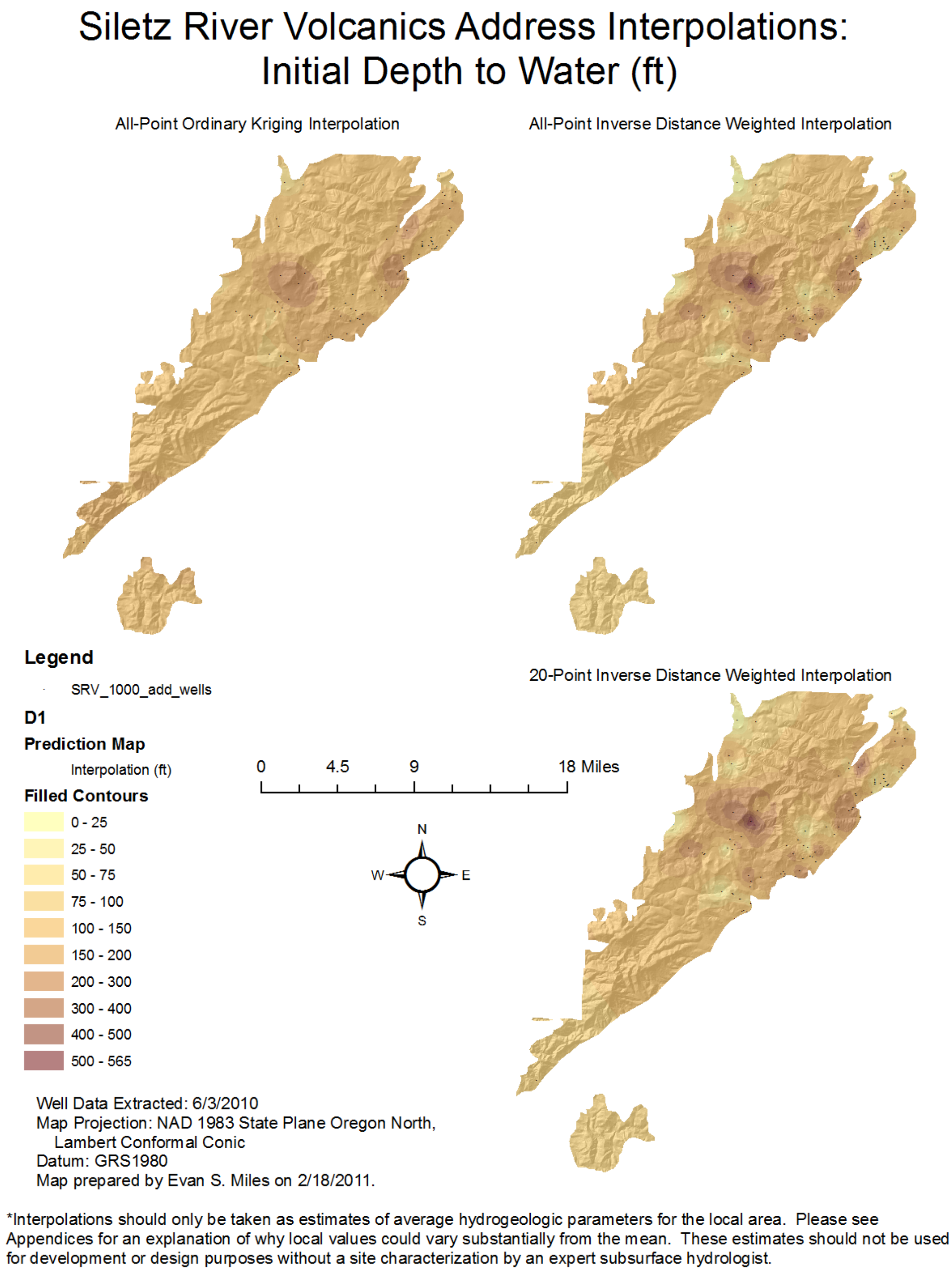


Figure 4.26 Estimates of depth to first water (ft) in the SRV for Address-georeferenced wells.

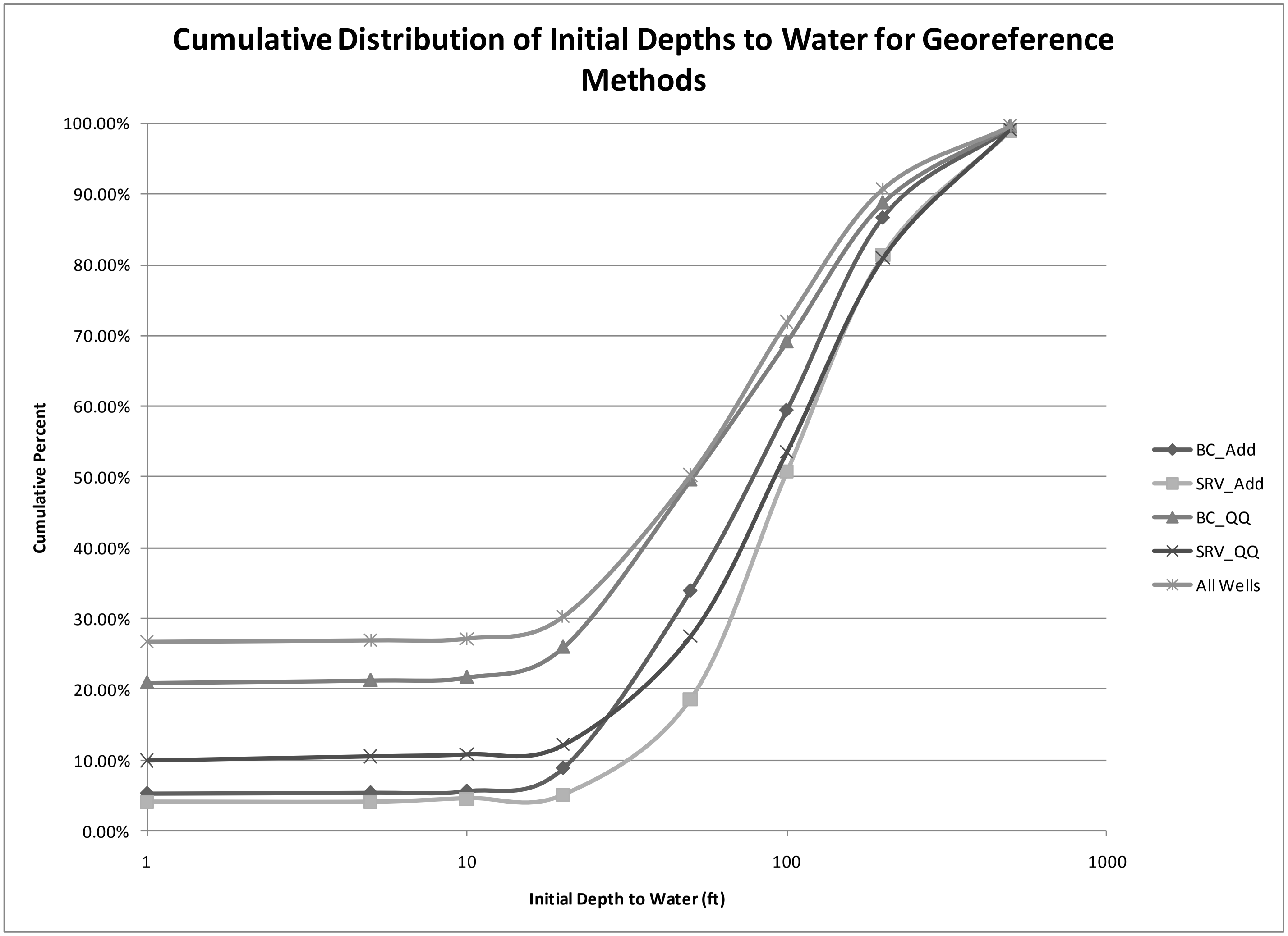


Figure 4.27 Cumulative distributions of depth to first water (ft) for georeference methods and extents.

	BC_QQ	SRV_QQ	BC_ADD	SRV_ADD	All Wells
Mean	84.45477	123.2387	109.4049	131.4171	78.37424
Standard Error	1.766292	4.131847	3.32394	7.237455	1.034938
Median	51.5	93	82	100	50
Mode	0	0	0	0	0
Standard Deviation	93.96274	107.9828	99.10695	102.0969	93.66048
Sample Variance	8828.997	11660.28	9822.187	10423.77	8772.285
Kurtosis	3.229028	1.953277	3.855038	3.232831	14.67055
Skewness	1.697037	1.363604	1.781709	1.57712	2.484434
Range	594	594	618	594	1645
Minimum	0	0	0	0	0
Maximum	594	594	618	594	1645
Sum	239007	84172	97261	26152	641885
Count	2830	683	889	199	8190
Confidence Level(95.0%)	3.46335	8.112668	6.523695	14.27239	2.028741

Table 4.28 Statistics of depth to first water (ft) for georeference methods and extents.

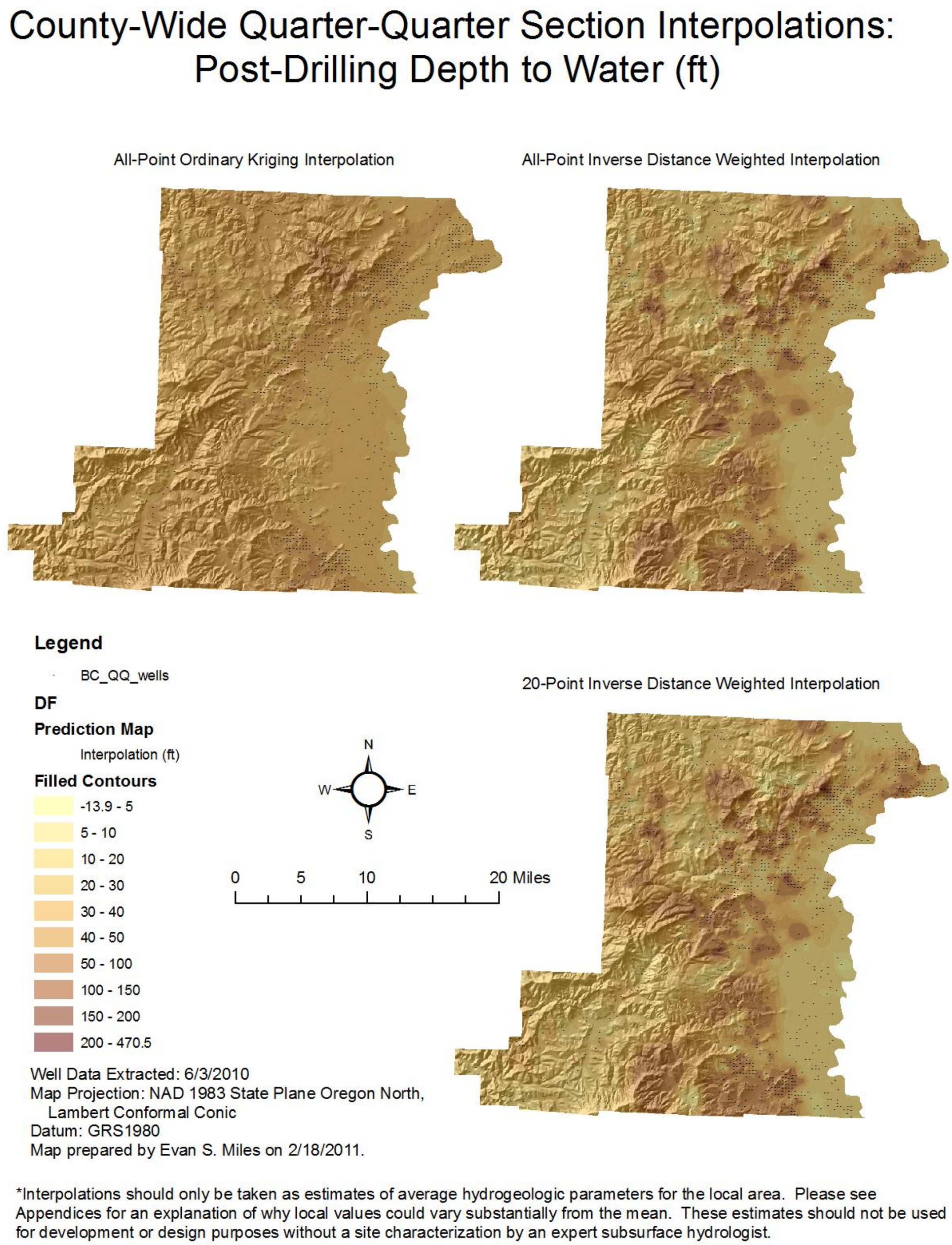


Figure 4.29 Interpolations of final depth to water (ft) for Quarter-Quarter-georeferenced wells.

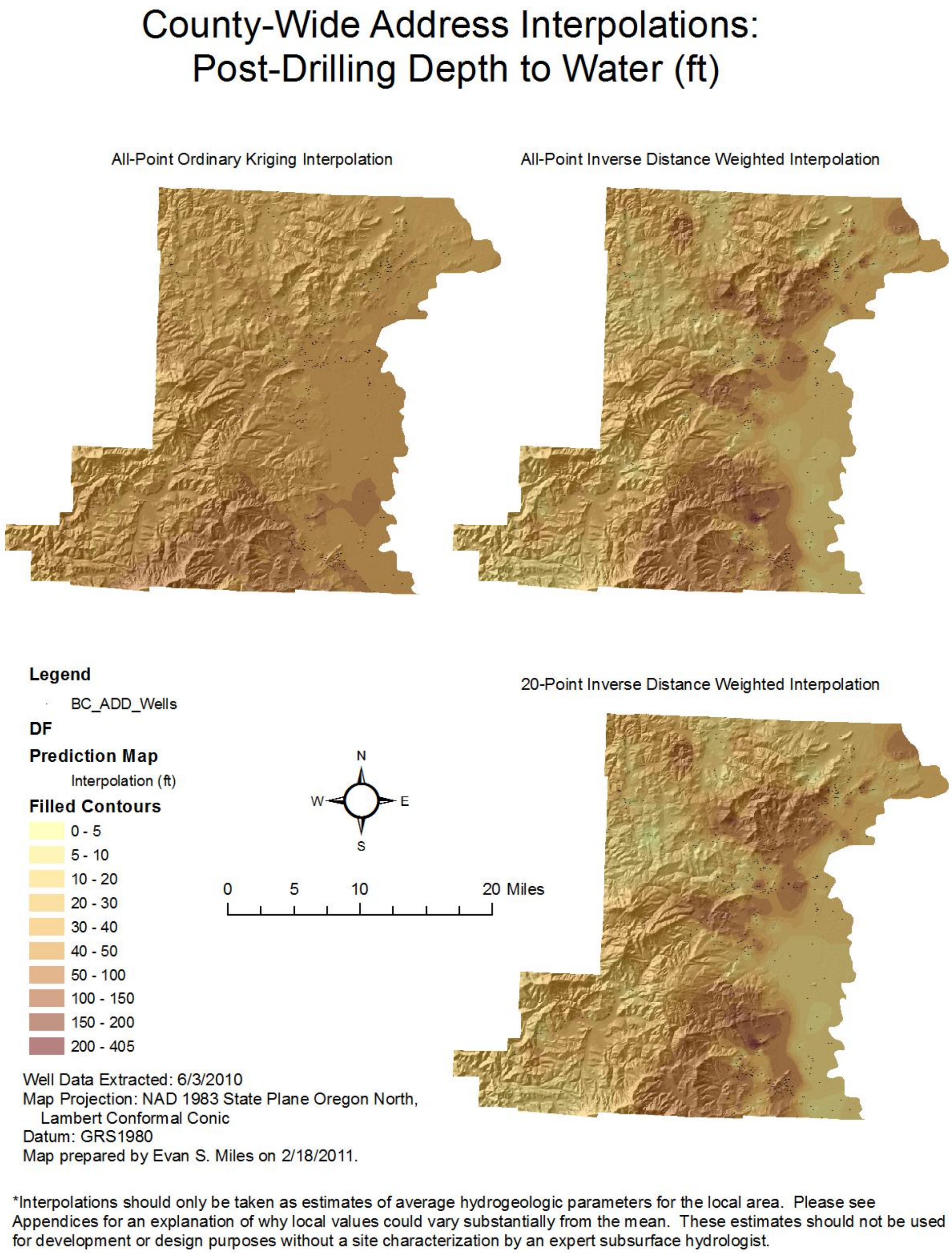


Figure 4.30 Interpolations of final depth to water (ft) for Address-georeferenced wells

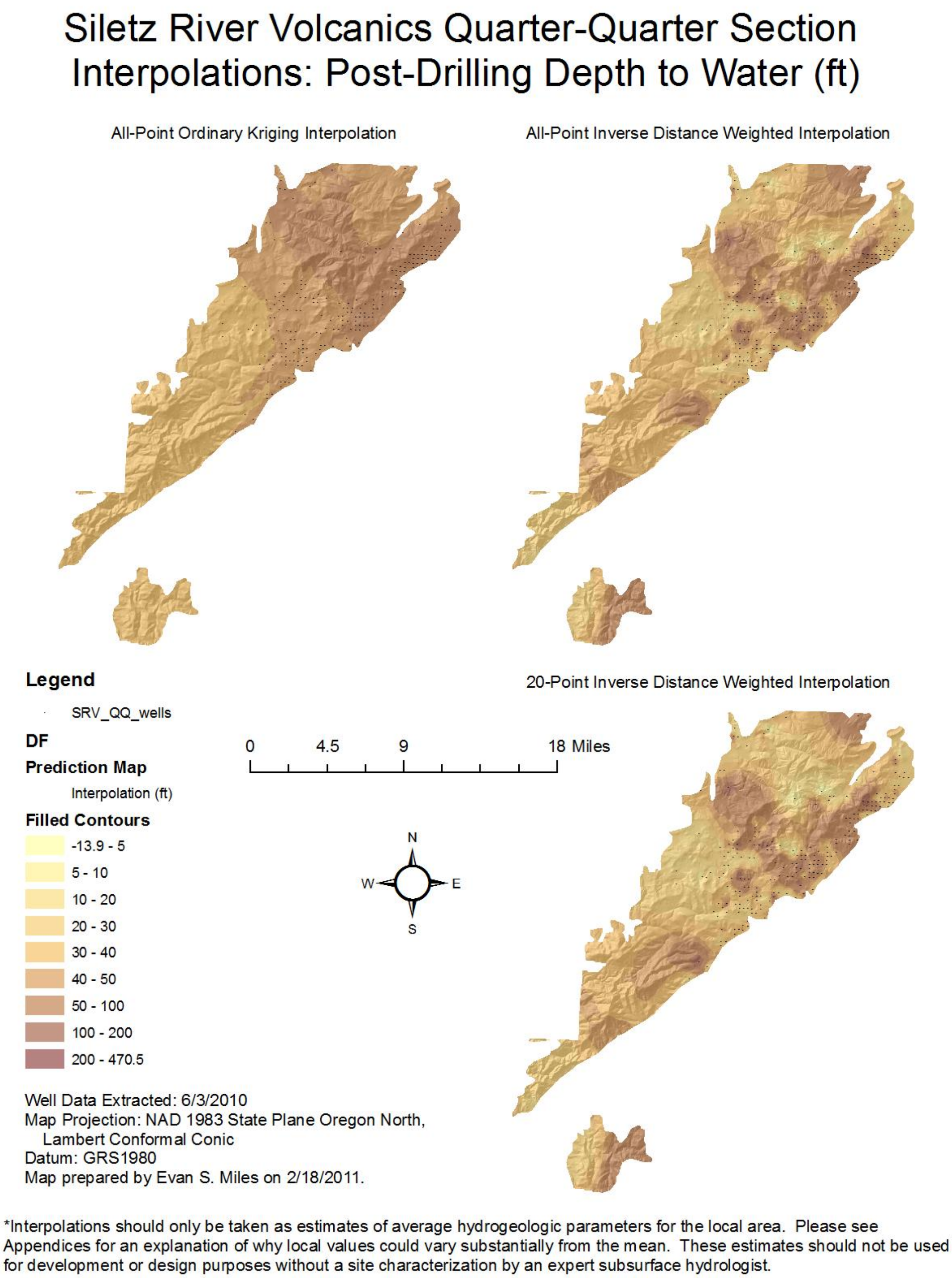


Figure 4.31 Interpolations of final depth to water (ft) in the SRV for Quarter-Quarter-georeferenced wells.

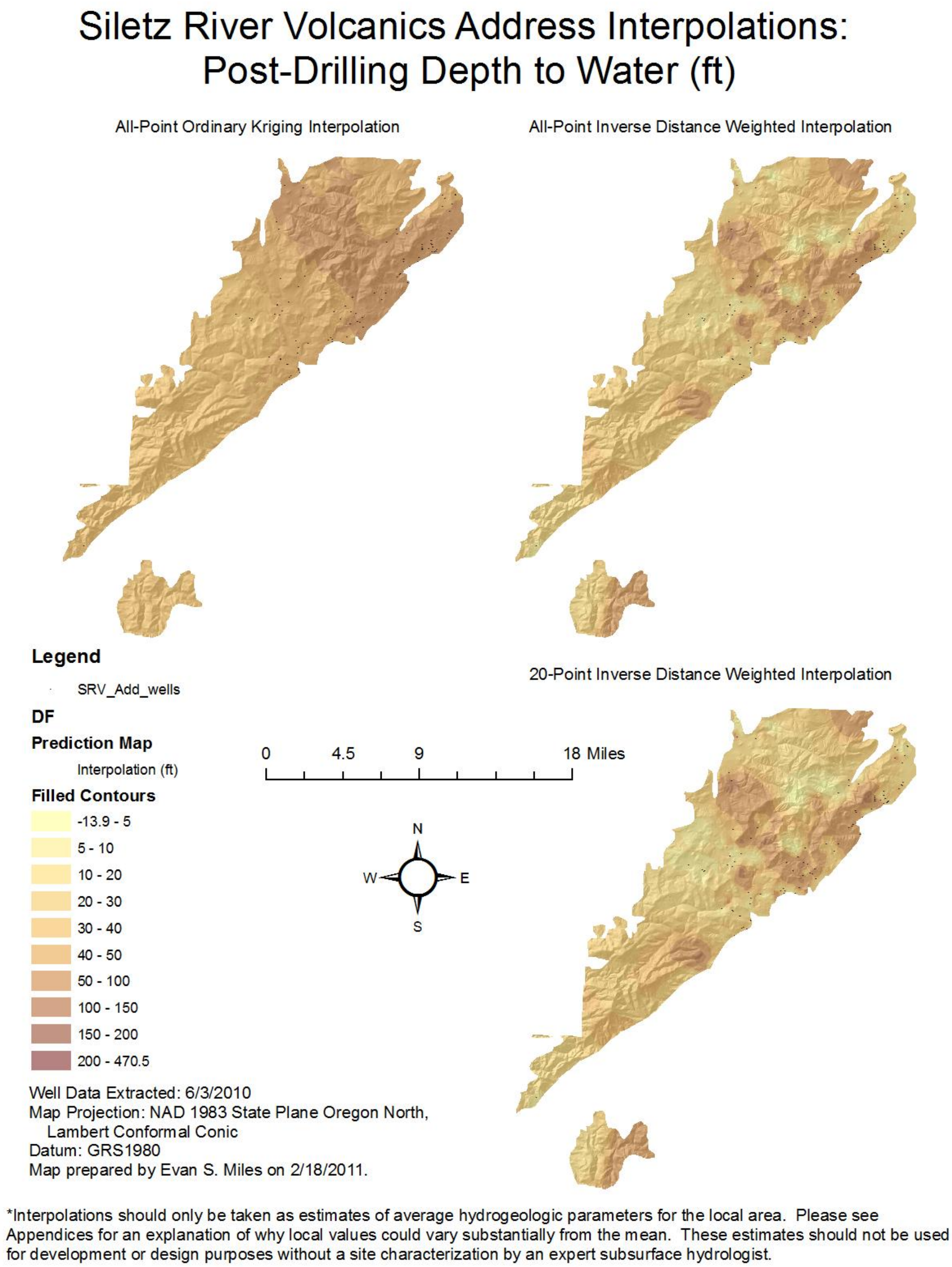


Figure 4.32 Interpolations of final depth to water (ft) in the SRV for Address-georeferenced wells.

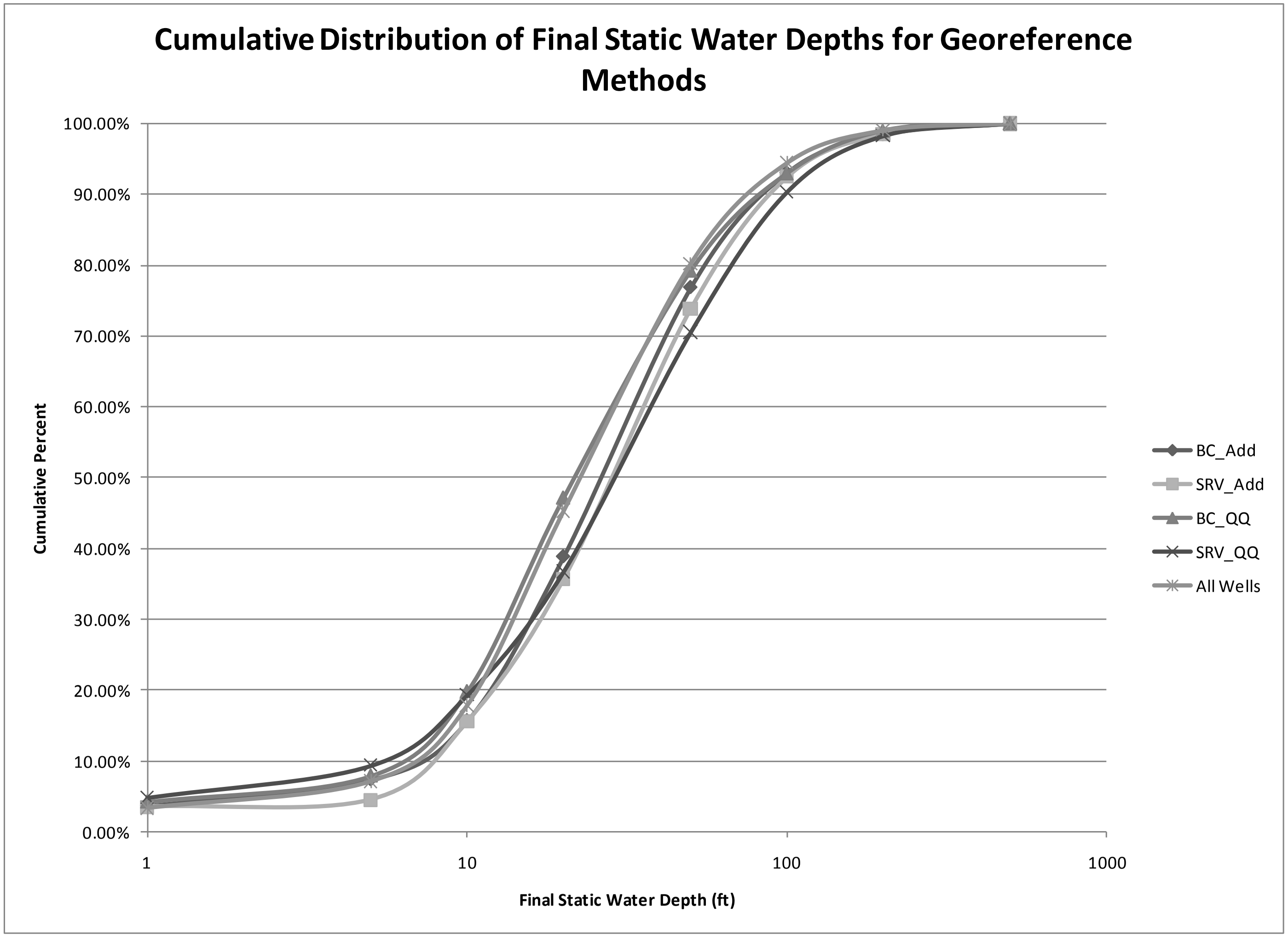


Figure 4.33 Cumulative distributions of final depth to water (ft) for georeference methods and extents.

ods and extents.

	BC_QQ	SRV_QQ	BC_ADD	SRV_ADD	All Wells
Mean	36.55293	45.37438	39.91327	41.76784	35.56207
Standard Error	0.805265	1.982703	1.480191	3.09825	0.441463
Median	22	30	27	28	23
Mode	10	18	18	10	18
Standard Deviation	42.83826	51.8165	44.13352	43.7062	40.19258
Sample Variance	1835.116	2684.95	1947.768	1910.232	1615.443
Kurtosis	16.17897	15.01723	16.80536	7.967144	19.15948
Skewness	3.179188	3.143499	3.327795	2.523823	3.501909
Range	594	453	437	297	594
Minimum	-155	-14	-25	-25	-155
Maximum	439	439	412	272	439
Sum	103444.8	30990.7	35482.9	8311.8	294774
Count	2830	683	889	199	8289
Confidence Level(95.0%)	1.578965	3.892936	2.90508	6.109804	0.865379

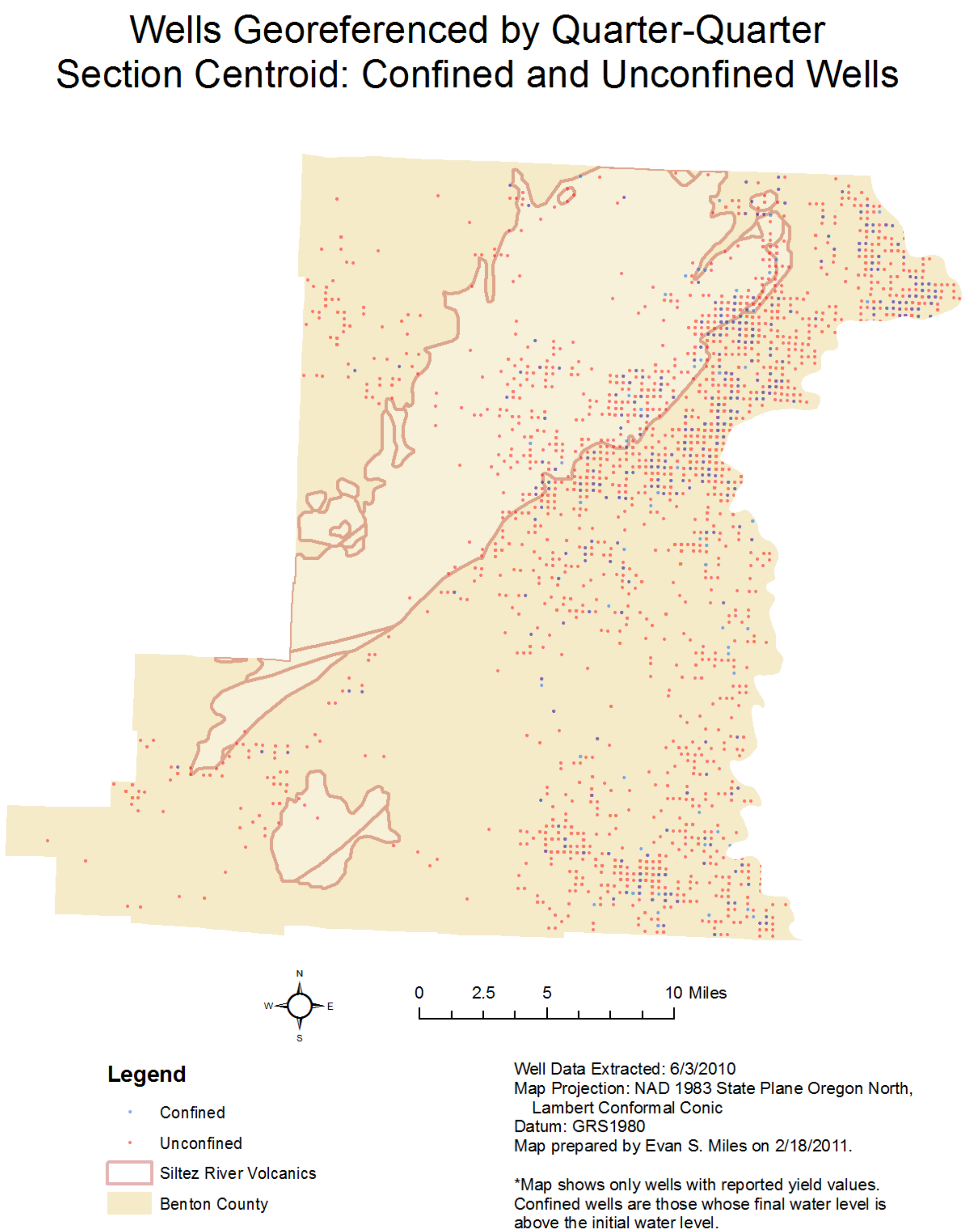


Figure 4.35 Distribution of wells penetrating confined and unconfined groundwater.

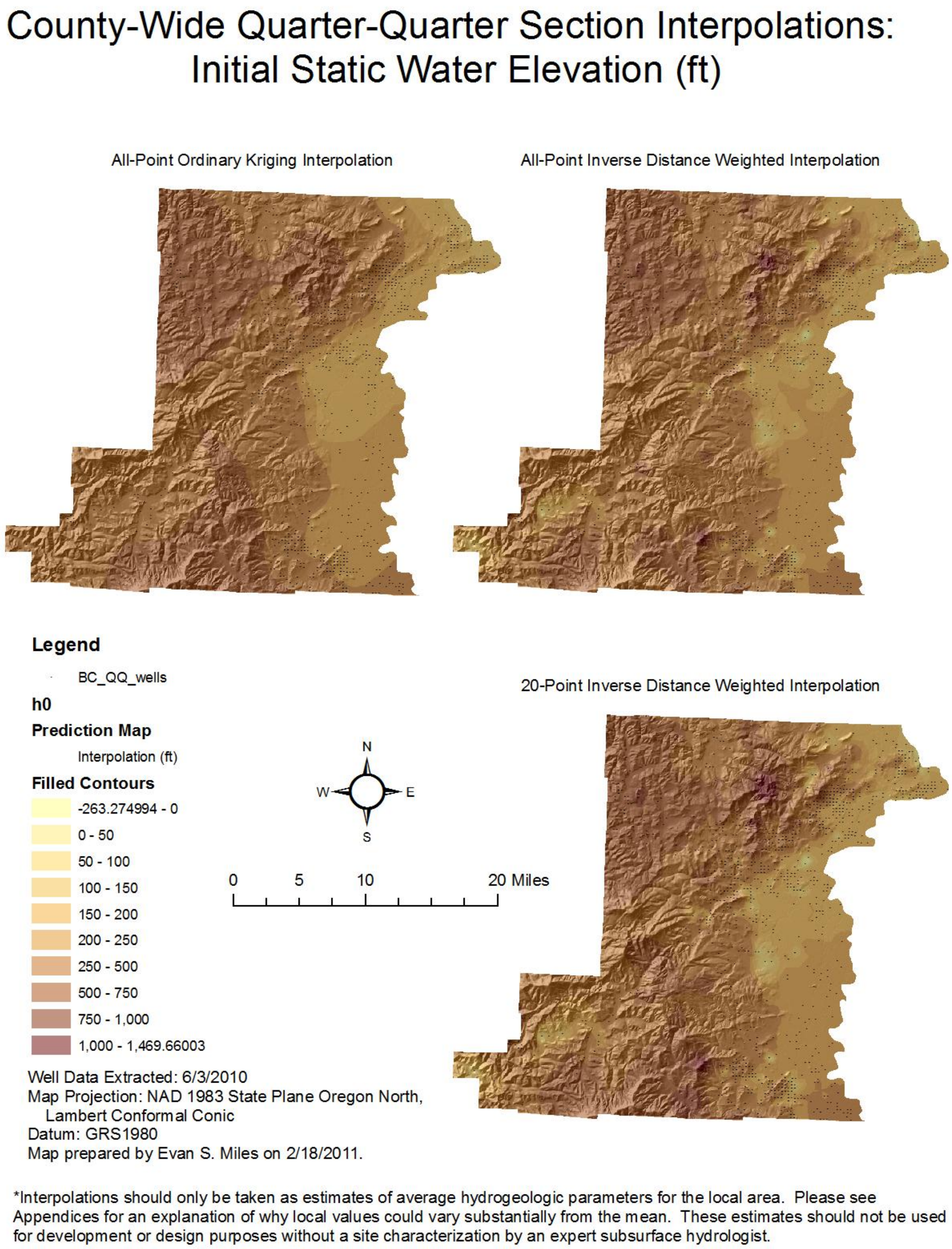


Figure 4.36 Initial static water elevation (ft) estimates for Quarter-Quarter-georeferenced wells.

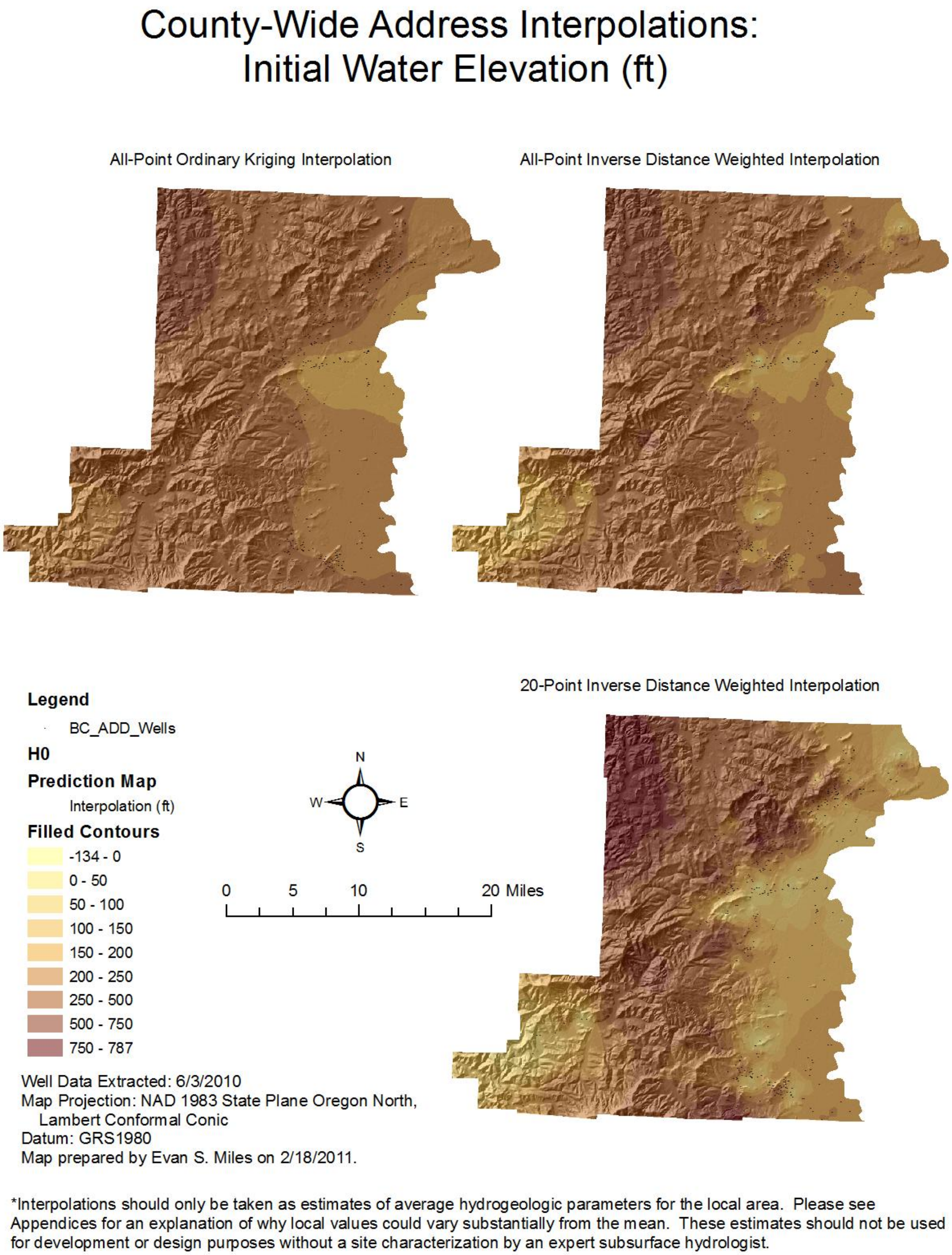


Figure 4.37 Initial static water elevation (ft) estimates for Address-georeferenced wells

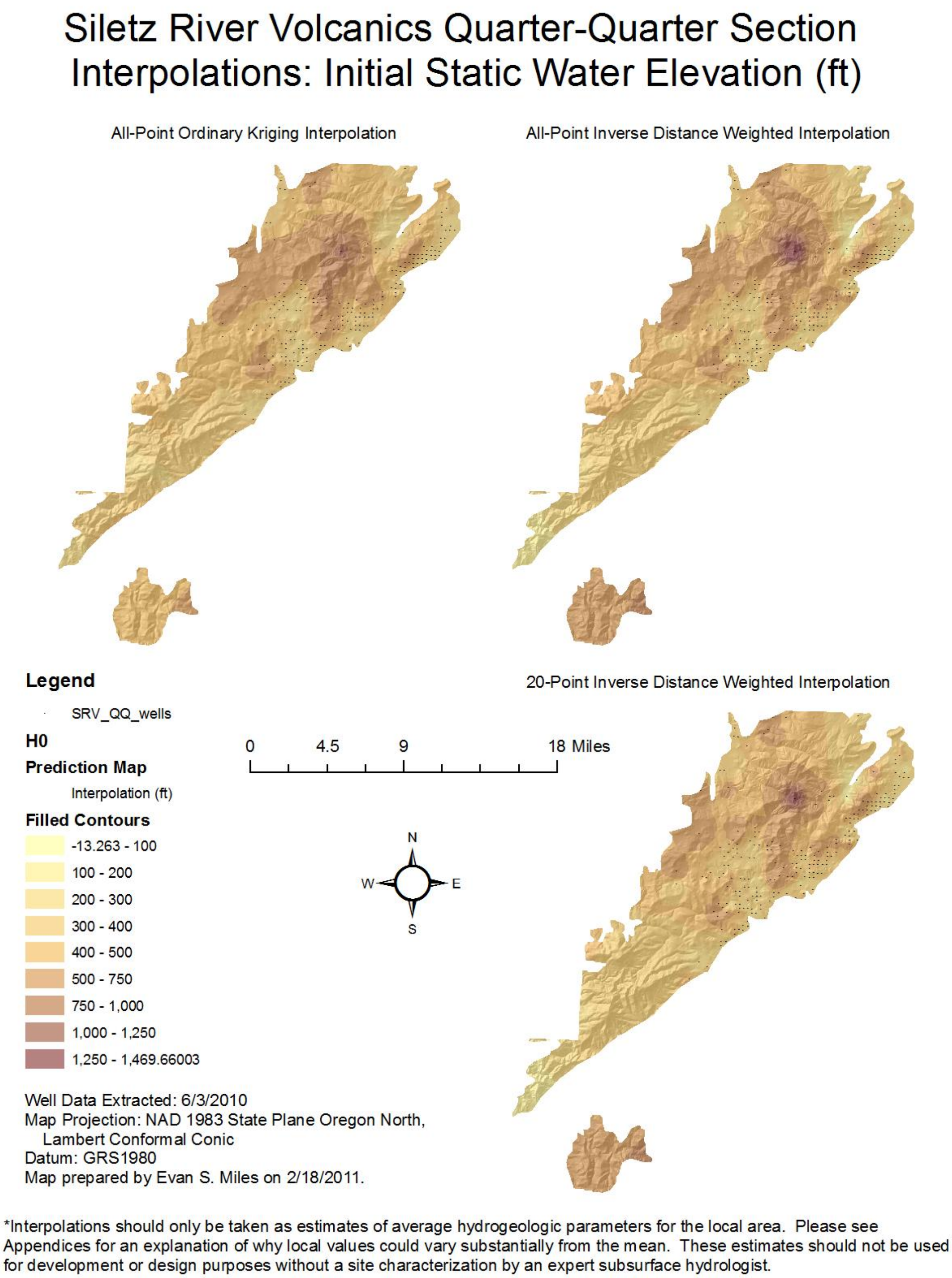


Figure 4.38 Initial static water elevation (ft) estimates in the SRV for QQ-georeferenced wells.

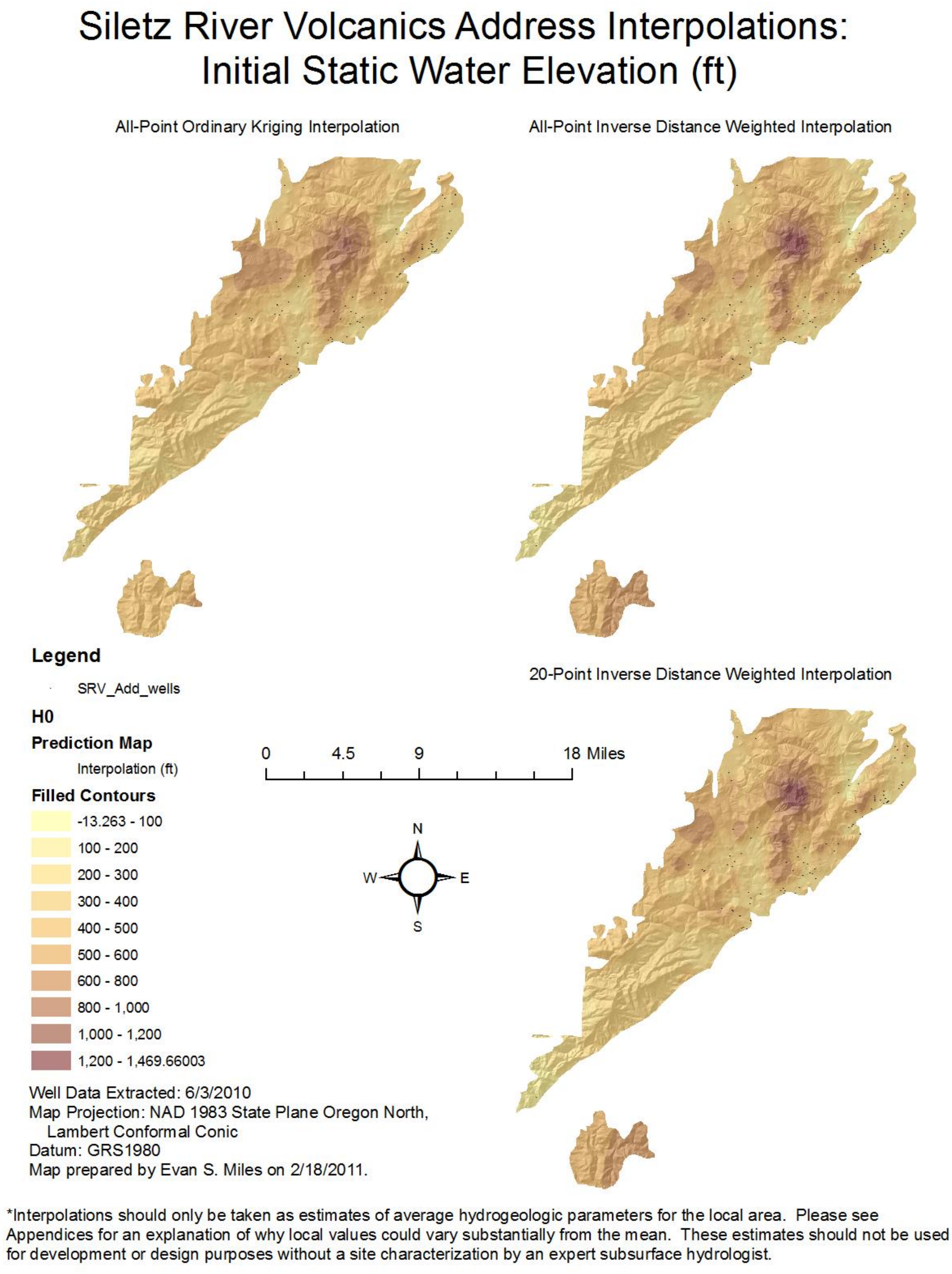


Figure 4.39 Initial static water elevation (ft) estimates in the SRV for Address-georeferenced wells.

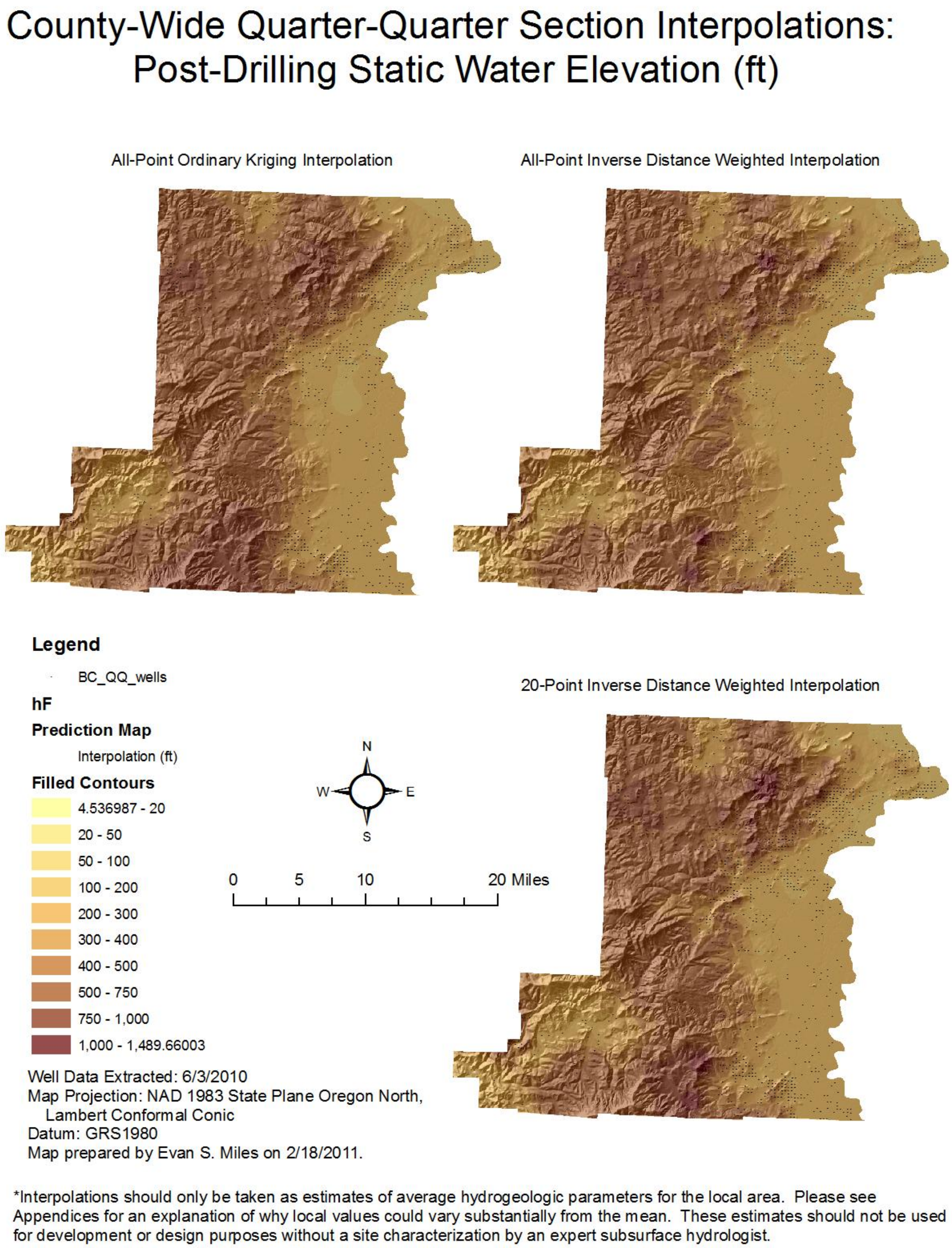


Figure 4.40 Final static water elevation (ft) estimates for Quarter-Quarter-georeferenced wells.

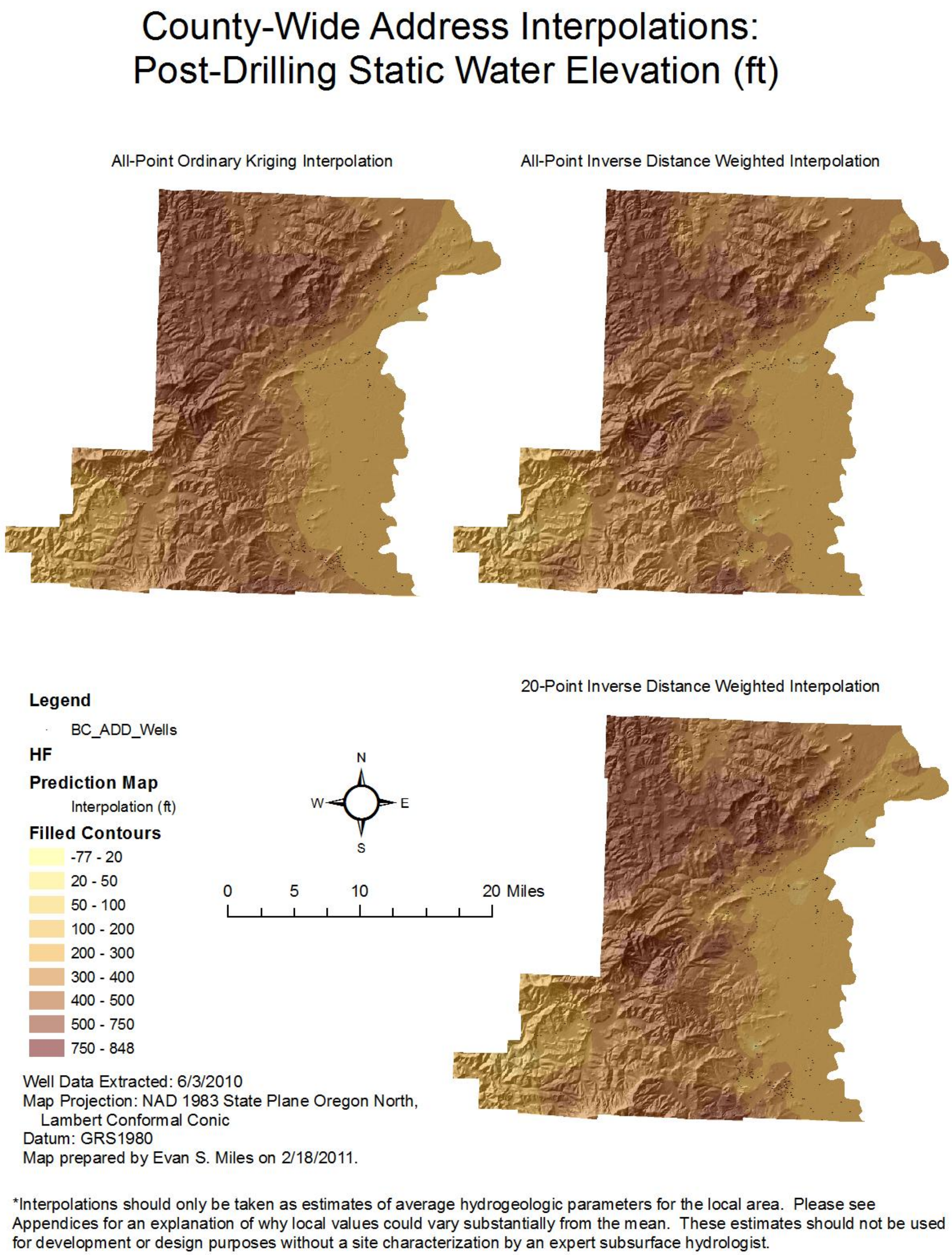


Figure 4.41 Final static water elevation (ft) estimates for Address-georeferenced wells

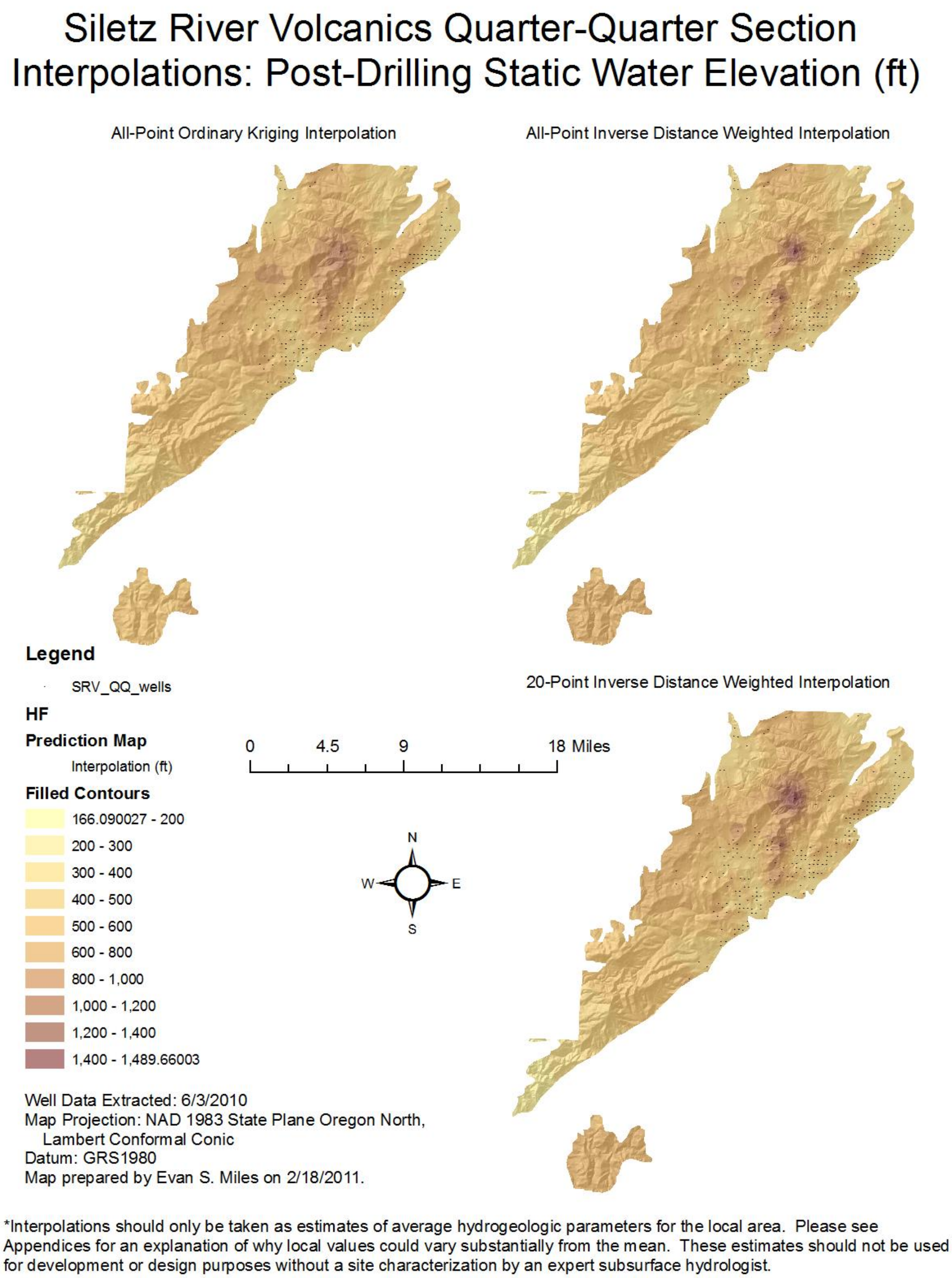


Figure 4.42 Final static water elevation (ft) estimates in the SRV for Quarter-Quarter-georeferenced wells.

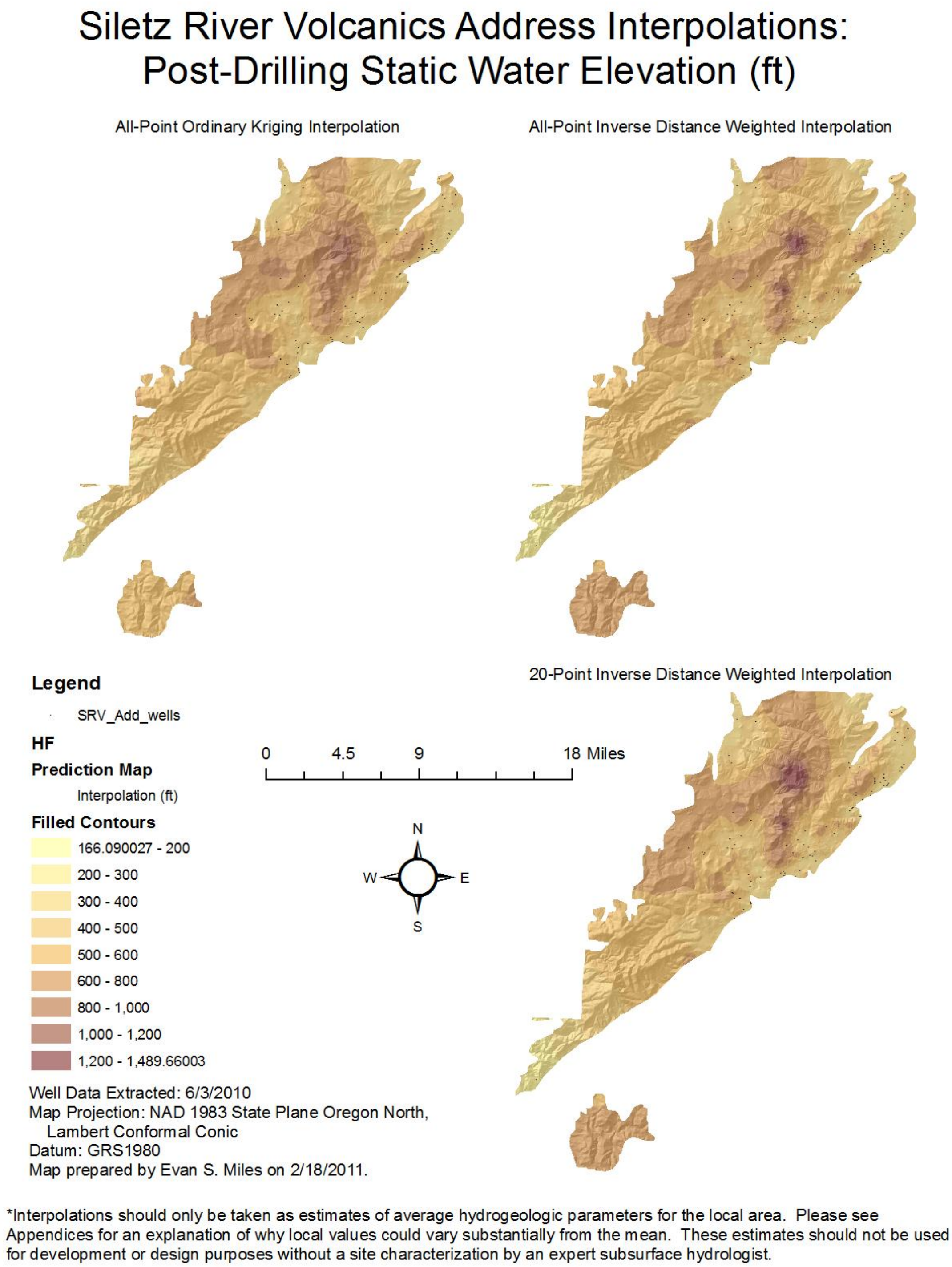


Figure 4.43 Final static water elevation (ft) estimates in the SRV for Address-georeferenced wells.

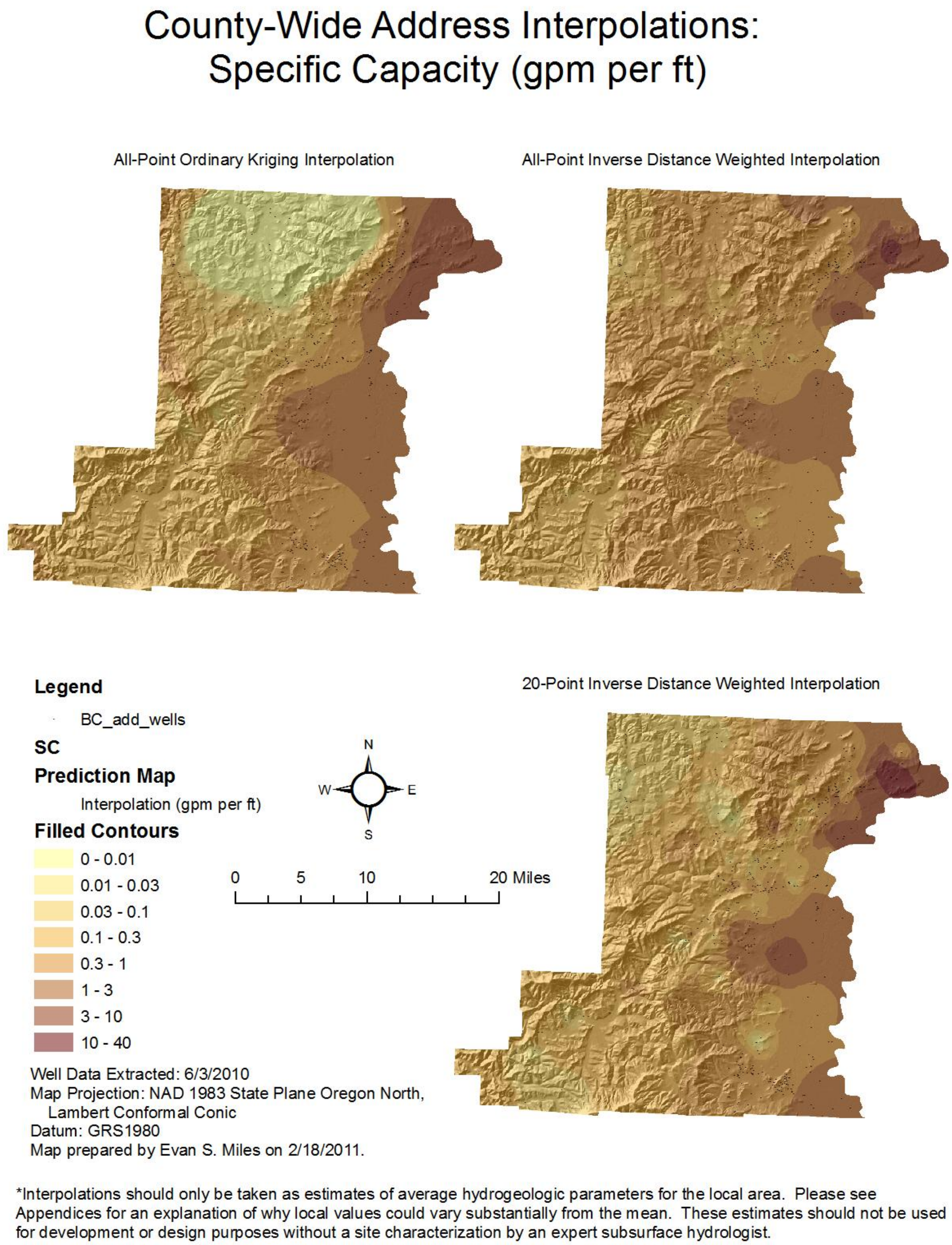


Figure 4.44 Specific capacity (gpm/ft) interpolations for Address-georeferenced wells.

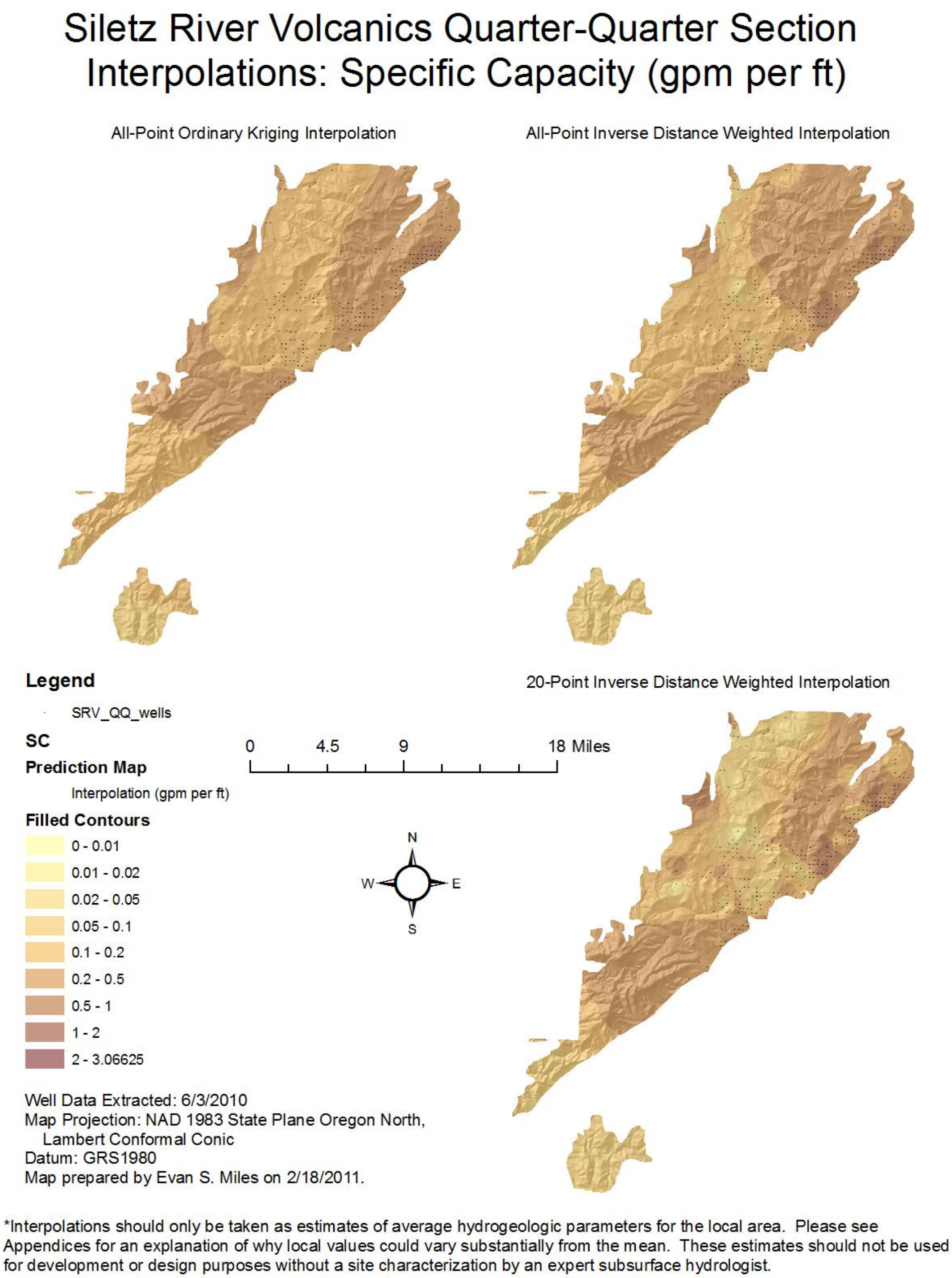


Figure 4.45 Specific capacity (gpm/ft) interpolations in the SRV for Quarter-Quarter-georeferenced wells.

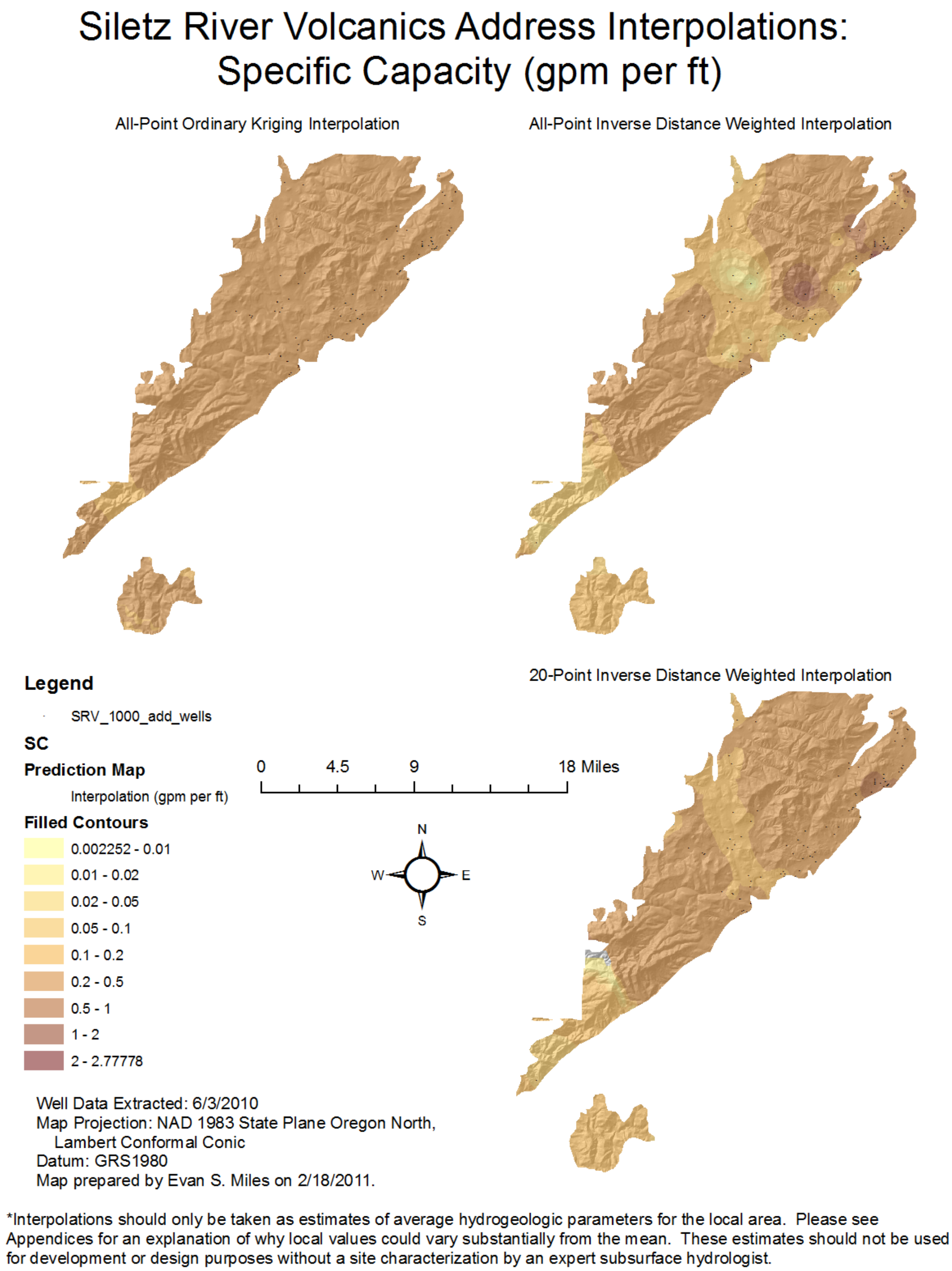


Figure 4.46 Specific capacity (gpm/ft) interpolations in the SRV for Address-georeferenced wells.

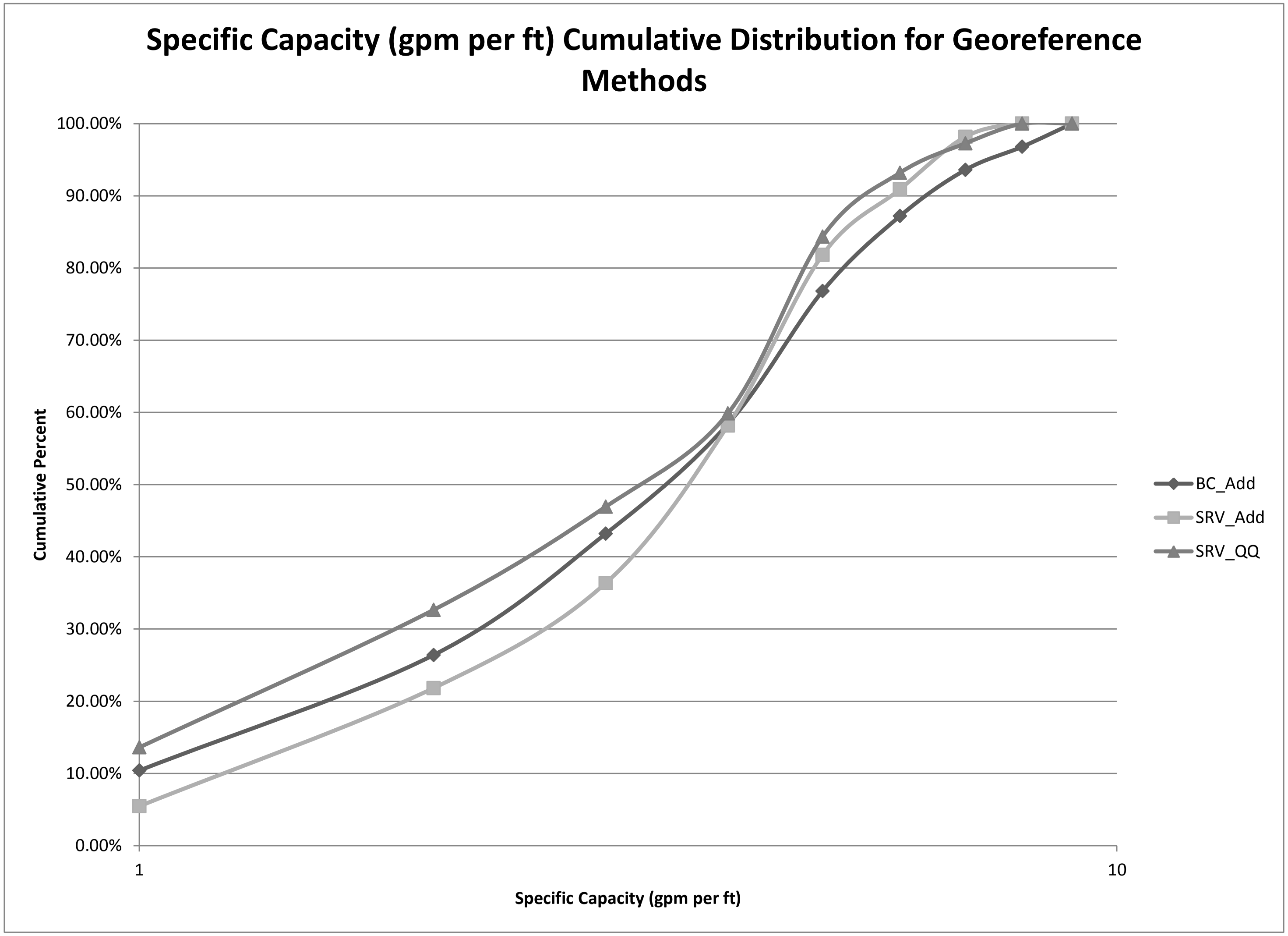


Figure 4.47 Cumulative distributions of specific capacity (gpm/ft) for georeference methods and extents.

	SRV_QQ	BC_ADD	SRV_ADD
Mean	0.025215	0.961608	0.324535
Standard Error	0.002681	0.354137	0.064283
Median	0.026432	0.125	0.125
Mode	0	0.5	0.044534
Standard Deviation	0.01988	3.959375	0.476736
Sample Variance	0.000395	15.67665	0.227277
Kurtosis	-0.81937	78.51706	12.61804
Skewness	0.476992	8.348505	3.132996
Range	0.068493	40	2.775528
Minimum	0	0	0.002252
Maximum	0.068493	40	2.77778
Sum	1.386851	120.201	17.8494
Count	55	125	55
Confidence Level(95.0%)	0.005374	0.700937	0.12888

Table 4.48 Statistics of specific capacity (gpm/ft) for georeference methods and extents.

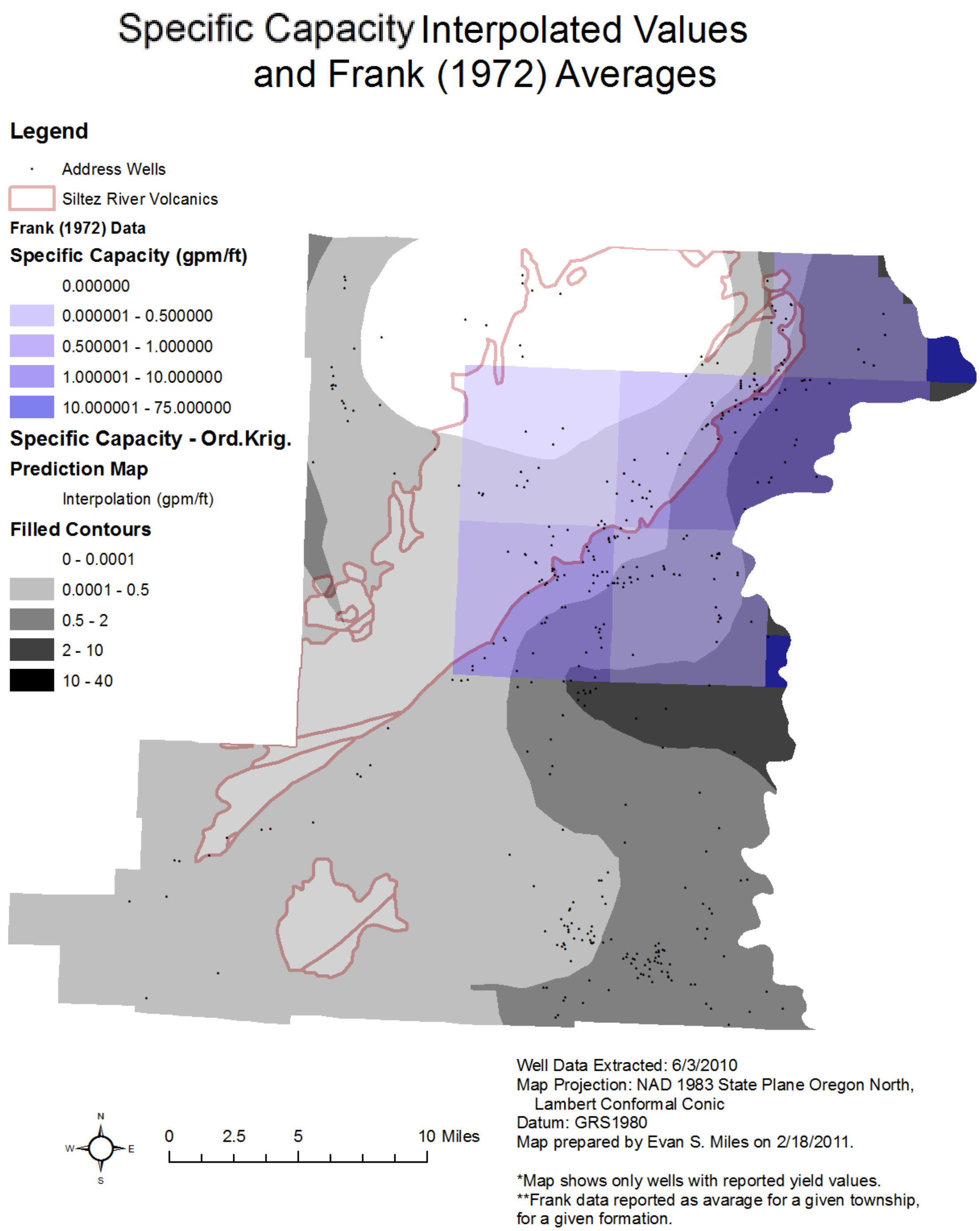


Figure 4.49 Comparison of specific capacity values reported by Frank (1972) and this study.

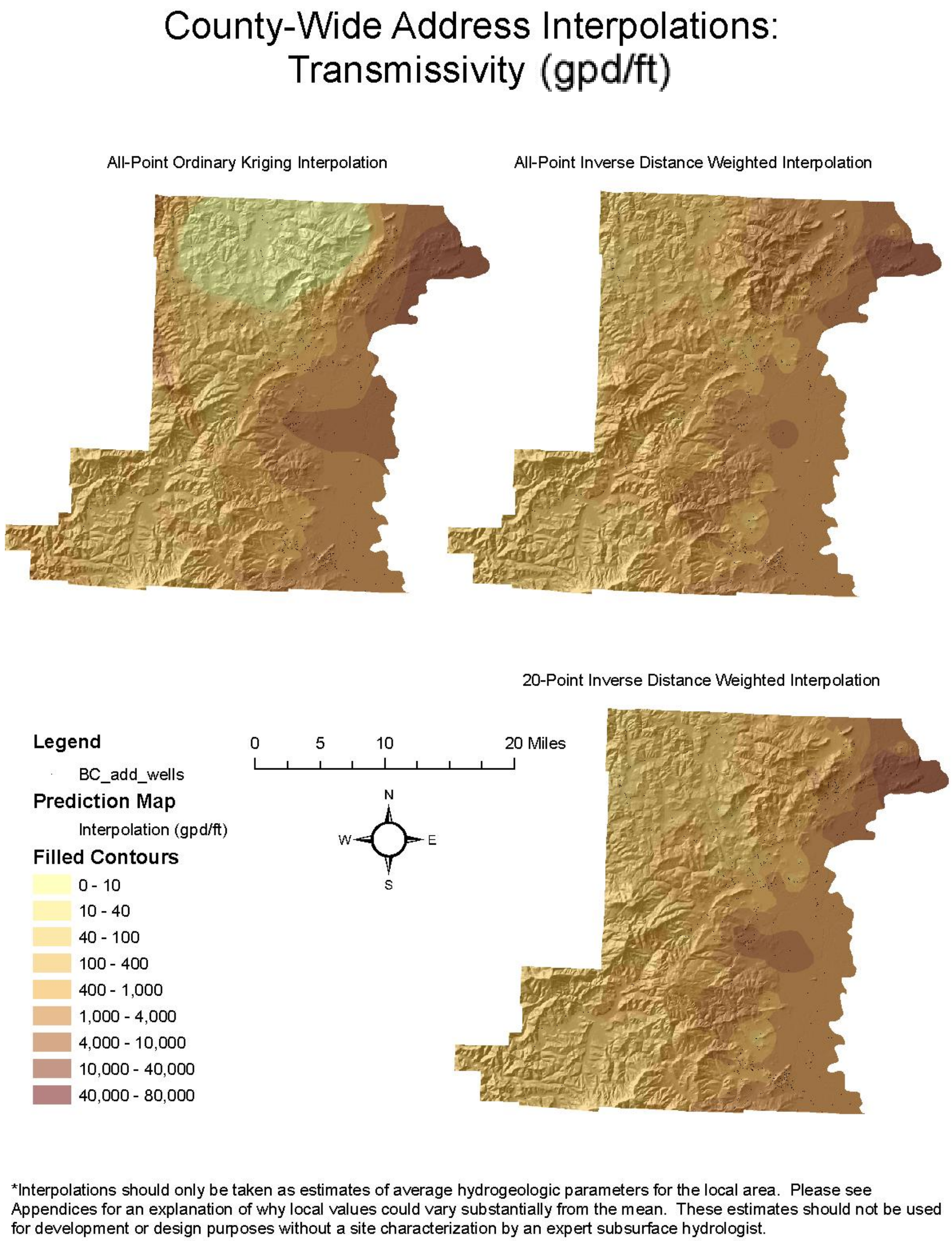


Figure 4.50 Transmissivity estimates (gpd/ft) across Benton County for Address-georeferenced wells

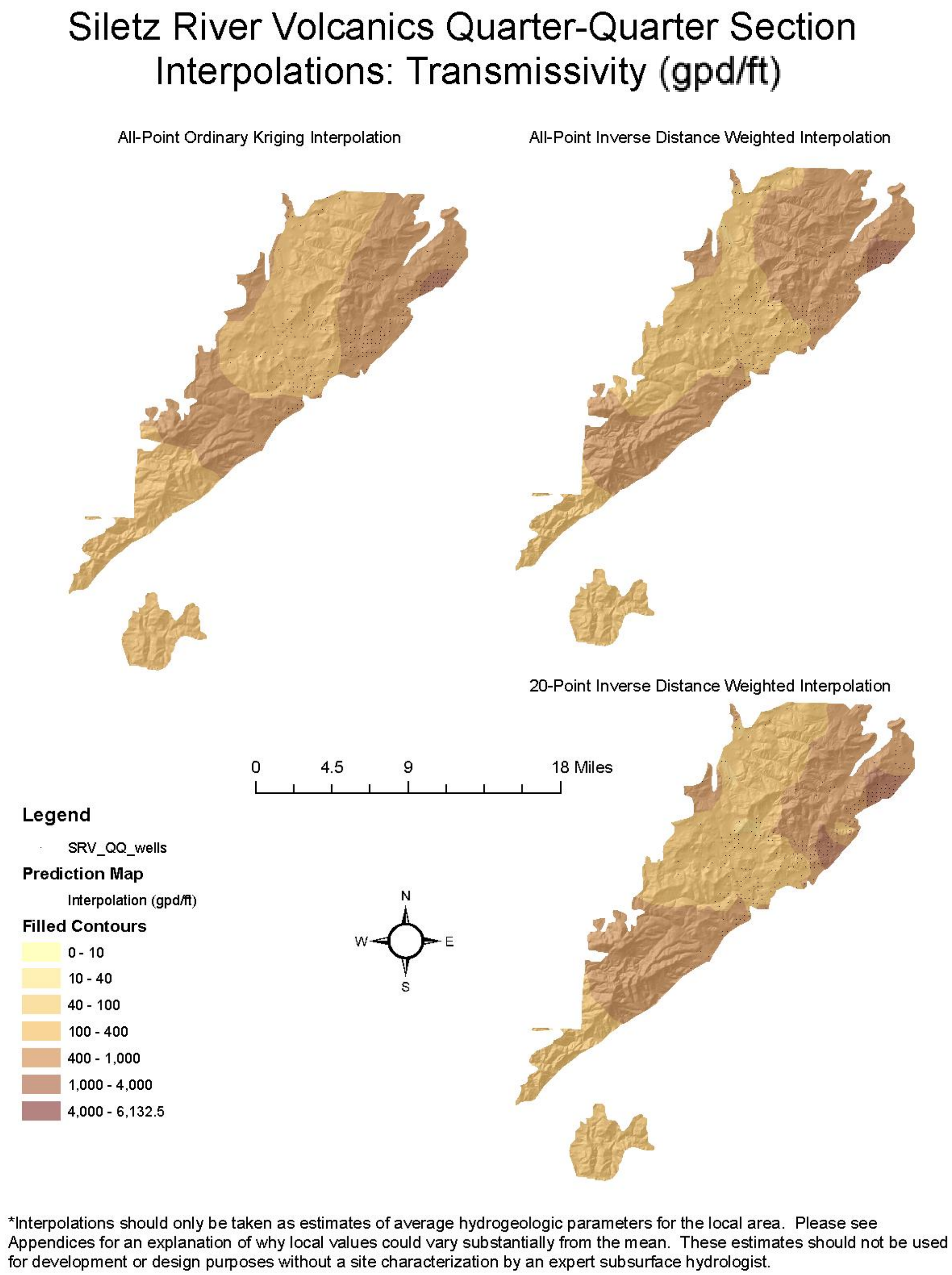


Figure 4.51 Transmissivity estimates (gpd/ft) in the SRV for Quarter-Quarter-georeferenced wells.

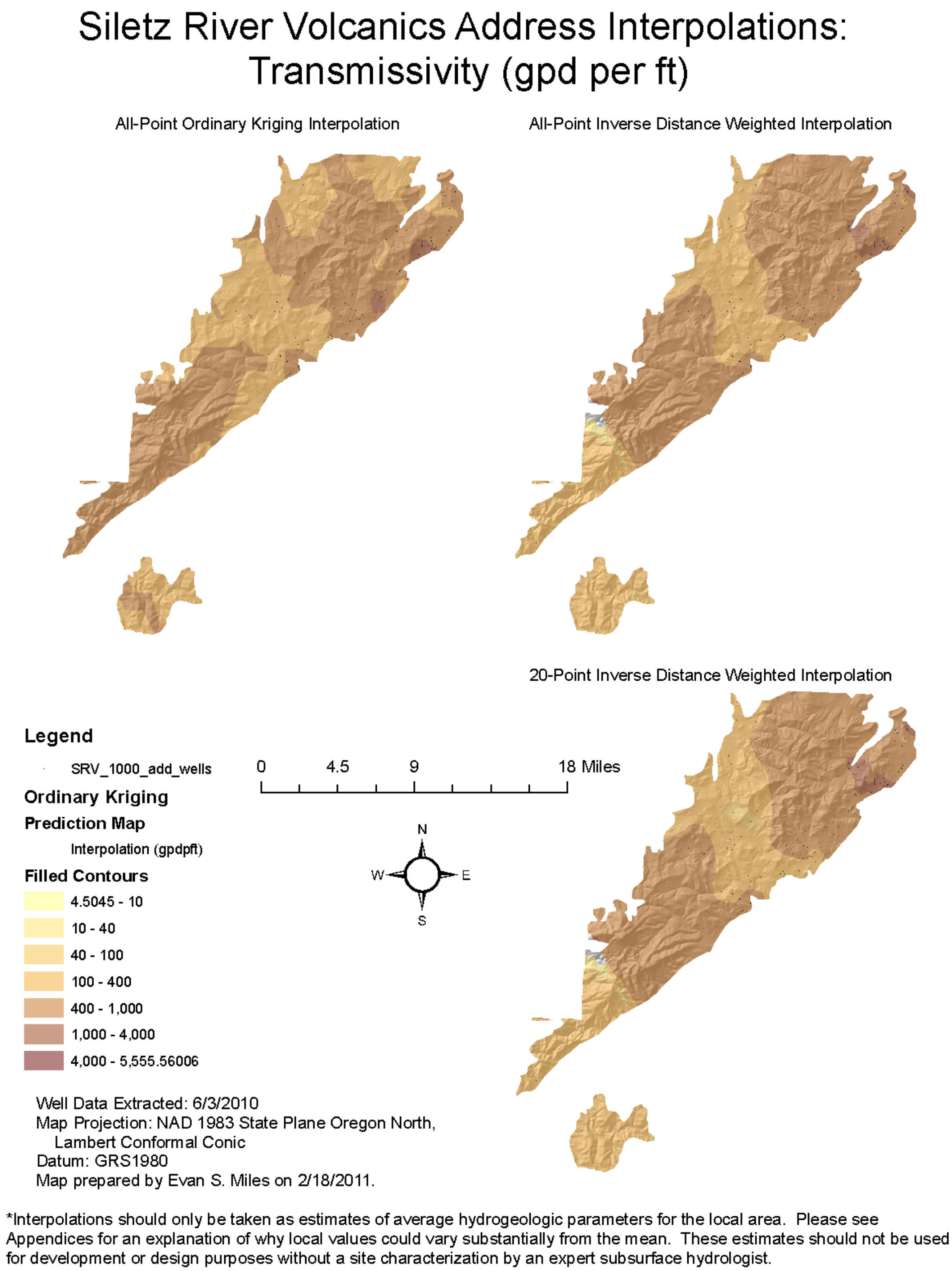


Figure 4.52 Transmissivity estimates (gpd/ft) within the SRV for Address-georeferenced wells.

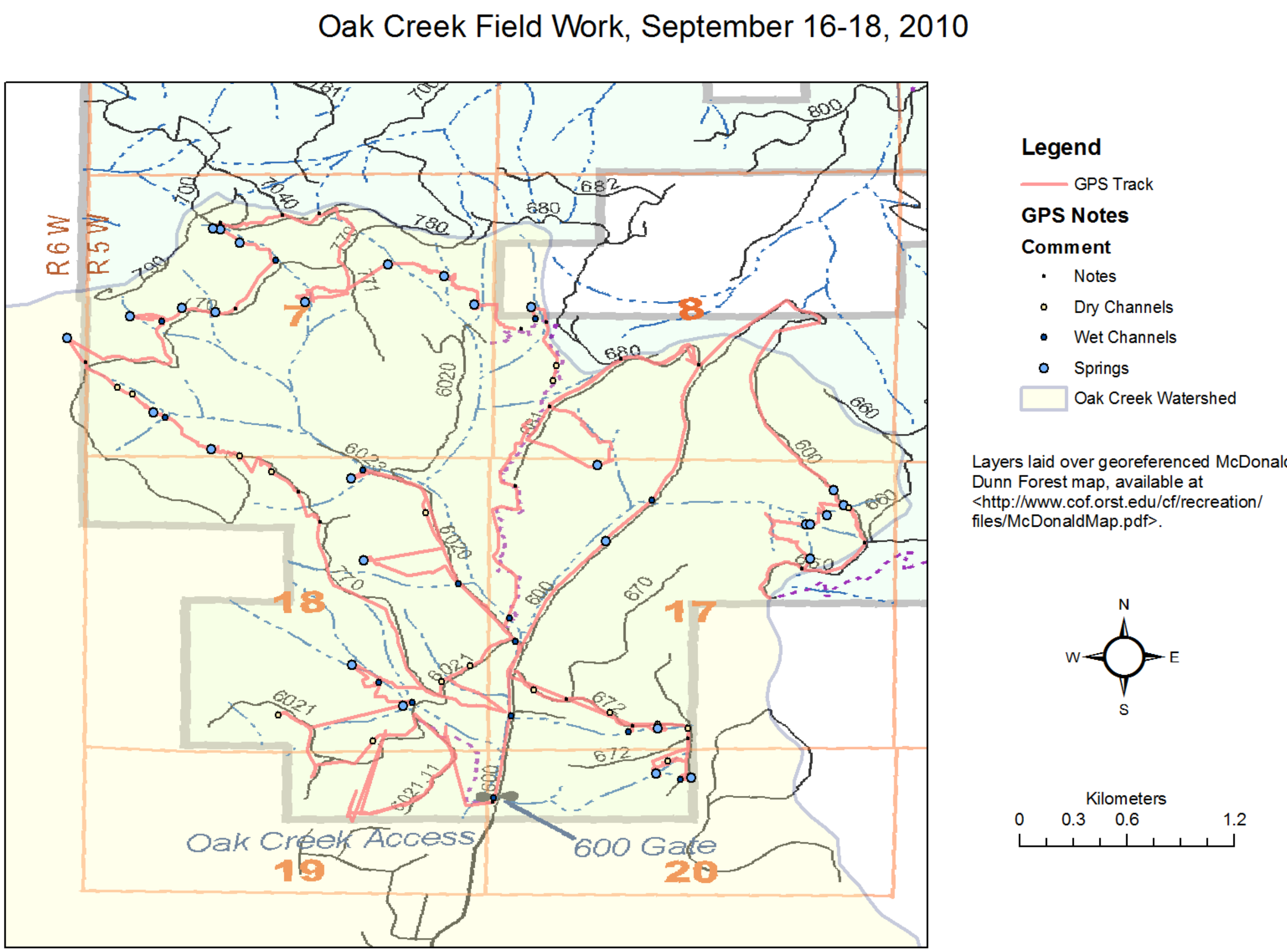


Figure 4.53 Spring locations, GPS Track and Notes from September 2010 field work.

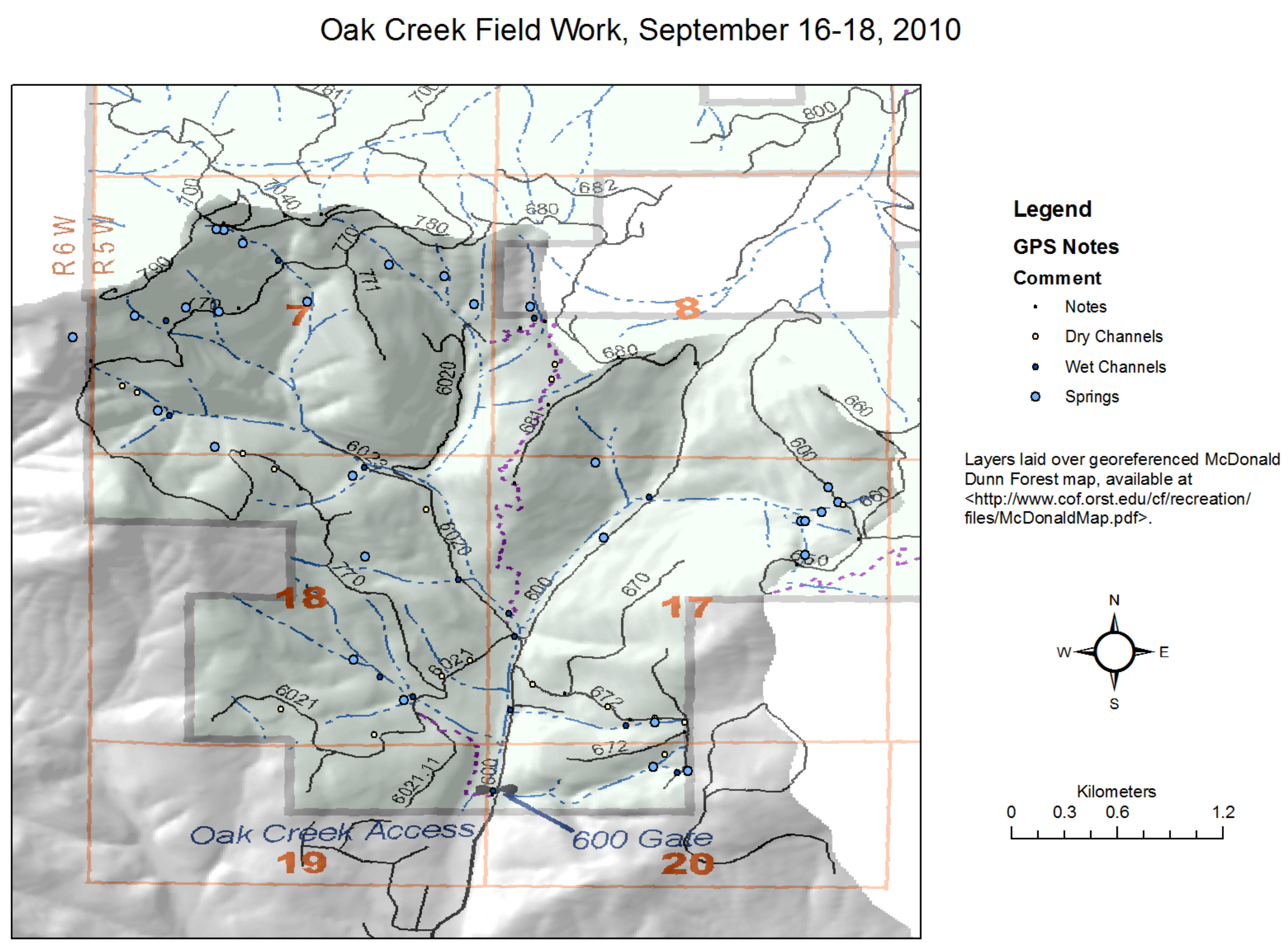


Figure 4.54 Spring locations and Notes from September 2010 field work over a 10m topographic hillshade.

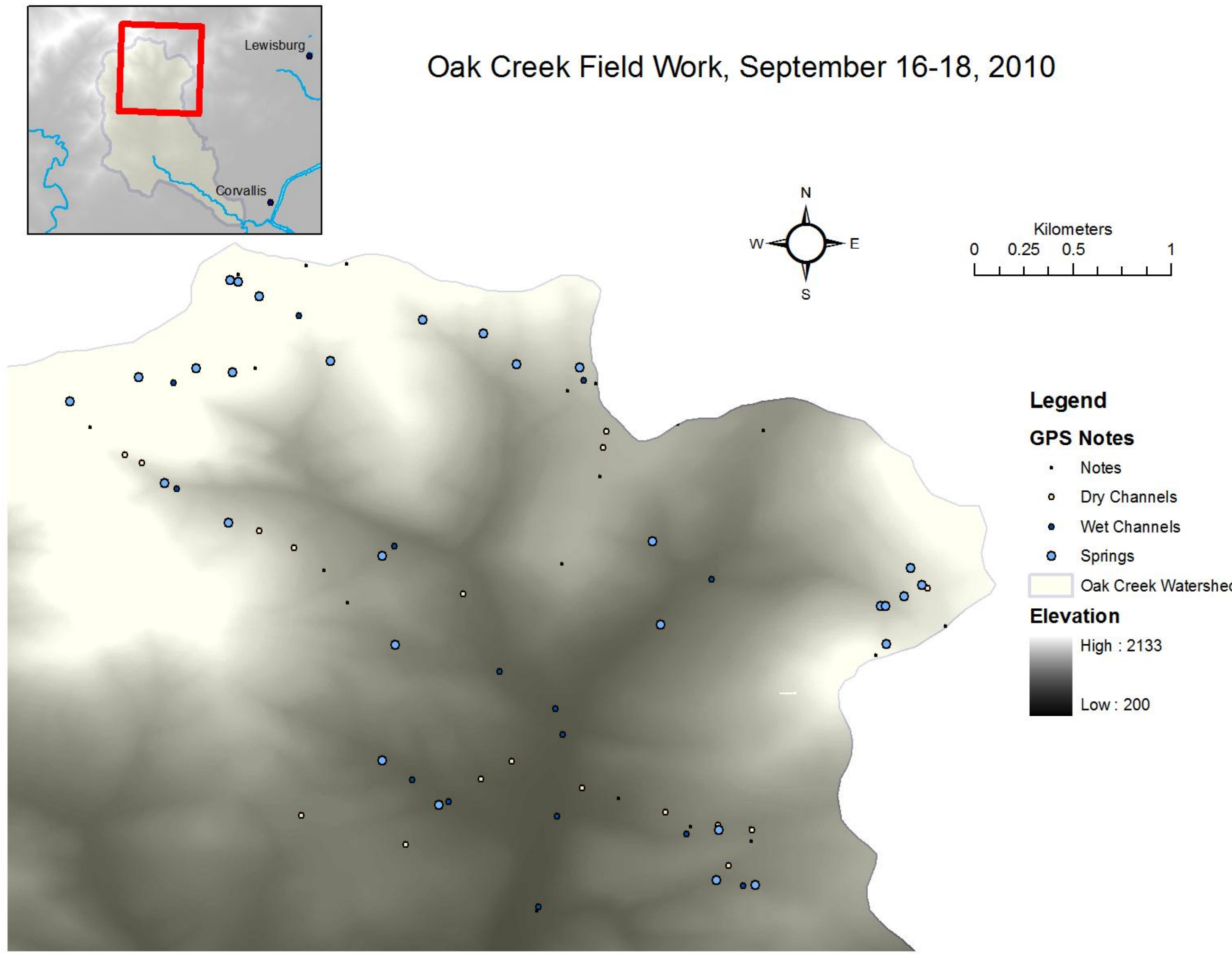


Figure 4.55 Spring locations and Notes from September 2010 field work and a 10m DEM.

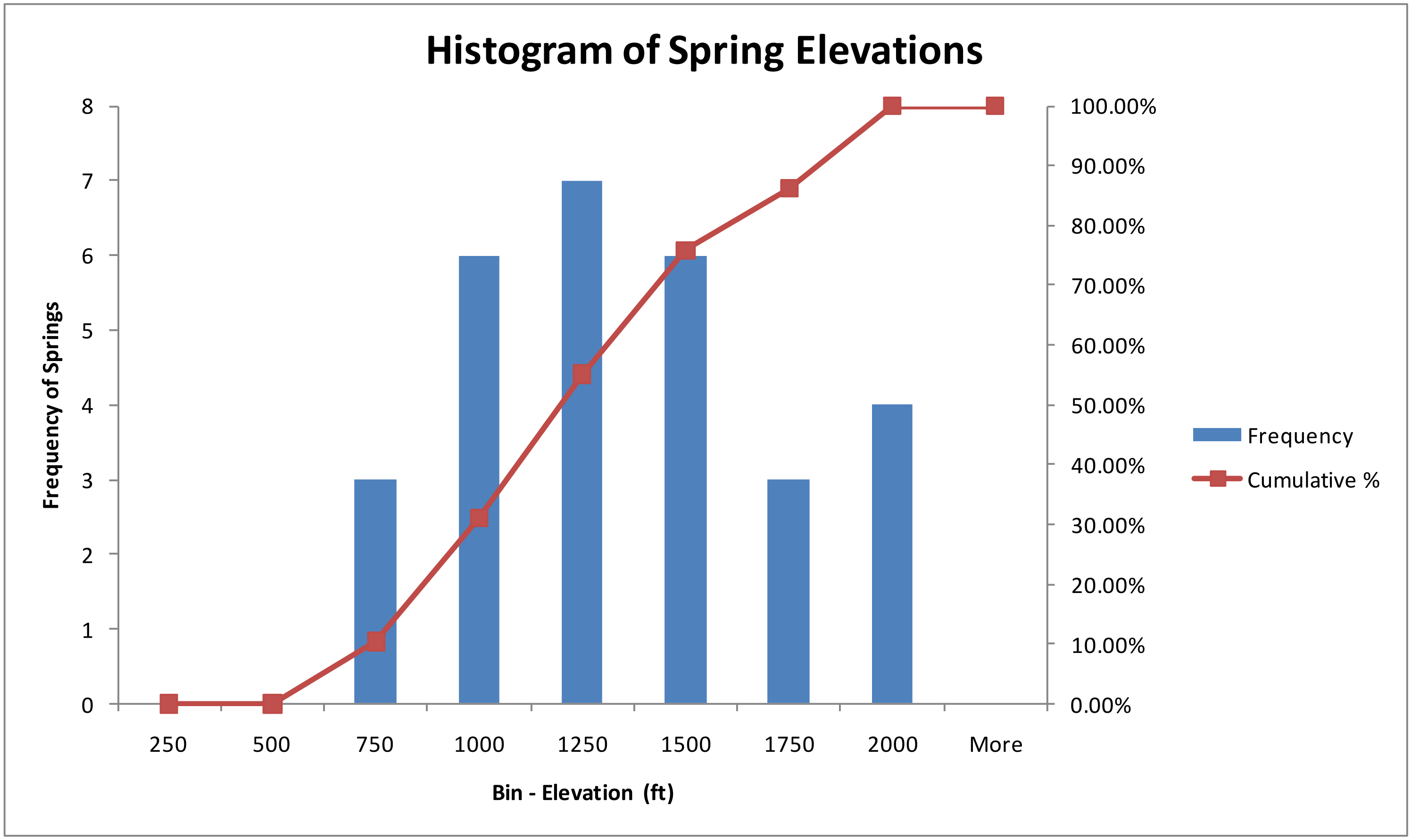


Figure 4.56 Distribution of sampled spring elevations in Oak Creek in late summer 2010.

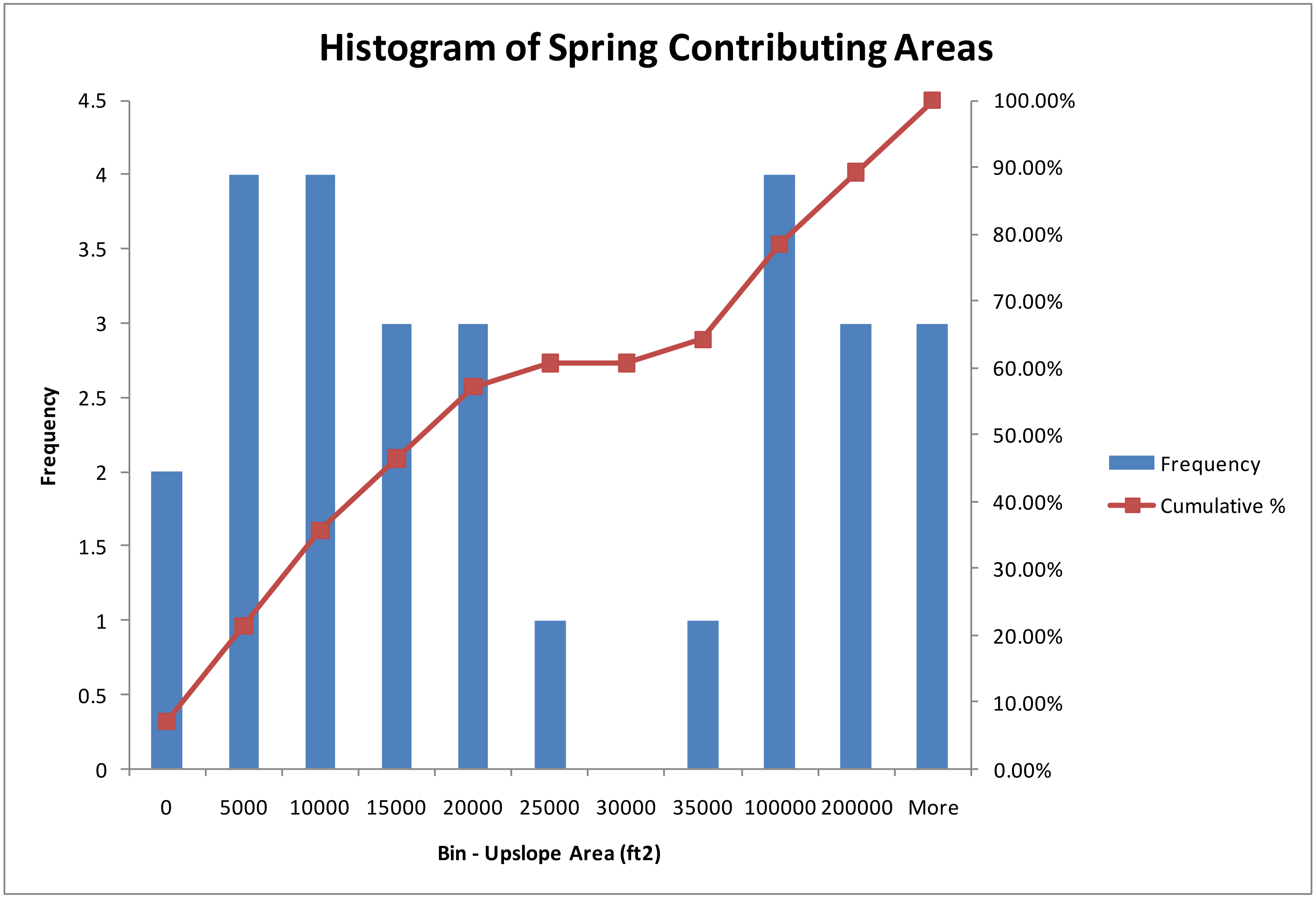


Figure 4.57 Distribution of spring contributing areas in Oak Creek in late summer 2010.

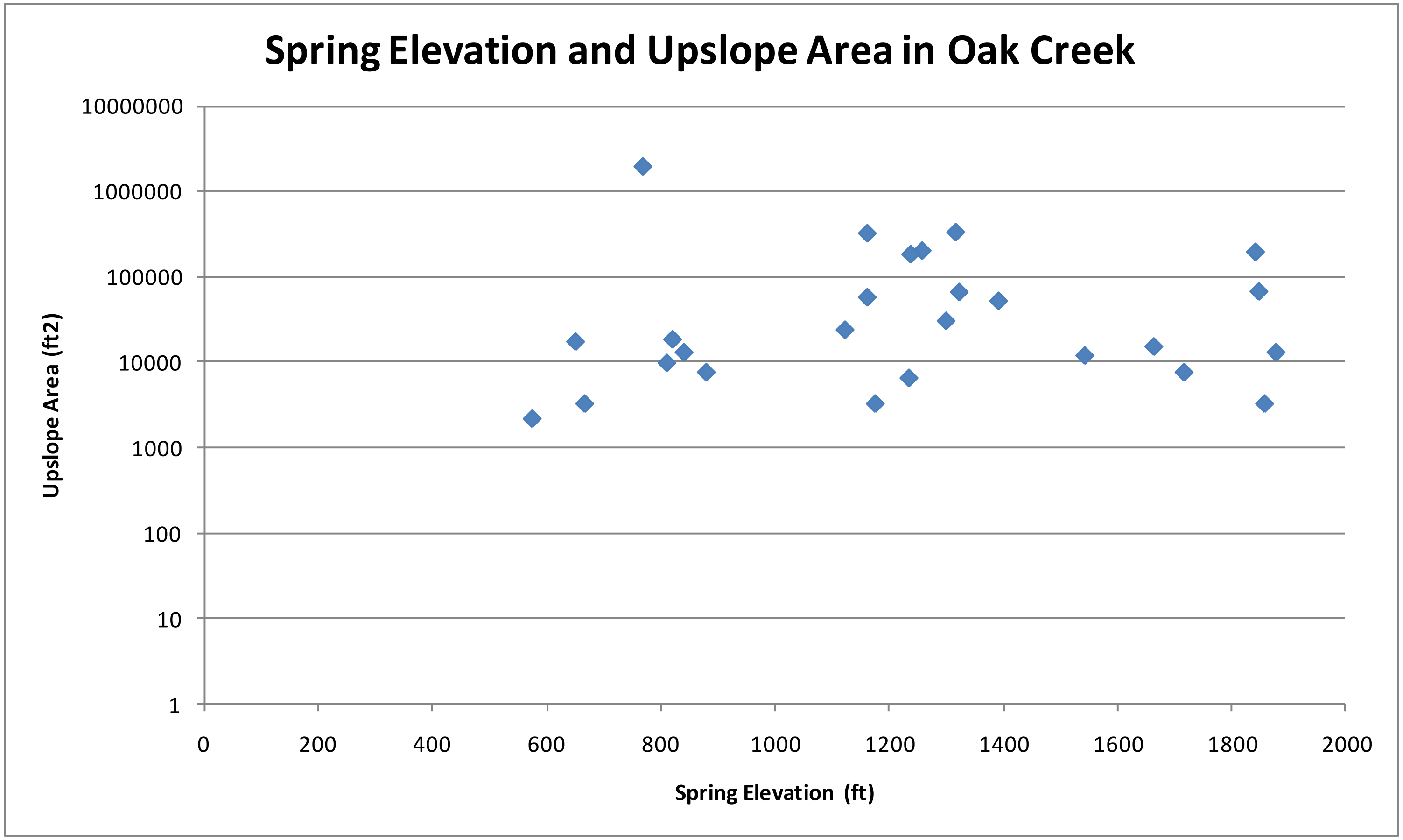


Figure 4.58 Relationship of spring contributing areas to elevation in Oak Creek in late summer 2010.

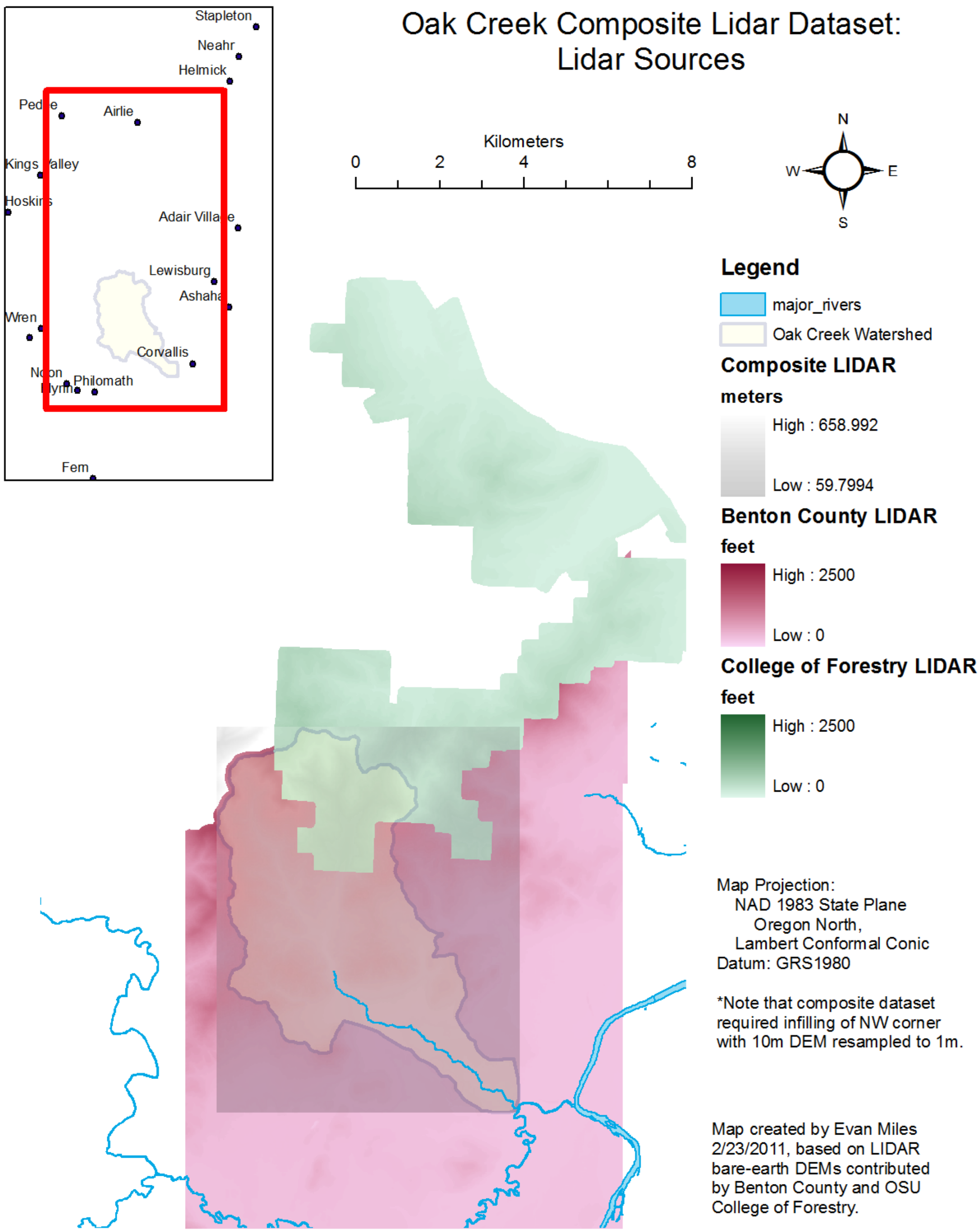


Figure 4.59 LIDAR data sources for creating an Oak Creek composite 1m DEM.

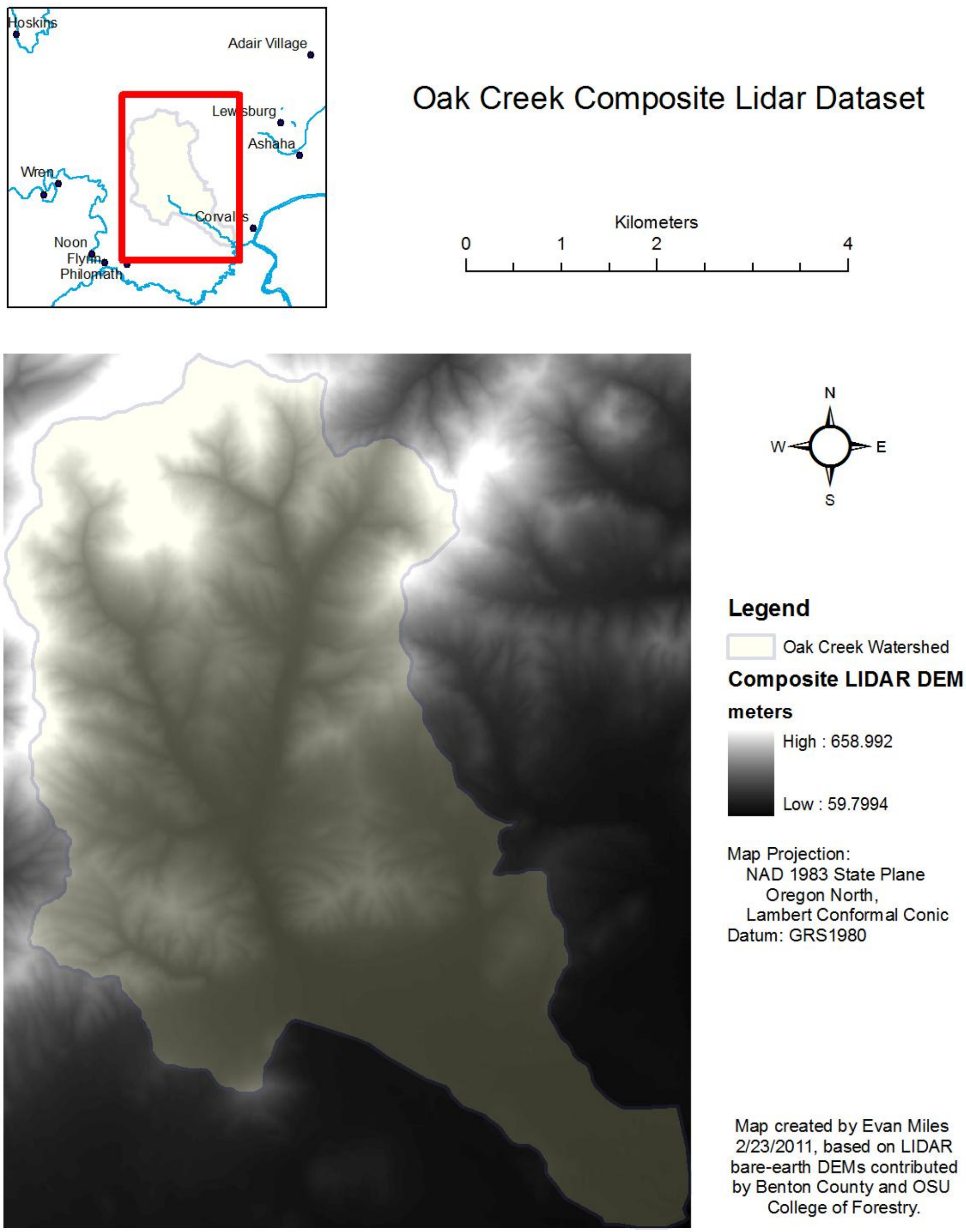


Figure 4.60 Composite LIDAR dataset encompassing Oak Creek.

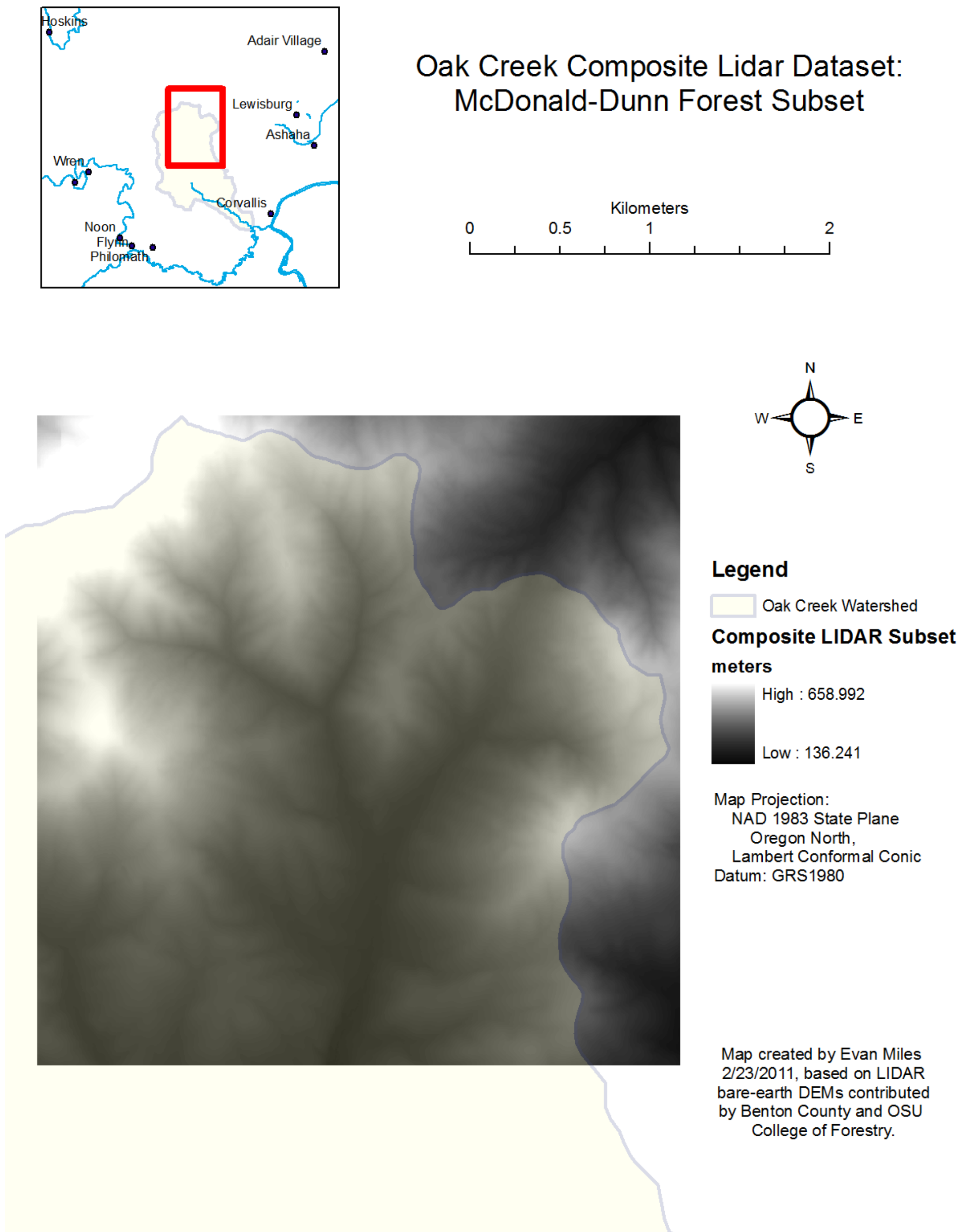


Figure 4.61 Composite LIDAR dataset, subset to portion of Oak Creek within McDonald-Dunn Forest.

5. DISCUSSION

5.1 Georeferencing of Wells

The three georeferencing methods (PLSS Sections, PLSS Quarter-Quarter Sections, and Addresses) have provided substantial new spatial information about the groundwater of Benton County. A tradeoff is apparent between data inclusion and accuracy for PLSS georeference methods, while the use of Addresses was only marginally successful overall. The georeferenced well-distributions representatively sampled the original dataset in most respects according to the cumulative distributions of several hydrogeologic parameters. In addition, the composition of wells in the Siletz River Volcanics appears to differ from the entirety of Benton County: a greater percentage of wells have positive reported yield in the SRV, and a larger portion are deepened or altered, while fewer wells located in the SRV are abandoned.

Maps showing the spatial distributions of wells are Figures 4.1 – 4.8, and the success of each method is shown in Table 4.9. Section 5.1.1 discusses the success of each georeferencing method, while Section 5.1.2 considers georeferencing limitations and alternate options to extend or improve the spatial distributions of well data.

5.1.1 Interpretations

Several dimensions of georeferencing success may be considered as indicators of the success of a georeference method. The percentage of records successfully geo-located is an important measure of completeness. In lieu of total completeness, a representative subset may be acceptable: to what degree the successfully located records represent the original dataset is important. Geographically, the spatial resolution and accuracy of placement locations is relevant for subsequent spatial analysis. Finally, the spatial coverage determines the usefulness of the results.

The composition of wells in the Siletz River Volcanics appears to be slightly different from that of Benton County as a whole, as is shown in Tables 4.9, 4.10, and 4.20. Address and Quarter-Quarter well datasets both indicate a higher percentage of "wet" wells in the Siletz River Volcanics according to Table 4.9. Relative to a baseline of 73.1% for all wells in Benton County, 84.3% of Address-georeferenced wells in the SRV and 78.0% of Quarter-Quarter-georeferenced wells have reported positive yields. In all of Benton County, 78.4% of Address-georeferenced wells and 69.9% of Quarter-Quarter-georeferenced wells have reported positive yields.

In addition, wells referenced within the Siletz River Volcanics are less often to be abandoned, but more often to be deepened or otherwise altered according to Tables 4.10 and 4.20. Of all well records in Benton County, 87.3% are for new wells, while 3.9% and 1.7% correspond to deepened and altered wells, respectively. For the extent of Benton County, both georeference methods report similar percentages of new wells and deepened wells, while reporting 2.5-3% altered wells. Within the SRV, however, these values are substantially different: 83% and 86% new wells, 7.2% and 5.1% deepened wells, and 5.5% and 4.0% otherwise altered wells for Address and Quarter-Quarter georeference methods, respectively.

According to Table 4.20, the rates of abandoned wells are also substantially different for the two extents. In all of Benton County, 15.8% of well records correspond to wells that have been abandoned. Address and Quarter-Quarter well distributions for the County report 10.3% and 19.0% of well records as abandoned wells, respectively. Limited to the extent of the Siletz River Volcanics buffered by 1000ft, these methods report 7.6% and 9.6% of wells as abandoned – a dramatic decrease.

In sum, the georeference methods may be rated qualitatively according to the dimensions specified at the beginning of this Section. Georeferencing by PLSS Section successfully located a very representative 97.6% of well records with great coverage, but at poor spatial discretization and accuracy. Georeferencing by Address located more than 1000 records (amounting to 9.8% of the original dataset), which was representative for some attributes, and at a good discretization, but had very poor coverage and questionable accuracy. The wells georeferenced by Quarter-Quarter Section may have provided the best balance of attributes for extended study: a representative 35% of the data was successfully georeferenced and the resultant dataset had good spatial coverage with moderate resolution and decent accuracy, making it the most useful of the datasets.

5.1.2 Limitations & Opportunities for Further Study

Still, substantial room for improvement geo-referencing wells exists in the accuracy-coverage tradeoff and the challenge of collocated wells (Section and Quarter-Quarter datasets). This section discusses the shortcomings of the georeferencing methods used and potential improvements, including spatial extent, accuracy, and well collocation. Finally, potential improvements and opportunities for future studies are discussed.

A first major limitation of this study is the inclusion of only two spatial extents: Benton County and the Siletz River Volcanics. While providing two very important lenses through which to examine the well data, this framework makes it difficult to compare the SRV to the rest of the County, which also includes the Tyee and Spencer formations, alluvial deposits, and igneous intrusions. This limitation is most apparent when considering, for example, the composition of wells georeferenced by each method, discussed in Section 5.1.1. Does the Siletz River Volcanics appear to have a higher portion of altered wells compared to the rest of the County in fact, or due to the subsets of wells that were successfully georeferenced by the two methods? Referring to Table 4.20, both Address and Quarter-Quarter georeference methods report high (relative to the original dataset) percentages of altered wells, in the extent of Benton County but especially within the SRV.

A better way to distinguish the SRV from its surroundings is to compare wells within the SRV directly to wells within other specific formations, such as the Tyee and Spencer Formations or the older and younger Willamette Valley alluvium, shown in Figure 2.5 [BCWP 2008]. The general characterization of hydrogeologic parameters within Benton County then becomes a synthesis rather than a comparator.

The second major drawback with this study is that no georeference method was able to produce consistently high accuracy. Placing wells at their PLSS Section centroid gives an accuracy of 3733 ft, which is generally unacceptable for hydrogeologic studies or reports, and certainly insufficient for water permitting or planning. Placing wells by the Quarter-Quarter Section centroid yields an improvement to 933 ft of lateral accuracy, which is still very imprecise for modern studies. In addition, the data that could be located to this level of detail was severely reduced from its original quantity. However, a spatial distribution to these levels is a substantial improvement on past work, which located wells to PLSS Townships of 36 square miles (Frank 1972).

Furthermore, the placement of wells by Section and Quarter-Quarter centroids results in collocated wells. In this situation, two values of a hydrogeologic parameter must be considered jointly (averaged), as their spatial features are directly superimposed. This further reduces the effective quantity of data available for further analysis – geostatistics for example – as only the mean value is available for analysis. Thus, both of these methods (Section and Quarter-Quarter georeferencing) result in data compression even when they have substantial success in placing wells. Data compression in the Benton County dataset of Quarter-Quarter georeferenced wells was 47.8%: only 1479 unique locations were found in 2830 records.

While georeferencing by address presumes to avoid this problem (assuming only 1 well per address), this method has substantial problems of its own. Addresses are hard to match to a record. First, while Sections and Quarter-Quarter Sections have standardized, consistent designations, addresses take different forms based on the type of property, whether the location is municipal, and depending on the type of street the property borders. Second, while PLSS designations are unchanging, addresses are transient in both time and space: streets change names and rural properties become subdivided. Finally, any spelling mistake or deviation in formatting can cause automated address geo-location protocols to make mistakes. These factors caused substantial trouble in locating wells by address, as is evidenced by the 9.6% success rate of well placement.

In addition, though, Address-geolocating poses a unique challenge in assessing the accuracy of the well location. The specified address corresponds to a property (rather than the well) and in the case of the Benton County Address shapefile, to the centroid of a particular taxlot associated with that address. This brings into consideration the size of the property when the well was built (which defines the accuracy of the location), a piece of data not available. Worse, if the property was later subdivided, there is no way to determine the parcel now containing the well without visiting the location. In essence, georeferencing by Address is challenging and provides questionable success.

There are several alternate options available to improve well georeferencing for accuracy, postprocessing, or completeness. Two very accurate but extremely time-consuming methods are available that could locate every well to within several meters. First, water-rights examiners are commonly required to prepare legal maps with wells located using a combination of tax lot surveys, aerial photography, and well location descriptions (metes and bounds to a nearby survey point). This process cannot currently be automated, but can be very precise and consistently performed.

A second simple method would be to visit each well with a GPS unit to log the well's geographic coordinates. While accurate and simple, this method requires substantial communication and labor to be applied consistently, and necessitates landowner permission. Benton County has been slowly accumulating the GPS coordinates of wells that its employees visit, but has only accumulated a few hundred such wells, mostly problematic, in the entire County. Locating wells in this manner has a very high accuracy and excellent spatial resolution, and could easily be carried out in conjunction with other programs, further enriching County data. For example, volunteer well monitoring (Lin et al 2009) can provide transient data for the County's water resources, while simultaneously locating wells with GPS coordinates. Similarly, a well rating program could be implemented, enriching the data available by locating wells and providing up-to-date information on the condition of the water resource, including ground-truthing of spatially-inferred data.

Two methods could be considered to leverage existing well distributions, as well. First, three reliable levels of well location are currently available: the Section level (accuracy 3733 ft, 97.6% of wells), the Quarter-Quarter Section level (accuracy 933 ft, 35.1% of wells), and the GPS level (accuracy to 10 feet, few hundred wells). It could be possible to apply geostatistics to a combination of these three datasets, weighting the influence each dataset has on the resultant surface. Second, large portions of the wells have been located within the large area extents of Quarter-Quarters and Sections, and these datasets suffer from data compression due to collocated wells. Alternatively, it could be possible to distribute the collocated wells randomly throughout their Section/Quarter-Quarter, thus negating data compression and preserving location accuracy. This method would be less useful for inverse-distance-weighted or other exact interpolations, but would be very useful for geostatistical methods such as kriging.

5.2 Hydrogeologic Parameter Interpolations

The interpolated surfaces created by this study are discussed below and organized by parameter. Section 5.2.1 discusses the implications of the surfaces created for each parameter. Section 5.2.2 discusses the shortcomings of the interpolation methods applied and opportunities for further study to improve the analysis.

5.2.1 Interpretations

Interpolations of well yield and depths to water were quite successful for providing spatial interpretations of the subsurface. Interpolations of specific yield and transmissivity were moderately successful, but less robust due to their small sample size and poor spatial coverage. In general, well yields and specific capacities are highest near the Willamette River, declining to the West. A proportional relationship between land surface elevation and depth to water appears.

More importantly, this study's synthesis of hydrogeologic parameters from well logs was able to spatially characterize (if only to a limited extent) the variability of the groundwater in Benton County. While there are several limitations to the interpolations performed, these data are powerful and dangerous in the hands of planners and developers. It is essential that follow up site investigations be performed to support or refute the spatial distributions of parameters resulting from this study. Nonetheless, the results from this study can be easily applied to further inform the 4 Priority Groundwater Monitoring Areas definitively identified by Lin et al 2009 (Figure 2.16):

The Thousand Oaks area is reported to exhibit many well deepenings and complex geology. Located just Northeast of Lewisburg, this area has a high density of wells (Figures 2.7 and 4.2). Figure 4.6 does not show an extraordinary number of altered, abandoned, or deepened wells that have been reported to OWRD in this area, but Figure 4.8 shows that this area has one of the higher concentrations of dry wells in the SRV. The interpolated surfaces estimate 20-50 gpm as an average well yield in the area (Figures 4.14 and 4.15), but Thousand Oaks is near a zone expected to have large values of depth to first water and post-drilling static water depth. Specific capacity and transmissivity are estimated higher than much of the Siletz River Volcanics, but are low relative to zones immediately to the East.

Brandis is located to the SW of Lewisburg, and has relatively few wells compared to its surroundings, including problematic wells. Moderate yields of 20-50 gpm are estimated by the Ordinary Kriging surfaces, but the IDW surfaces note a local low estimate of yield. Similarly, IDW interpolations expect a locally deeper water table, relative to the ground surface. The interpolations also report that this area's wells frequently have a deep post-drilling static water surface. Again, specific capacity and transmissivity appear normal compared to adjacent areas.

Wren Hill is situated in the middle of Benton County's SRV formation. Again, Figure 4.6 does not show an extraordinary number of altered, abandoned, deepened, or dry wells that have been reported to OWRD in this area. Moderate yield values of 10 – 50 gpm are estimated for the area, although about 1 mile East is the most productive well that could be georeferenced in the SRV. Figures 4.23-4.26 all expect initial depths to water in the several hundred feet, with somewhat shallower static water levels. Specific capacity for this area is predicted to be between 0.02 and 0.05 gpm/ft, indicating that wells in the area experience substantial drawdown.

Alpine is a community situated on the TSS in southern Benton County, and boasts a dense set of wells just West of Monroe (Figure 4.5). The area around Alpine does show several deepened wells (Figure 4.6), but wells generally appear to produce decent amounts of groundwater (Figures 4.14 and 4.15). The initial depth to water for the area is not extraordinary, but oddly enough the interpolated post-drilling static water depths are substantial (Figures 4.29 and 4.30). The substantial drop in water levels could be associated with perched lenses of water-bearing siltstone underlain by a less conductive matrix. As these water levels are dropping into the hundreds of feet of depth, it may be prudent to monitor qroundwater quality. It is possible that this area has not been drained substantially since its marine consolidation.

5.2.2 Limitations & Opportunities for Further Study

While the georeferenced datasets allowed an improved and spatial characterization of several hydrogeologic parameters thoughout Benton County and particularly within the Siletz River Volcanics, the results should not be accepted without considering a few limitations. A foremost limitation was the quality of data captured on the well logs that form the basis of this study. Second, there is a fundamental question of whether interpolations are appropriate to investigate a hydrogeologic formation dominated by fracture flow. A third major limitation to the study was the ability of the specific interpolation methods applied to adequately characterize the spatial variability of desired parameters. Certainly improved procedures could be developed and followed to more accurately capture the spatial variability of parameters.

This study examines the numerical and spatial distributions of several hydrogeologic, with the hope of informing future scientists, planners, and developers of the local formation. However, the quality of interpolated surfaces and numerical analyses performed in this study are dependent on the quality of the original well logs. Errors and missing data on the well logs submitted to OWRD limited the ability of this study to accurately georeference wells and reduced the benefit of considering specific capacity due to the small number of data points. Varying well log quality can affect the validity of subsequent hydrogeologic analyses. In addition, this study acknowledges that occasional errors may have been made when these paper forms were digitized into the Well Log Query tool. Lastly, it was noted that additional data sometimes captured on well logs (drawdown, rock descriptions, water-bearing intervals) could have been useful for further study.

This analysis applied interpolation methods to understand the spatial variability of hydrogeologic parameters under the assumption that such parameters would vary continuously at some scale. For the interpolations to possibly be accurate, the resolution of the interpolated dataset generally needs to approach to scale at which a surface appears continuous. For the Willamette Valley, some of the parameters studied seem to vary little spatially, and water level interpolations have been performed with a great degree of success (Delhomme 1978, Desbarats 2001). In the heterogeneous Coast Range, the scale at which these parameters are continuous may be much smaller. In the Siletz River Volcanics, in particular, previous studies have suggested fracture flow mechanisms [EGR 1994, Braun 1995, EGR 1998], for which well yields and transmissivities may vary at scale of several feet [Berkowitz 2002]. Although this study was able to locate a large number of wells to a new level of accuracy for Benton County, the 933ft accuracy does not approach the resolution required to consider the interpolated surfaces as reliable estimates. Furthermore, Chapter 2 of this thesis showed examples of annual water level fluctuations. These water fluctuations can further confound the interpolated surface, depending on the season in which the wells were drilled; the result would be simulated local variability in the water level due to spatial water level sampling at distinct hydrologic conditions. In sum, although these surfaces may not be sufficiently accurate for site-specific planning, they are useful for visualizing the spatial variability of the different parameters investigated, and may be useful for county-wide planning.

The interpolation methods applied were found to be moderately rigid routines for characterizing the subsurface of Benton County. Cross-validation of the Ordinary Kriging surfaces, for example, resulted in poor fits for many parameters. This supports the hypothesis that the Siletz River Volcanics exhibit substantial variability, even at local scales. Again, it is important that the prediction surfaces be used primarily for visualization, regional characterization, and trend identification, rather than planning, design, or site characterization of the subsurface. It is strongly emphasized that for site characterizations or for planning or design of developments, the services of an expert hydrogeologist should be consulted.

To work past the shortcomings of these results, contemporary and traditional methods could be simultaneously applied. First, the opportunities discussed in Section 5.1.2 would greatly enrich the reliability and accuracy of the interpolated surfaces. Second, standard hydrogeologic characterizations including well and tracer tests could be applied at select locations to greatly enrich knowledge of the subsurface, especially within the Siletz River Volcanics. A multi-well study of hydraulic conductivity, carried out in a few locations, could better establish the variability or hydrogeologic parameters within the Siletz River Volcanics. Such studies could be located to provide data for locations with exceptional values (estimated from this study), simultaneously serving the purpose of sampling a range of values while supporting or refuting the estimates of this study.

In addition, improvement could be made to the interpolation method, which involved applying the same interpolation criteria to each of the variables and datasets. Instead, a more accurate, but more time-and computationally intense, method would be to find a best-fit surface by varying interpolation parameters, then to utilize the optimal set of parameters as a characterization of the parameter's variability. This method would be exponentially more demanding of computational resources, and would require substantial planning.

This thesis was meant to update some of the information reported by Frank (1972) and to extend his hydrogeologic characterizations spatially. However, there are numerous additional studies that could be performed to update additional sections of the Water-Supply Paper. In particular, this study did not examine groundwater-surface water interactions, groundwater storage volumes within the County, or groundwater use. Additionally, this paper gave only the briefest consideration to water quality, which could form the basis of several important local studies in consideration of expected groundwater development. Finally, the Benton County Water Project has clearly laid out its priorities for County-wide groundwater synthesis (BCWP 2008), creating excellent opportunities to perform studies that directly inform policy.

6. CONCLUSIONS

This thesis sought to spatially characterize the Siletz River Volcanics formation by georeferencing well log-derived hydrogeologic parameters and performing interpolations across Benton County. To accomplish this goal, a PLSS Quarter-Quarter grid was created and applied as a georeference dataset to provide a balance of criteria. This resulted in a sufficiently complete and representative subset of the original data, with good spatial coverage, moderate resolution, and decent accuracy.

While improvements in resolution and accuracy could be desirable, this method provided a spatially-derived characterization of the SRV. This study found that (relative to the entirety of Benton County): the SRV has a lower well density, a higher percent of wells in the SRV have positive yields (84.3%), SRV wells have lower average well yields (18.9-21.8 gpm), appear to have a higher frequency of confined groundwater, and have much lower mean specific capacity (0.0252 – 0.324 gpm/ft). Furthermore, the study produced SRV values of well yield and transmissivity comparable to literature, while expected specific capacity values were an order of magnitude lower than previously published values.

More importantly, this study has taken a first step towards accomplishing some of the data needs established by Benton County. Referring to Section 2.2.3, base data for items A, D, H, and I have formed been enriched by this study. Additionally, fundamental LIDAR and spring location datasets were prepared for upper Oak Creek Watershed in association with this study, opening the door for topography-groundwater studies.

Finally, the interpolations of spatially-distributed hydrogeologic parameters have provided interpretable results to understand the documented variability of the County, including the Siletz River Volcanics. Acknowledging the constraining limitations of source data, ability to georeference, and interpolation accuracy, the surfaces produced by this study provide basic and preliminary information about any location of inquiry. Application of the data produced by these methods to Priority Groundwater Monitoring Areas in Benton County (Section 2.2.3) can substantiate complaints and provide impetus for full hydrogeologic site investigations as Benton County seeks to further understand its groundwater resources and hydrogeologic setting.

BIBLIOGRAPHY

Benton County Water Project. 2008. Phase 1: Benton County Water Analysis and Demand Forecast.

Berkowitz, B. 2002. Characterizing flow and transport in fractured geological media: A review. Advances in Water Resources, 25(8-12):861-884.

Bolstad, P., Jenks, A., Berkin, J., Horne, K., and Reading, W. 2005. A comparison of autonomous, WAAS, real-time, and post-processed global positioning systems (GPS) accuracies in northern forests. Northern Journal of Applied Forestry, 22(1):5–11.

Braun Intertec Northwest. 1995. A Hydrogeologic Evaluation Draft Report for Peterson and Associates, Madrone Estates Subdivision, Benton County, Oregon.

Cascade Earth Sciences, Ltd. 2001. Pinot Gris Hydrogeological Study, Corvallis, Oregon.

CH2M Hill. 1993. Aquifer Storage and Recovery feasibility study. Echo Junction, OR.

College of Forestry (COF), Oregon State University. "McDonald-Dunn Forest Map". Accessed 3/5/2011. <http://www.cof.orst.edu/cf/recreation/files/McDonaldMap.pdf>.

Conlon, K.J., Wozniak, K.C., Woodcock, D., Herrera, N.B., Fisher, B.J., Morgan, D.S., Lee, K.K., and Hinkle, S.R. 2005. Groundwater hydrology of the Willamette Basin, Oregon. U.S. Geological Survey Scientific Investigations Report 2005-5168. 95 p.

Craner, J.D. 2006. Hydrogeologic Field Investigation and Groundwater Flow Model of the Southern Willamette Valley, Oregon. MS Thesis, Department of Geosciences, Oregon State University.

Delhomme, J. P. 1978. Kriging in the hydrosciences. Advances in Water Resources, 1(5):251-266. DOI: 10.1016/0309-1708(78)90039-8.

Desbarats, A. J., Logan, C. E., Hinton, M. J., and Sharpe, D. R. 2002. On the kriging of water table elevations using collateral information from a digital elevation model, Journal of Hydrology, 255(1-4):25-38. DOI: 10.1016/S0022-1694(01)00504-2.

Driscoll, F.G. 1986. Groundwater and Wells. Johnson Division. 2nd Edition. St Paul, Minnesota. 1089 p.

Duncan, R. A. 1982. A Captured Island Chain in the Coast Range of Oregon and Washington. J. Geophys. Res., 87(B13):10,827–10,837. DOI:10.1029/JB087iB13p10827.

EGR & Associates, Inc. 1994. Use and Susceptibility Waiver Application for the Cascade View Water System, PWS # 4101456, Lewisburg, Benton County, Oregon.

EGR & Associates, Inc. 1998. Hydrogeologic Evaluation of the Groundwater Resource at Highland Dell Estates Subdivision, Corvallis, Oregon.

Frank, F.J., and Johnson, N.A. 1972. Ground-water Data in the Corvallis-Albany Area, Central Willamette Valley, Oregon. Oregon Water Resources Department, Ground Water Report No. 17.

Frank, F.J. 1973. Ground Water in the Eugene-Springfield Area, Southern Willamette Valley, Oregon. USGS Water-Supply Paper 2018.

Frank, F.J. 1974. Ground Water in the Corvallis-Albany Area, Central Willamette Valley, Oregon. USGS Water-Supply Paper 2032.

Frank, F.J. 1976. Ground Water in the Harrisburg-Halsey Area, Southern Willamette Valley, Oregon. USGS Water-Supply Paper 2040.

Gannett, M.W. and Caldwell, R.R. 1998. Geologic framework of the Willamette lowland aquifer system, Oregon and Washington. USGS Professional Paper 1424-A.

Glenn, J.L. 1962. Gravel deposits in the Willamette Valley between Salem and Oregon City, Oregon. The Ore Bin, 24(3):33-47.

Golder Associates Inc. 2005. Aquifer Storage and Recovery Hydrogeologic Feasability Study, City of Dallas, Oregon, Water Treatment Plant.

Golder Associates Inc. 2008. Results from the Second Year of ASR Pilot Testing at the City of Dallas, Oregon.

Goldfinger, C. 1990. Evolution of the Corvallis fault and implications for the Oregon coast range. MS Thesis, Department of Geosciences, Oregon State University, 129 p.

Hinkle, S.R. and Polette, D.J. 1999. Arsenic in ground water of the Willamette Basin, Oregon. USGS Water-Resources Invesitgations Report 98-4025.

Institute for Water and Watersheds (IWW), Oregon State University. “Oak Creek.” Accessed 3/5/2011, Updated 11/2008. <http://water.oregonstate.edu/oakcreek/index.htm>.

Johnston, K., Ver Hoef, J.M., Krivoruchko, K. and Lucas, N. 2001. ArcGIS9: Using ArcGIS Geostatistical Analyst. ESRI White Papers.

Krivoruchko, K. Introduction to Modeling Spatial Processes using Geostatistical Analyst. Accessed 3/5/2011. ESRI White Papers, <http://www.esri.com/library/whitepapers/pdfs/intro-modeling.pdf>.

Kumar, V. and Remadevi. 2006. Kriging of Groundwater Levels – A Case Study. Journal of Spatial Hydrology, 6(1).

Laton, W.R. 2009. Boring Logs – What's Important and What's Not: A Scientific Viewpoint. NGWA National McEllhiney Lecture 2009, Sponsored by NGWAREF.

Lin, E., Stebbins, A., Jarvis, T., and Brown, A. 2009. A Groundwater Monitoring Program in Benton County? Research, Analyses and Focus Group Findings.

Marklund, L. 2009. Topographic Control of Groundwater Flow. KTH. TRITA-LWR PhD Thesis 1052.

McFarland, W.D. 1983. Description of aquifer units in western Oregon. USGS Open-File Report 82-165.

Morgan, D.S. and Weatherby, D.G. 1992. Bibliography of Hydrogeology for the Willamette Valley, Oregon. US Geological Survey, Open-File Report 91-473. 143p.

Mutti, J.G. 2006. Temporal and Spatial Variability of Groundwater Nitrate in the Southern Willamette Valley of Oregon. MS Thesis, Department of Geosciences, Oregon State University.

Neretnieks, I. 1983. A note on fracture flow dispersion mechanisms in the ground, Water Resour. Res., 19(2), 364–370, DOI:10.1029/WR019i002p00364.

O'Connor, J.E., Sarna-Wojcick, A., Woznikak, K.C., Polette, D.J., and Fleck, R.J. 2001. Origin, Extent, and Thickness of Quaternary Geologic Units in the Willamette Valley, Oregon. U.S. Geological Survey Professional Paper 1620, 51 p.

Oderwald, R. and Boucher, B. 2003. GPS after selective availability: How accurate is accurate enough? Journal of Forestry, 101(4):24–27.

Oregon Blue Book. 2011. "Benton County." Accessed 3/5/2011. <http://bluebook.state.or.us/local/counties/counties02.htm>.

Oregon Communities Reporter. 2010. "Benton County." Accessed 3/5/2011. <http://oe.oregonexplorer.info/rural/CommunitiesReporter/>.

Oregon Department of Geology and Mineral Industries (DOGAMI). 2006. Oregon Geologic Data Compilation (OGDC) v. 3. <http://www.oregongeology.org/sub/ogdc/metadata/OGDCv3.txt>.

Oregon Water Resources Department (OWRD). "OWRD Well Log Query FAQ." Accessed 3/5/2011, updated 1/19/2011. <http://apps.wrd.state.or.us/apps/gw/well_log/well_log_faq.aspx>.

Orzol, L.L., Wozniak, K.C., Meissner, T.R., and Lee, D.B. 2000. Ground-water and waterchemistry data for the Willamette Basin, Oregon. U.S. Geological Survey Water-Resources Investigations Report 99-4036, 140p.

Scientific Consensus Statement on the Likely Impacts of Climate Change on the Pacific Northwest (Consensus). June 15, 2004. "Impacts of Climate Change on the Pacific Northwest" Symposium.

Tuppan Consultants, LLC. 2009. 2008 Annual Monitoring Report, Coffin Butte Landfill, Benton County, Oregon.

Uhrich, M.A. and Wentz, D.A. 1999. Environmental Setting of the Willamette Basin, Oregon. U.S, Department of the Interior, U.S. Geological Survey. Water-Resources Investigations Report 97–4082–A.

United States Census Bureau. Updated 11/4/2010. "Benton County Quick Facts." Accessed 3/5/2011. <http://quickfacts.census.gov/qfd/states/41/41003.html>.

Walker, G.W. and MacCleod, N.S. 1991. Geologic Map of Oregon: U.S. Geological Survey.

Webb, E.L. 2005. Hydrogeology Report Guidelines. Prepared for Oregon State Board of Geologist Examiners.

Woodward, D.G., Gannett, M.W., and Waccaro, J.J. 1998. Hydrogeologic framework of the Willamette lowland aquifer system, Oregon and Washington. USGS Professional Paper 1424-B.

Woody, J. 2007. A Preliminary Assessment of Hydrogeologic Suitability for Aquifer Storage and Recovery (ASR) in Oregon. MS Thesis, Department of Geosciences, Oregon State University.

Western Region Climate Center (WRCC). 2010. "CORVALLIS STATE UNIV, OREGON (351862). Period of Record Monthly Climate Summary." Accessed 3/5/2011. <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?or1862.>.

Yeats, R.S., Graven, E.P., Werner, K.S., Goldfinger, C., and Popowski, T.A. 1996. Tectonics of the Willamette Valley, Oregon. In: Rogers AM, Walsh TJ, Kockelman WJ, Priest GR (eds) Assessing earthquake hazards and reducing risk in the Pacific Northwest. Paper 1560. vol. 1. USGS, Washington, DC, pp 183–222

APPENDICES

Appendix A: ArcGIS Scripts

A.1: VBA script for gridding quadrilaterals

Modified from code created by Miles Hitchen. See the following link for original code and instructions:
http://forums.esri.com/Thread.asp?c=93&f=987&t=206832&mc=30#msgid952509

```
Option Explicit

Const xSplit As Long = 4
Const ySplit As Long = 4
Dim dCoords(xSplit, ySplit, 1) As Double


Public Sub GridSelectedQuadrilaterals()
Dim pMxDoc As IMxDocument
Dim pInFtrLyr As IFeatureLayer
Dim pFtrSel As IFeatureSelection
Dim pPolygon As IPolygon
Dim pEnumIDs As IEnumIDs
Dim lID As Long

   ' Get the first selected polygon on the first layer
   Set pMxDoc = ThisDocument
   Set pInFtrLyr = pMxDoc.FocusMap.Layer(0)
   Set pFtrSel = pInFtrLyr
   Set pEnumIDs = pFtrSel.SelectionSet.IDs
   pEnumIDs.Reset

   lID = pEnumIDs.Next
   While lID >= 0
      Set pPolygon = pInFtrLyr.FeatureClass.GetFeature(lID).Shape
      GridQuadrilateral pPolygon
      lID = pEnumIDs.Next
   Wend

   MsgBox "Finished"

End Sub


Private Sub GridQuadrilateral(pPolygon As IPolygon)
Dim pSegColl As ISegmentCollection
Dim lIdx As Long
Dim cx(3) As Double, cy(3) As Double
Dim dx(3) As Double, dy(3) As Double
```

```
Dim dx2 As Double, dy2 As Double
Dim x1 As Double, x2 As Double, x3 As Double
Dim y1 As Double, y2 As Double, y3 As Double
Dim l As Long, xs As Long, ys As Long

    Set pSegColl = pPolygon

    ' Get the corner coords of the quad
    lIdx = 0
    For l = 0 To 3
        lIdx = GetIndexOfNextCornerSegment(lIdx, pPolygon)
        cx(l) = pSegColl.Segment(lIdx).FromPoint.X
        cy(l) = pSegColl.Segment(lIdx).FromPoint.Y
    Next l

    dx(0) = (cx(1) - cx(0)) / xSplit
    dx(1) = (cx(1) - cx(2)) / ySplit
    dx(2) = (cx(2) - cx(3)) / xSplit
    dx(3) = (cx(0) - cx(3)) / ySplit

    dy(0) = (cy(1) - cy(0)) / xSplit
    dy(1) = (cy(1) - cy(2)) / ySplit
    dy(2) = (cy(2) - cy(3)) / xSplit
    dy(3) = (cy(0) - cy(3)) / ySplit

    For ys = 0 To ySplit
      x1 = cx(3) + dx(3) * ys
      y1 = cy(3) + dy(3) * ys
      x2 = cx(2) + dx(1) * ys
      y2 = cy(2) + dy(1) * ys
      dx2 = (x2 - x1) / xSplit
      dy2 = (y2 - y1) / xSplit

      For xs = 0 To xSplit
        x3 = x1 + dx2 * xs
        y3 = y1 + dy2 * xs
        dCoords(xs, ys, 0) = x3
        dCoords(xs, ys, 1) = y3
      Next xs

    Next ys

    BuildGrid

End Sub
```

```
Private Function GetIndexOfNextCornerSegment(lStartIdx As Long, pPolygon As IPolygon)
As Long
Dim PI As Double
Dim pSegColl As ISegmentCollection
Dim pLine1 As ILine, pLine2 As ILine
Dim l As Long
Dim lNxtIdx As Long
Dim dAng As Double

   PI = Atn(1) * 4
   Set pSegColl = pPolygon
   For l = 0 To pSegColl.SegmentCount - 2
      lNxtIdx = lStartIdx + l
      If lNxtIdx = pSegColl.SegmentCount Then lNxtIdx = 0
      Set pLine1 = pSegColl.Segment(lNxtIdx)
      lNxtIdx = lNxtIdx + 1
      If lNxtIdx = pSegColl.SegmentCount Then lNxtIdx = 0
      Set pLine2 = pSegColl.Segment(lNxtIdx)
      dAng = Abs(pLine1.Angle - pLine2.Angle) * 180 / PI
      If dAng > 20 Then
         ' The start point of this segment is a corner point
         GetIndexOfNextCornerSegment = lNxtIdx
         Exit Function
      End If
   Next l

GetIndexOfNextCornerSegment = -1
End Function


Private Sub BuildGrid()
' Now create the polygons on 2nd layer
Dim pMxDoc As IMxDocument
Dim pOutFtrLyr As IFeatureLayer
Dim i As Long, j As Long
Dim pFtrCls As IFeatureClass
Dim pFtrCsr As IFeatureCursor
Dim pFtrBfr As IFeatureBuffer
Dim pPtColl As IPointCollection
Dim pPt As IPoint

   Set pMxDoc = ThisDocument
   Set pOutFtrLyr = pMxDoc.FocusMap.Layer(1)
```

```
    Set pFtrCls = pOutFtrLyr.FeatureClass
    Set pFtrBfr = pFtrCls.CreateFeatureBuffer
    Set pFtrCsr = pFtrCls.Insert(True)

    For i = 0 To ySplit - 1
        For j = 0 To xSplit - 1

            Set pPtColl = New Polygon
            Set pPt = New Point
            pPt.PutCoords dCoords(j, i, 0), dCoords(j, i, 1)
            pPtColl.AddPoint pPt
            pPt.PutCoords dCoords(j, i + 1, 0), dCoords(j, i + 1, 1)
            pPtColl.AddPoint pPt
            pPt.PutCoords dCoords(j + 1, i + 1, 0), dCoords(j + 1, i + 1, 1)
            pPtColl.AddPoint pPt
            pPt.PutCoords dCoords(j + 1, i, 0), dCoords(j + 1, i, 1)
            pPtColl.AddPoint pPt
            pPt.PutCoords dCoords(j, i, 0), dCoords(j, i, 1)
            pPtColl.AddPoint pPt

            Set pFtrBfr.Shape = pPtColl
            pFtrCsr.InsertFeature pFtrBfr

        Next j
    Next i

    pMxDoc.ActiveView.Refresh

End Sub
```

A.2. Definition of QQID by Distance and Direction to Section Centroid

Note that direction grid measured angles counter-clockwise from South, and a value of 1 degree was added to break values to accurately capture phenomena at right angles.

```
Dim result as Integer

If  [dir_to_sec_ctr] < 31 Then
    result  = 123
ElseIf  [dir_to_sec_ctr] < 61 Then
If  [dist_to_se] < 1866 Then
    result  = 120
Else
    result = 122
EndIf
ElseIf  [dir_to_sec_ctr] < 91 Then
```

```
   result = 121
ElseIf  [dir_to_sec_ctr] < 121 Then
   result  = 112
ElseIf  [dir_to_sec_ctr] < 151 Then
If  [dist_to_se] < 1866 Then
   result  = 113
Else
   result = 111
EndIf
ElseIf  [dir_to_sec_ctr] < 181 Then
   result = 110
ElseIf  [dir_to_sec_ctr] < 211 Then
   result  = 101
ElseIf  [dir_to_sec_ctr] < 241 Then
If  [dist_to_se] < 1866 Then
   result  = 102
Else
   result = 100
EndIf
ElseIf  [dir_to_sec_ctr] < 271 Then
   result = 103
ElseIf  [dir_to_sec_ctr] < 301 Then
   result  = 130
ElseIf  [dir_to_sec_ctr] < 331 Then
If  [dist_to_se] < 1866 Then
   result  = 131
Else
   result = 133
EndIf
Else
   result = 132
End If
```

A.3. Case Select Quarter-Quarter Numerical Identifier to Text

```
Dim result as String

Select Case [qq]
Case 100
 result = "NENE"
Case 101
 result = "NWNE"
Case 102
 result = "SWNE"
```

```
Case 103
 result = "SENE"
Case 110
 result = "NENW"
Case 111
 result = "NWNW"
Case 112
 result = "SWNW"
Case 113
 result = "SENW"
Case 120
 result = "NESW"
Case 121
 result = "NWSW"
Case 122
 result = "SWSW"
Case 123
 result = "SESW"
Case 130
 result = "NESE"
Case 131
 result = "NWSE"
Case 132
 result = "SWSE"
Case 133
 result = "SESE"
End Select
```

A.4. Case Select Quarter-Quarter Text Identifier to Numerical

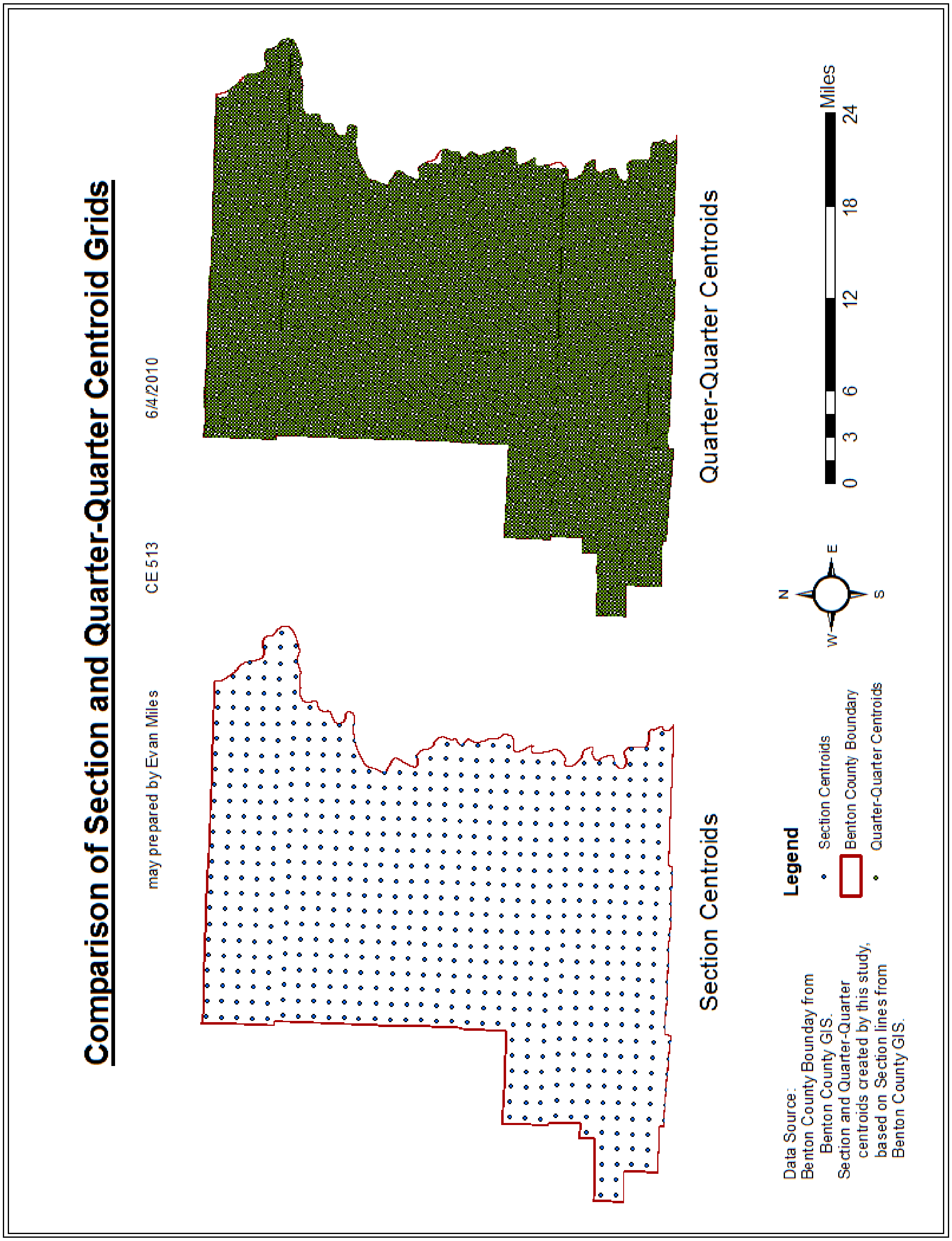
```
Dim result as Integer

Select Case [concat]
Case "NENE"
 result = 100
Case "NWNE"
 result = 101
Case "SWNE"
 result = 102
Case "SENE"
 result = 103
Case "NENW"
 result = 110
Case "NWNW"
```

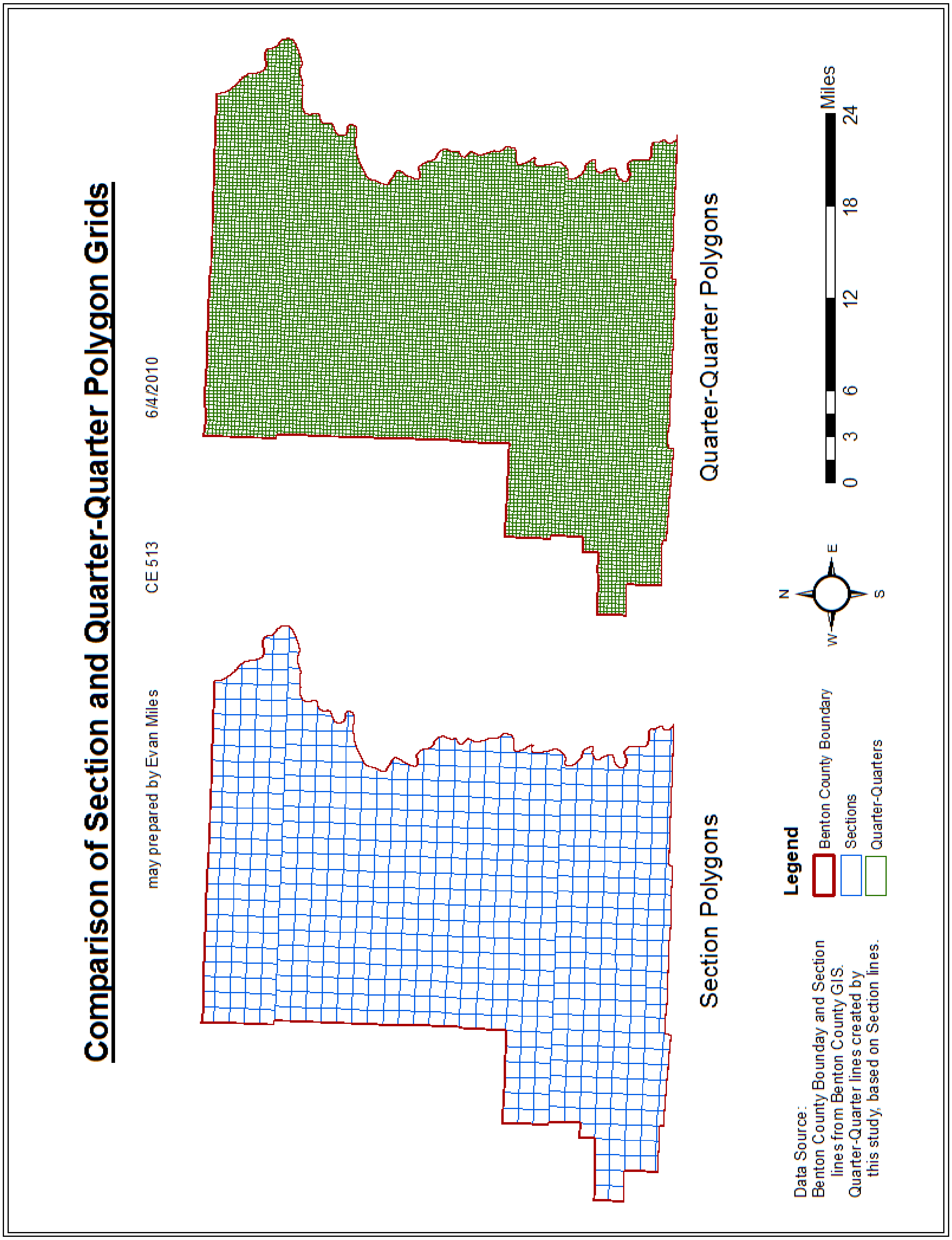
```
 result = 111
Case "SWNW"
 result = 112
Case  "SENW"
 result = 113
Case "NESW"
 result = 120
Case "NWSW"
 result = 121
Case "SWSW"
 result = 122
Case "SESW"
 result = 123
Case "NESE"
 result = 130
Case "NWSE"
 result = 131
Case "SWSE"
 result = 132
Case "SESE"
 result = 133
End Select
```

Appendix B: Benton County PLSS Quarter-Quarters

B.1Comparison of Section and Quarter-Quarter polygon grids



B.2. Comparison of Section and Quarter-Quarter centroid grids



Appendix C: Interpolation Documentation and Limitations

C.1. Limitations of Interpolations – Excerpts from Results and Discussion

The quality of interpolated surfaces and numerical analyses performed in this study are dependent on the quality of the original well logs. Errors and missing data on the well logs submitted to OWRD limited the ability of this study to accurately georeference wells and reduced the benefit of considering specific capacity due to the small number of data points. Varying well log quality can affect the validity of subsequent hydrogeologic analyses. In addition, this study acknowledges that occasional errors may have been made when these paper forms were digitized into the Well Log Query tool. Lastly, it was noted that additional data sometimes captured on well logs (drawdown, rock descriptions, water-bearing intervals) could have been useful for further study.

This analysis applied interpolation methods to understand the spatial variability of hydrogeologic parameters under the assumption that such parameters would vary continuously at some scale. For the interpolations to possibly be accurate, the resolution of the interpolated dataset generally needs to approach to scale at which a surface appears continuous. For the Willamette Valley, some of the parameters studied seem to vary little spatially, and water level interpolations have been performed with a great degree of success (Delhomme 1978, Desbarats 2001). In the heterogeneous Coast Range, the scale at which these parameters are continuous may be much smaller. In the Siletz River Volcanics, in particular, previous studies have suggested fracture flow mechanisms [EGR 1994, Braun 1995, EGR 1998], for which well yields and transmissivities may vary at scale of several feet [Berkowitz 2002]. Although this study was able to locate a large number of wells to a new level of accuracy for Benton County, the 933ft accuracy does not approach the resolution required to consider the interpolated surfaces as reliable estimates. Furthermore, Chapter 2 of this thesis showed examples of annual water level fluctuations. These water fluctuations can further confound the interpolated surface, depending on the season in which the wells were drilled; the result would be simulated local variability in the water level due to spatial water level sampling at distinct hydrologic conditions. In sum, although these surfaces may not be sufficiently accurate for site-specific planning, they are useful for visualizing the spatial variability of the different parameters investigated, and may be useful for county-wide planning.

The interpolation methods applied were found to be moderately rigid routines for characterizing the subsurface of Benton County. Cross-validation of the Ordinary Kriging surfaces, for example, resulted in poor fits for many parameters. This supports the hypothesis that the Siletz River Volcanics exhibit substantial variability, even at local scales. Again, it is important that the prediction surfaces be used primarily for visualization, regional characterization, and trend identification, rather than planning, design, or site characterization of the subsurface. **It is strongly emphasized that for site characterizations or for planning or design of developments, the services of an expert hydrogeologist should be consulted.**

C.2. Ordinary Kriging Interpolation Method Specification


```
<?xml version="1.0" ?>
- <model xml:lang="en" sDecimal="." name="Kriging">
    <dataset ID="0" Label="Dataset" dataset-type="DVA" />
    <dataset Label="Dataset 2" dataset-type="DVA" optional="true" />
    <dataset Label="Dataset 3" dataset-type="DVA" optional="true" />
    <dataset Label="Dataset 4" dataset-type="DVA" optional="true" />
    <dataset Label="Decluster's Clipping Dataset" dataset-type="Generic" sub-
        type="polygon" optional="true" />
    <dataset Label="Decluster's Clipping Dataset 2" dataset-type="Generic" sub-
        type="polygon" optional="true" />
    <dataset Label="Decluster's Clipping Dataset 3" dataset-type="Generic" sub-
        type="polygon" optional="true" />
    <dataset Label="Decluster's Clipping Dataset 4" dataset-type="Generic" sub-
        type="polygon" optional="true" />
    <enum name="KrigingMethodType">Ordinary</enum>
    <enum name="KrigingResultType">Prediction</enum>
  - <items name="Datasets">
    - <item name="Dataset">
        <enum name="TrendType">None</enum>
      - <model xml:lang="en" sDecimal="." name="NeighbourSearch"
            options="">
          <enum name="Type">Standard</enum>
          <bool name="Continuous">false</bool>
          <value name="NeighboursMax" auto="false">50</value>
          <value name="NeighboursMin" auto="false">0</value>
          <enum name="SectorType">Four45</enum>
          <value name="Angle">0</value>
          <value name="MajorSemiaxis" auto="false">100000</value>
```

```
        <value name="MinorSemiaxis" auto="false">100000</value>
      </model>
    </item>
  </items>
- <model xml:lang="en" sDecimal="." name="Variogram">
    <value name="DatalayerCount">1</value>
    <value name="NumberOfLags" auto="false">12</value>
    <value name="LagSize" auto="false">11591</value>
    <enum name="PairsType" auto="false">Semivariogram</enum>
    <bool name="NuggetOn">true</bool>
    <value name="Nugget" auto="false">2465.9567002745725</value>
    <value name="MeasurementError">0</value>
    <bool name="ShiftOn">false</bool>
    <bool name="VariogramModelAuto">false</bool>
  - <model xml:lang="en" sDecimal="." name="VariogramModel">
      <enum name="ModelType">Spherical</enum>
      <value name="Range" auto="false">100000</value>
      <bool name="Anisotropy">false</bool>
      <value name="Sill" auto="false">0</value>
    </model>
  </model>
</model>
```


C.3. 20-Point Inverse-Distance-Weighted Interpolation Method Specification


```
<?xml version="1.0" ?>
- <model xml:lang="en" sDecimal="." name="IDW">
    <dataset ID="0" Label="Dataset" dataset-type="DVA" />
    <value name="Power">3</value>
  - <model xml:lang="en" sDecimal="." name="NeighbourSearch">
      <enum name="Type">Standard</enum>
      <bool name="Continuous">false</bool>
      <value name="NeighboursMax" auto="false">20</value>
      <value name="NeighboursMin" auto="false">0</value>
      <enum name="SectorType">One</enum>
      <value name="Angle">0</value>
      <value name="MajorSemiaxis" auto="false">100000</value>
      <value name="MinorSemiaxis" auto="false">100000</value>
    </model>
  </model>
```


C.4. All-Point Inverse-Distance-Weighted Interpolation Method Specification


```
<?xml version="1.0" ?>
- <model xml:lang="en" sDecimal="." name="IDW">
    <dataset ID="0" Label="Dataset" dataset-type="DVA" />
```

```
  <value name="Power">3</value>
- <model xml:lang="en" sDecimal="." name="NeighbourSearch">
    <enum name="Type">Standard</enum>
    <bool name="Continuous">false</bool>
    <value name="NeighboursMax" auto="false">241</value>
    <value name="NeighboursMin" auto="false">0</value>
    <enum name="SectorType">One</enum>
    <value name="Angle">0</value>
    <value name="MajorSemiaxis" auto="false">100000</value>
    <value name="MinorSemiaxis" auto="false">100000</value>
  </model>
</model>
```

Appendix D: Geodatabase Structure

Geodatabase is available on ScholarsArchive via the Oregon State University Library's website, attached to the electronic copy of this thesis, and titled "Miles_2011_Benton_County_Groundwater.gdb".

The contents are specified below:

Parent Container	Dataset(s)	Description
Base Rasters	bc_hillsh_10m	Hillshade of Benton County derived from 10m DEM.
	mac_dunn_road_map	Map of McDonald-Dunn Forest prepared by OSU College of Forestry.
	orveg10	2010 composite land-use/landcover raster for Oregon
	dem10bcgrd	10m DEM of Benton County.
Basemap_Data	Benton_County_Addresses	Mapped addresses for Benton County, courtesy of the County.
	Benton_County_Boundary	Boundary of Benton County, courtesy of the County.
	Benton_County_known_faults	Subset of faults mapped by DOGAMI located within Benton County.
	Benton_County_Major_Rivers	Major rivers polygons within Benton County, courtesy of the County.
	Benton_County_Roads	Mapped roads for Benton County, courtesy of the County.
	GNIS_Populated_Places	USGS GNIS populated places dataset for Oregon
	Siletz_River_Volcanics	Units mapped by DOGAMI and associated with the Siletz River Volcanics, in Benton County.
BC_Add_Interpolations	21 interpolated surfaces	Interpolations performed in this study using an extent of Benton County and wells georeferenced by Address.
BC_QQ_Interpolations	21 interpolated surfaces	Interpolations performed in this study using an extent of Benton County and wells georeferenced by Quarter-Quarter.
Georeferenced_Wells	BC_ADD_Wells	Wells georeferenced by Address in this study.
	BC_QQ_Wells	Wells georeferenced by Quarter-Quarter in this study.
	SRV_ADD_Wells	Wells georeferenced by Address in the SRV by this study.
	SRV_QQ_Wells	Wells georeferenced by Quarter-Quarter in the SRV by this study.
OakCr_Results	Line_gen	Raw GPS track from fieldwork.
	OakCr	Oak Creek watershed.
	OakCrSprings	Processed GPS points noting spring locations, elevation, flow accumulation.
	Point_ge	Raw GPS points from fieldwork
SRV_Add_Interpolations	21 interpolated surfaces	Interpolations performed in this study using an extent of SRV units and wells georeferenced by Address.
SRV_QQ_Interpolations	21 interpolated surfaces	Interpolations performed in this study using an extent of SRV units and wells georeferenced by Quarter-Quarter.
N/A	oakccompdem	Composite 1m LIDAR Bare-earth DEM produced for this study, encompassing Oak Creek.
	RAW_Well_logs	Raw well logs for Benton County, downloaded from OWRD Well Log Query tool.