HYDROGEOLOGICAL CHARACTERIZATION OF THE PALOUSE BASIN BASALT AQUIFER SYSTEM, WASHINGTON AND IDAHO

By

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CHAPTER ONE

INTRODUCTION

Erupting as a series of flows between 17 to 6 million years ago, the flood basalt flows of the Columbia River Basalt Group (CRBG) have spread over eastern Washington, northeastern Oregon and western Idaho (Tolan et al. 2000). The CRBG aquifer systems provide water supplies for a broad range of domestic, municipal, industrial and agricultural uses (Tolan et al. 2000).

The cities of Pullman, Washington, and Moscow, Idaho, are situated within a physiographic basin (Foxworthy and Washburn 1963) that is part of the larger Palouse Basin (PBAC 1999) on the eastern margin of the Columbia Basalt Plateau (Crosby and Cavin 1960; Brown 1976) (Figure 1). Straddling the border of Washington and Idaho, the two metropolitan areas are eight miles apart, and both obtain the majority of their water resources from two basalt aquifers in the CRBG (Crosby and Cavin 1960; Foxworthy and Washburn 1963; Jones and Ross1972; PBAC 1999). The two basalt aquifers are the shallower Wanapum and the deeper Grande Ronde as part of the Palouse Basin basalt aquifer system. Discovered in 1884 (Foxworthy and Washburn 1963), this aquifer system has become one of the most important resources in the region, and currently is the source of drinking water for about 50,000 people (PBAC 1999).

Presently, the Grande Ronde aquifer is producing about 90% of the total water supply in this area (PBAC 2000). The water elevation in this aquifer, however, has been continually declining at a rate of about 0.3–0.6 m (1–2 feet) per year since the start of the aquifer development (Smoot and Ralston 1987; PBAC 2000). The continuous water-level decline and the projected future development have led to serious public concern (PBAC 1999).

Studies have been conducted to describe and quantify the ground-water flow system in the basin. Two modeling efforts (Barker 1979; Lum et al. 1990) by the U.S. Geological Survey focused on

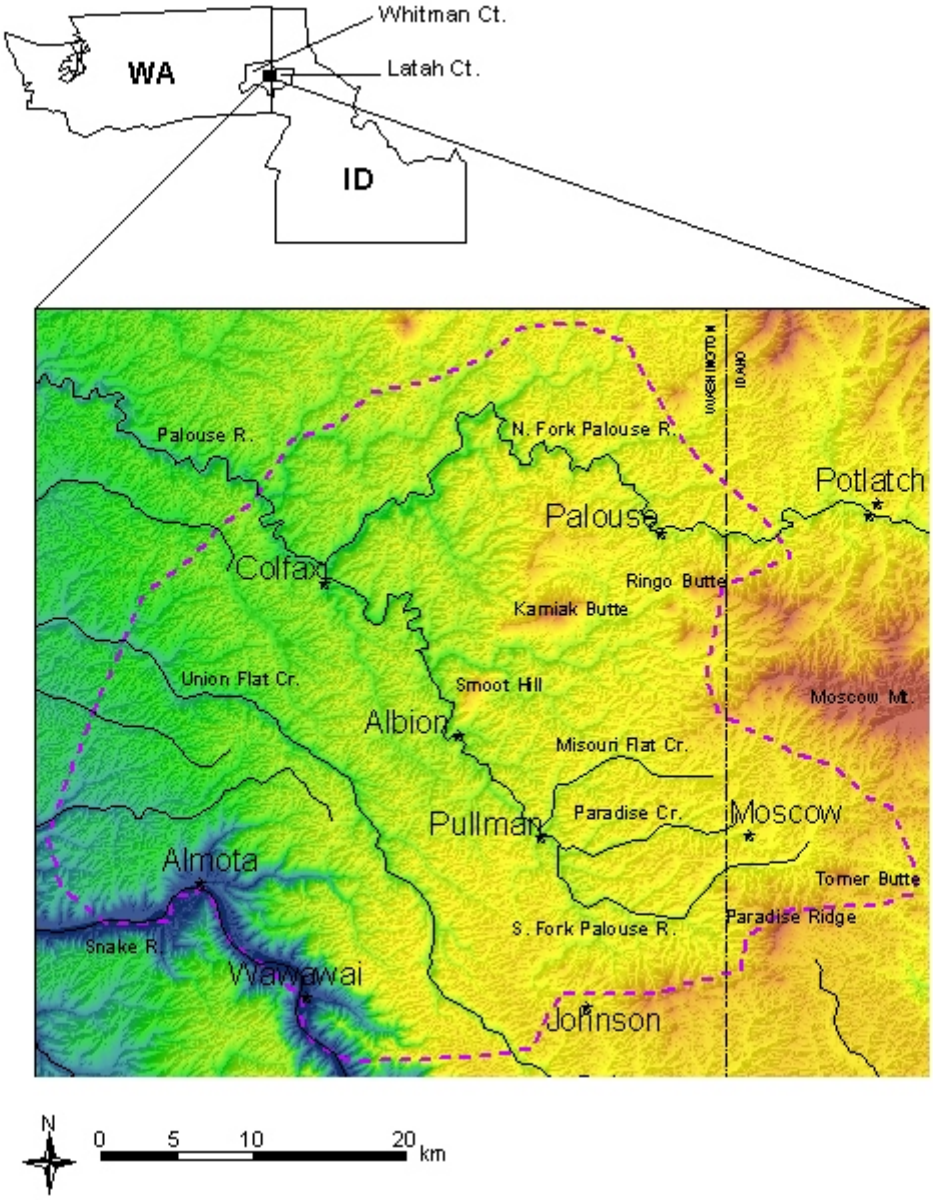

Figure 1. Study area. The dashed line represents the tentative basin boundary (Barker 1979; Smoot and Ralston 1987; Lum et al. 1990). This boundary encompasses areas of study that have been determined to be important to the Palouse Basin water issues.

developing and using a flow model as a tool for the Pullman-Moscow ground-water management. Yet both models have yielded inadequate predictions of ground-water levels, rendering them unsuitable for future management and planning (Smoot and Ralston 1987; Owsley 2003; O'Geen et al. 2005).

Although debates have been persistent regarding the causes of the ground-water level decline, generally increasing ground-water pumping has been considered one of the major reasons (Barker 1979; Smoot and Ralston 1987; Lum et al. 1990). Additionally, there are numerous unanswered questions with respect to ground-water recharge-discharge mechanisms, change in storage with pumping stress and climatic change, boundary locations, hydraulic connections between the Pullman and Moscow areas, and the long-term basin sustainability. To answer these essential questions requires detailed hydrogeologic knowledge of the basin. Nonetheless, our current knowledge about the basin is incomplete due, to a great extent, to the lack of a comprehensive database and related analysis of the data. Limited access to organized data has, in the past, restricted analysis in previous studies. Data from previous studies have been archived in a variety of forms and in different localities. Therefore, compilation of all available historical hydrogeologic data, as well as the conversion of the data into a digital format, has been urgently needed.

In this study we have attempted to develop a foundation for the improvement of the management and assessment of the Palouse Basin basalt aquifer system. Our specific objectives were to (1) develop a hydrogeology Geographic Information Systems (GIS) database for the Palouse Basin to improve data accessibility, data processing and analysis efficiency, and (2) better characterize the hydrogeology of the basalt aquifer system based on newly available spatial and temporal data.

CHAPTER TWO

HYDROGEOLOGIC SETTING

The Pullman-Moscow area occupies approximately 660 km^2 (256 mi^2) within the Palouse Basin (Brown 1976), with 448 km^2 (173 mi^2) within Whitman County, Washington, and 215 km^2 (83 mi^2) within Latah County, Idaho (Barker 1979). The basin is drained by the South Fork of the Palouse River and its two main tributaries: Missouri Flat Creek and Paradise Creek (Smoot and Ralston 1987; Heinemann 1994). The climate for this region is considered semiarid (Hansen et al. 1994). Average annual precipitation in the area ranges from 538 mm (21.2 in) in Pullman to 561 mm (22.1 in) in Moscow, based on 63 and 110 years of climatic records, respectively (U.S. National Oceanic and Atmospheric Administration 2005) (Figure 2). Sixty percent of the annual precipitation occurs during November to March. The average temperature in both Pullman and Moscow is 47.3°F (8.5°C) with mean maximum temperatures of 81.8°F (27.7°C) and 82.7°F (28.2°C) in July and mean minimum temperatures of 22.7°F (−5.2°C) and 22.4°F (−5.3°C) in January for Pullman and Moscow, respectively. Primary land use includes dryland farming, range land and forests (U.S. Census Bureau 2005).

The study area consists of pre-CRBG metamorphic and igneous rocks overlain by a sequence of Miocene basalt flows, which are topped by Pleistocene loess in the Pullman area and by Miocene sediments, which are in turn overlain by Pleistocene loess in the Moscow area (Barker 1979; Smoot and Ralston 1987). There are outcrops of pre-basalt rocks forming hills and buttes to the north, east and south of the basin (Foxworthy et al. 1963). Generally, they have lower permeabilities than the basalt, and withdrawal from this formation is mainly used for domestic water supplies (Foxworthy et al. 1963; Lum et al. 1990).

The Pleistocene loess is composed primarily of wind-blown silt and is designated as the Palouse

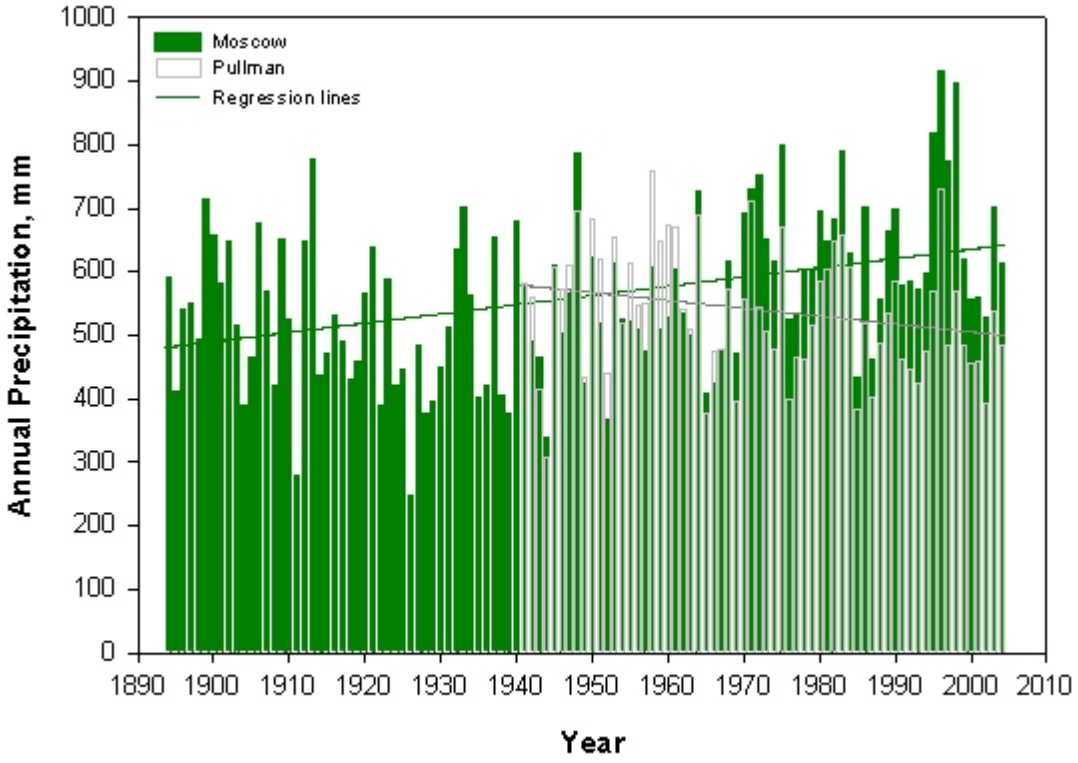

Figure 2. Annual precipitation of Pullman and Moscow (Data source: NOAA National Climatic Center, 2005). Linear regression analysis indicated no statistical significance of the slope of annual precipitation for both Pullman and Moscow.

Formation (Crosby and Cavin 1960). The loess deposits form a landscape of rolling hills (Barker 1979) and cover over 75% of the basin (O'Geen et al. 2005). Within the Palouse Basin the loess is up to 91 m (300 ft) thick (Foxworthy and Washburn 1963). Wells drilled in the loess unit are generally sufficient for domestic purposes (Brown 1991).

The basalt flows of the CRBG are interbedded, overlain and underlain by transported sedimentary deposits, which are collectively referred to as the Latah Formation (Crosby and Cavin 1960; Lin 1967; Bush et al. 1998). The sedimentary interbeds consist of clay, silt, sand, and gravel (Bush and Provant 1998; Bush et al. 2000) with many of them deposited as the result of basalt flows that dammed pre-existing streams (Crosby and Cavin1960). In the Moscow sub-basin, sedimentary interbeds make up a large portion of the water-bearing materials (Lum et al. 1990).

Following combined stratigraphic, lithologic, chemical, and magnetic criteria, the CRBG is divided into four formations (Drost et al. 1990; Bush and Provant 1998): from the oldest to youngest, Imnaha, Grande Ronde, Wanapum, and Saddle Mountains (Provant 1995; Bush and Provant 1998; Bush et al. 2000). The Imnaha Basalt has been identified near the bottom of the basin's deepest well, Washington State University (WSU) Well 7, in the Pullman sub-basin (Owsley 2003). The Saddle Mountains Formation is composed mainly of intra-valley flows with the least spatial extent (Drost et al. 1990; Provant 1995; Bush 2000). Occasional outcrops of this formation are present in both Pullman and Moscow.

The dominant aquifers of the basin reside in the Grande Ronde and Wanapum Basalts. The Grande Ronde Basalt is laterally extensive over the entire Pullman-Moscow area (Foxworthy and Washburn 1963). It is about 400 m (1,300-ft) thick in Moscow (Sokol, 1966) and 790 m (2,600-ft) in Pullman (Barker 1979). The Grande Ronde Basalt may be composed of up to hundreds of individual basalt flows (Drost et al. 1990; Tolan 2000). In the Palouse Basin up to seventeen flows

have been identified using paleomagnetic, geochemical and stratigraphic correlations (Teasdale 2002). The upper part of the Grande Ronde Formation exhibits high permeability and constitutes the major source of water (Foxworthy and Washburn 1963).

The basalt of the Wanapum Formation, which overlies the Grande Ronde Formation, consists of only one flow within the Palouse Basin (Provant 1995). It thickens in the Moscow area and is thinner in the Pullman area, with a thickness ranging 0–76 m(0–250 ft) (Heinemann 1994). In Moscow, the older city wells and most private wells produce water from the Wanapum Basalt (Ralston, 1989).

CHAPTER THREE

METHODOLOGY

3.1. Hydrogeology GIS Database Development

Geographic Information Systems (GIS) have been progressively applied for geohydrological research studies (Maidment 1993; Harris et al. 1993; Gupta et al. 1996). GIS is an efficient computer tool for capturing, archiving, manipulating, analyzing and visualizing geographically referenced data (Chang 2000). A GIS database can be easily used, shared and updated by multiple users. ArcGIS (v8.3), a comprehensive GIS software developed by ESRI (Ormsby et al. 2001), was used in this study in developing the hydrogeology GIS database for the Palouse Basin.

Existing hydrological data for the study area were mostly in printed form. These data were from different sources under different coordinate systems. Compared to other hydrological information (topography, stream networks, land-use, and soil), well data provided crucial insights into the subsurface and were therefore first compiled and digitized.

The well numbering used in most previous Palouse Basin basalt aquifer system studies was based on the township and range system (Appendix A). Both Washington and Idaho identify wells on this basis, although they divide the sections differently (Foxworthy and Washburn 1963; Jones and Ross 1972). The wells, previously inventoried, were manually digitized on township and range maps, which were obtained from the Washington State Department of Natural Resources (2005) for the Whitman County, Washington, and the INSIDE Idaho (2005) network for the Latah County, Idaho, respectively. Digitizing wells involved assigning detailed township and range values to them using the Editor tool in ArcGIS. The digitized wells were re-projected to the Universal Transverse Mercator (UTM, Zone 11) North American Datum of 1983 (NAD 1983). The old, township and range coordinates, were then appended to the well attribute table under the new, UTM system. For

this study, more than 800 wells were digitized and included in the Palouse Basin hydrogeology GIS database.

Complete records for all the wells within the study area were not available from any single source. Instead, they were archived by different agencies in different forms. During the compilation of these records in this study selected important attributes were added. The well attributes were: construction information (owner name, drilling time, well depth, land surface datum, depth to water, well productivity, and screen position), well type (production vs. monitoring, domestic vs. municipal), formation yielding water (Palouse Formation, Latah Formation, Saddle Mountains, Wanapum, Grande Ronde, pre-CRBG rocks), altitude of basalt units (top of Wanapum and Grande Ronde). Major municipal and industrial wells were digitized into GIS format; however, those wells that were less than nine meters (30 ft) deep that lacked crucial attribute information (e.g.,construction information) were not included in the hydrogeology database There are no agricultural wells in this dryland farming region.

The 1:24,000-scale digital elevation model, acquired from the U.S. Geological Survey (2005a), was the foundation of all the GIS coverages. The approximate extent and boundary conditions of the Palouse Basin were proposed in several previous studies (Barker 1979; Smoot and Ralston 1987; Lum et al. 1990)(Appendix H). The crystalline uplands were commonly suggested as the eastern and southern boundaries of the basin. The western and northern boundaries, however, were delineated differently. Barker (1979) proposed that a geological barrier might be present underneath the Union Flat Creek and accordingly delineated this as the western boundary. He considered the northern boundary to be the ridges of the pre-basalt rocks encircling the Smoot Hill, Kamiak Butte and Ringo Butte. Smoot and Ralston (1987) and Lum et al. (1990) believed a significant amount of seepage occurs on the canyon walls of the Snake River, and therefore set the Snake River as the western

boundary. For their model, they set the northern boundary along the Palouse River, sufficiently far away from either of the major pumping centers, Moscow and Pullman. By referring to these literature, we extended our study area, for the development of the hydrogeology GIS database, to the Snake River on the west, to the North Fork of the Palouse River on the north, and, to the crystalline uplands on the east and south.

Other coverages, such as wells, land cover, stream networks, watershed, land-use, and soil were subsequently overlaid to the basemap (Appendix F). Map units and attribute data for the coverages were primarily obtained from the U.S. Department of Interior (2005) and the U.S. Department of Agriculture (2005).

Long-term data of water level, pumping and weather were compiled in order to detect changes in ground-water level as affected by climate and disturbances (Appendix C–E). Records of ground-water level and pumpage were extracted from the literature (Foxworthy and Washburn 1963; Jones and Ross 1972; Crosthwaite 1975) or obtained from the major water users, namely, the cities of Pullman and Moscow, and the two universities of WSU and University of Idaho (UI), as well as from the web site of the U.S. Geological Survey (2005b).

Geological features, including fold structures (Bush et al. 2001; Bush 2005) and well lithological logs (Heinemann 1994; Owsley 2003)(Appendix B) were obtained from previous research and from the web sites of Washington State Department of Ecology (2005) and Idaho Department of Water Resources (2005). The folds (anticlines, monoclines and synclines) were digitized in order to detect and describe correlations between the geology and hydrogeology of the basin. Additionally, interpretation of well logs provided information on lithology, stratigraphy, and characteristics of water-bearing formations, which has been valuable for ascertaining the areal extent of the basalt aquifers.

3.1.1. Contour Maps of Subsurface Structure and Potentiometric Surface

Structural maps for the two basalt aquifers were constructed using their top altitude data from the hydrogeology GIS database. Kriging interpolation, an embedded function in ArcGIS Statistical Analyst (Johnston et al. 2001), was used to estimate unknown values of altitude. The boundary of the exposed pre-CRBG rocks was manually digitized from the DEM and included. These structural maps helped to reveal the spatial variability of subsurface relief.

Water-level data recorded at different times (1960s, 1980s and 1990s) and the kriging technique in ArcGIS were used to construct a series of potentiometric surface contour maps of the Wanapum and Grande Ronde Basalt aquifers. These maps should be helpful in describing the hydrogeologic context of the study area and the synergistic relationship of the sub-basins in response to long-term pumping disturbances. Since data on water levels were documented in different time sequences in previous studies, it was not possible to construct potentiometric surface maps of the basalt aquifers for any exact time period from the same wells. Consequently, available water-level data were grouped around 1960s, 1980s and 1990s. For instance, water-level data in late 1950s and early 1960s were both included to create the potentiometric surface map for the 1960s.

3.1.2. Long-term Hydrograph Assessment

Historical water-level data from major wells in the Palouse Basin were used to construct composite ground-water hydrographs. These data were also used to construct hydrographs for each aquifer and sub-basin. These hydrographs helped to establish the initial hydrostatic conditions within the entire aquifer system, and to clarify aquifer behavior under the influences of climate and pumping stress.

3.1.3. Development of Hydrogeological Cross-sections

Roughly 140 borehole logs were used to construct hydrogeologic cross-sections along strategic directions within the Palouse Basin (Appendix G). Among these borehole logs, 40% were achieved

in a spreadsheet program included in our hydrogeology GIS database and the rest was accessible at the web sites of Washington State Department of Ecology (2005) and Idaho Department of Water Resources (2005). These cross-sections enabled us to establish the vertical and lateral extent of individual basalt flows, as well as the interconnectivity of the water-bearing units. The Bovill interbed and the Vantage interbed were determined as the contact between the Palouse Formation and Wanapum, and Wanapum and Grande Ronde, respectively, following Bush et al. (1998, 2000). In a number of cases where stratigraphic description from the borehole logs was poor, regional trends from previous studies by Heinemann (1994) and Bush et al. (1998, 2000) were used to aid in interpreting the sequence of geological units. These cross-sections helped to reveal possible geological structures and their impact on ground-water flow regime.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Hydrogeology GIS Database

A total of 17 maps were created and included in the hydrogeology GIS database for the Palouse Basin. These are: topography, stream networks, land-use, soil, HUC (Hydrologic Unit Code) watershed boundary, township and range coordinate (Whitman County and Latah County, respectively), well location, structural contour maps (top altitude of the land surface, Wanapum and Grande Ronde Formations, respectively), potentiometric surface contour maps for Wanapum and Grande Ronde Basalt aquifers at 1960s, 1980s and 1990s, respectively.

Figure 3 shows the spatial distribution of the wells in the Palouse Basin. Wells shown on the map are linked to their attribute table, allowing efficient display and analysis of relevant well properties. Additionally, the attributes stored in the database can be easily maintained and updated by other researchers, enabling effective collaboration.

4.1.2. Subsurface Topographic Relief

Structural contour maps of the top altitude of the Wanapum and Grande Ronde Basalt aquifers are illustrated in Figure 4. For comparison, the land surface map, which coincides with the top altitude of the Palouse Formation in most of the study area except the Snake River canyon, was also included. All elevation data, including topographic, top altitudes of the major aquifers elevations of water levels, were measured with reference to the sea level.

The loess surface shows a general westward sloping trend with elevation changing from 1,010 m (3,314 ft) along the eastmost boundary of the basin to 520 m(1,706 ft) in the west (Figure 4a). The altitude of the loess in the cities of Moscow and Pullman is 780 m (2,559 ft) and 725 m (2,379 ft), respectively.

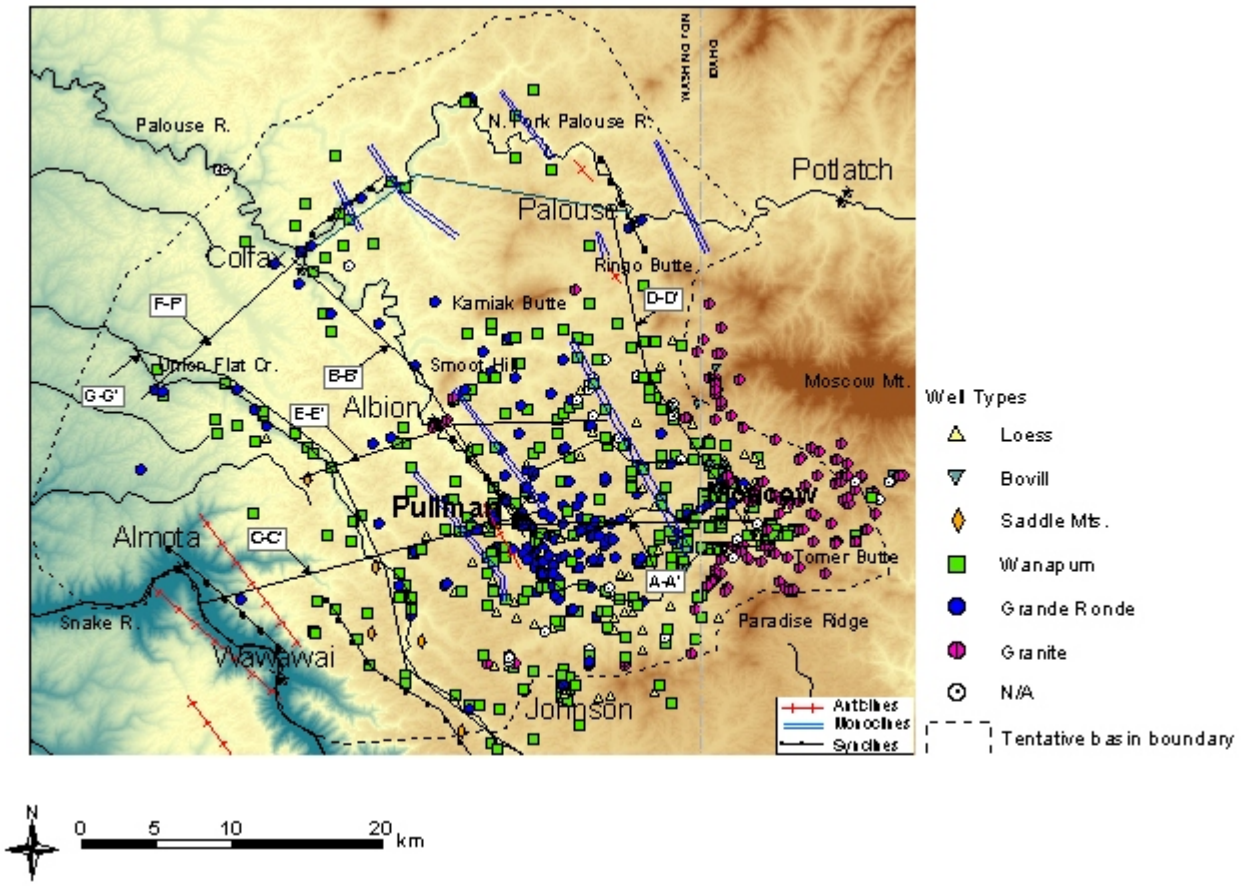

Figure 3. Location map of wells in the Palouse Basin. A-A′, B-B′ and C-C′ represent the three hydrogeological cross-sections shown in Figures 10, 11 and 12, respectively. The cross-sections D-D′, E-E′, F-F′ and G-G′ are presented in Appendix G. Locations of folds (monoclines, anticlines and synclines) were adapted from Bush (2005).

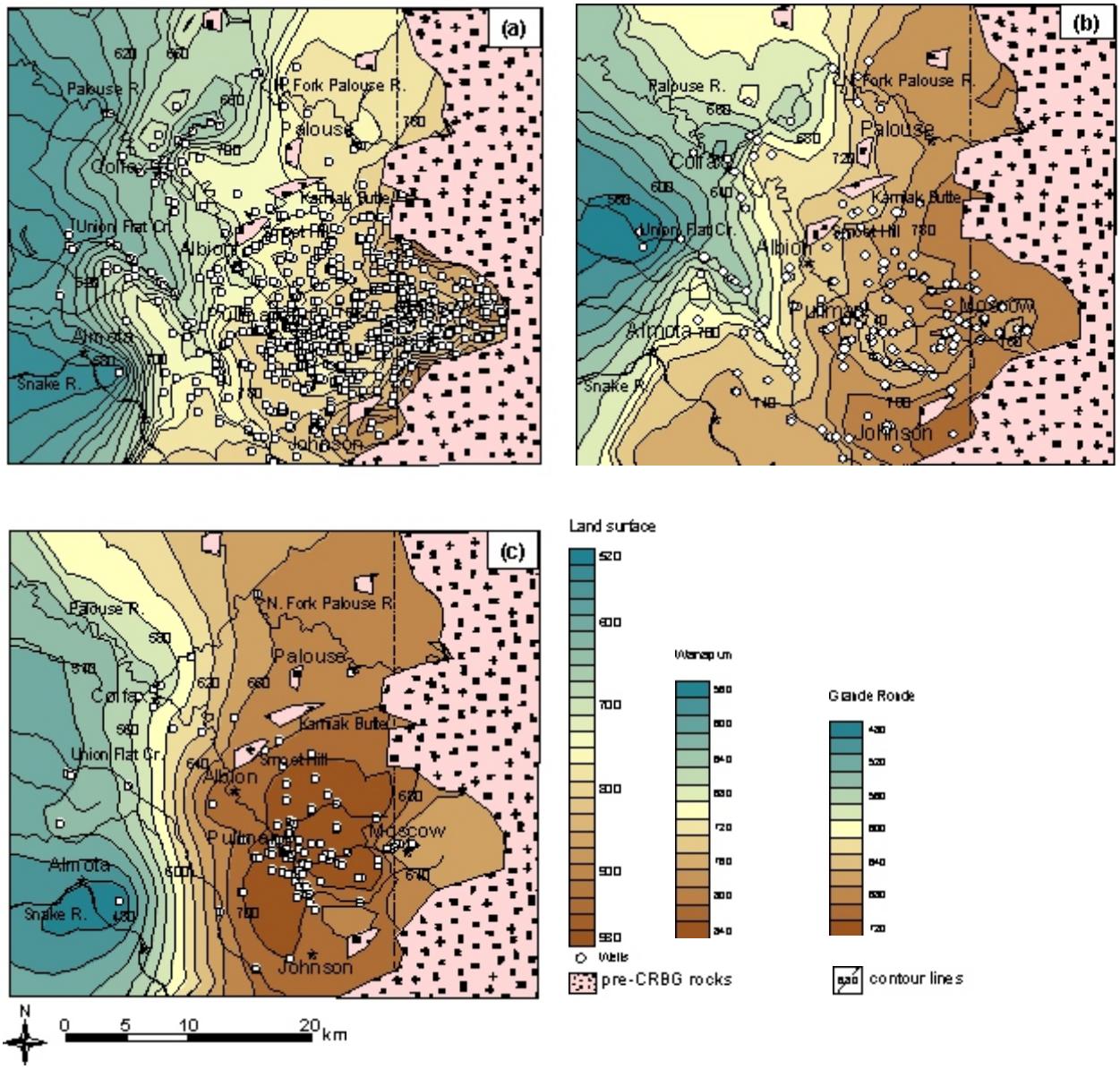

Figure 4. Structural contour maps of the top altitude (m, a.s.l.) of (a) land surface, (b)Wanapum Formation, (c) Grande Ronde Formation.

The top altitude of the Wanapum Formation displays a similar general trend as the Palouse Formation, sloping from Moscow Mountain in the east to the Snake River in the west. The altitude is 770 m (2,526 ft) at Moscow and is 715 m (2,346 ft) at Pullman. However, from Moscow towards Palouse, the trend reverses, with altitude increasing to 790 m (2,592 ft) near the state line, and then dipping slowly to 760 m (2,493 ft) at the city of Palouse, reflecting a complicated nature of the geometric configuration of the Wanapum.

The top altitude of the Grande Ronde Formation is undulating with a local mound around Pullman yet it generally decreases from the east to the west following the same trend as the Palouse and Wanapum Formations. The altitude is 695 m (2,280 ft) at Pullman and 640 m (2,100 ft) at Moscow, with a local high at an altitude of 715 m (2,345 ft) in between. A significant drop in the top altitude is evident from Pullman towards the Snake River. Additionally, the top altitude decreases from Pullman to the Colfax area at 570 m (1,870 ft), thus, displaying major dips west and northwest away from Pullman. Hence, both basalt formations exhibit a sloping trend to northwest and west, although local irregularities exist, which is consistent with the findings of Teasdale (2002).

4.1.3. Potentiometric Surfaces

The potentiometric surface in the Wanapum Formation exhibits a clear decreasing trend from southeast to northwest with noticeable changes over a period of three decades (Figure 5). The major flow direction of SE–NW is roughly parallel to the Union Flat Creek as well as the Snake River.

In the 1960s, the ground-water level was 755 m (2,477 ft) near Moscow and was 720 m (2,362 ft) in the Pullman area, and dropped to 620 m (2,034 ft) near Colfax. Essentially all water supply for the Moscow area had been drawn from the Wanapum aquifer before 1964. Pumping was largely shifted from Wanapum to the lower Grande Ronde thereafter. Between 1965 to 2004, withdrawals from the Wanapum aquifer averaged only about 14% of total pumping in the Moscow area. Figure

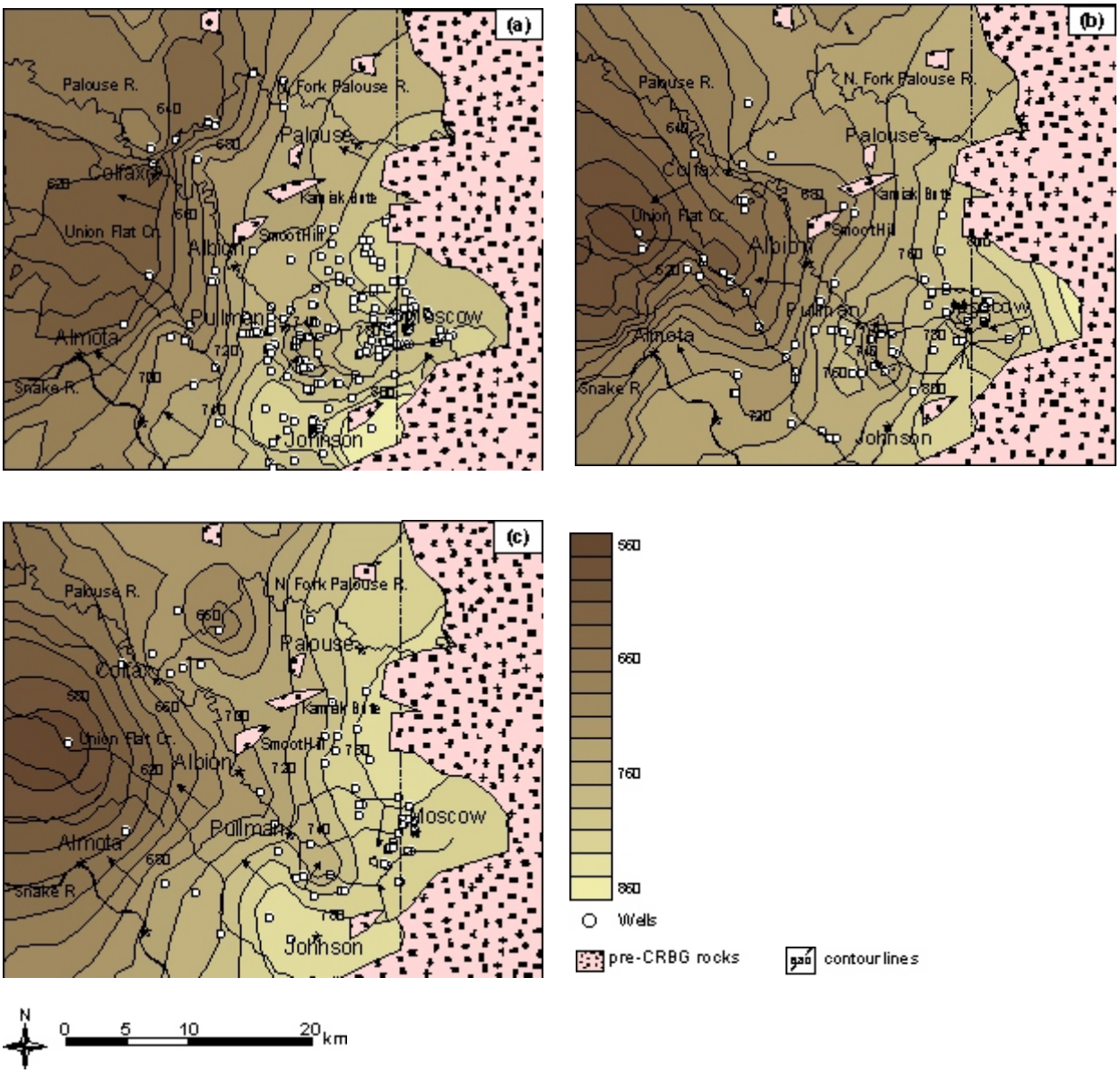

Figure 5. Contour maps of potentiometric surface (m, a.s.l.) for the Wanapum aquifer based on water-level data in (a) 1960s, (b) 1980s, and (c) 1990s. The arrows indicate lateral ground-water flow directions.

6a shows historical pumpage summed for the whole basin as well as for Pullman and Moscow sub-basins, respectively, and Figure 6b depicts the fraction of ground-water withdrawal from Wanapum versus Grande Ronde for Moscow over time. The cone of depression appears most evident in the 1980s contour map, suggesting a time lag in ground-water level recovery in the Wanapum aquifer (Figure 5b).

Wanapum thins and becomes less productive towards the Pullman area. As a result, this aquifer has never been subjected to heavy use in Pullman. Less than five million gallons per year was taken from Wanapum (Foxworthy and Washburn 1963) accounting for only 1.2% of the total pumpage. The pumpage decreased over time with an average of 0.7% for the period of 1940–2004. Yet there appears a cone of depression near Pullman in the 1980s contour map as well (Figure 5b). By 1990s, these cones of depression had largely disappeared and the water level in the Moscow area rose to 765 m (2,510 ft). This recovery was likely due to the shifting of the pumping from Wanapum to Grande Ronde in Moscow, and suggests a hydraulic connection between the Wanapum aquifer and the Miocene sediments and loess.

The potentiometric surface contour maps of the Grande Ronde aquifer display a general pattern similar to those of the Wanapum aquifer, throughout 1960s, 1980s, and 1990s (Figure 7). The exception to the SE–NW trend of ground-water level of the Grande Ronde aquifer occurs near Almota, where a deep well drilled in the 1980s revealed significantly lower ground-water level (Figure 7b). For accuracy of the kriging interpolation, the 1980s water level was added to the 1960s as well as 1990s potentiometric contour maps. No data were available beyond the initial water level from borehole logs. From this sole record, the water level in the Grande Ronde aquifer appears to dip towards the Snake River at that location.

The two pumping centers of Moscow and Pullman maintained nearly the same ground-water

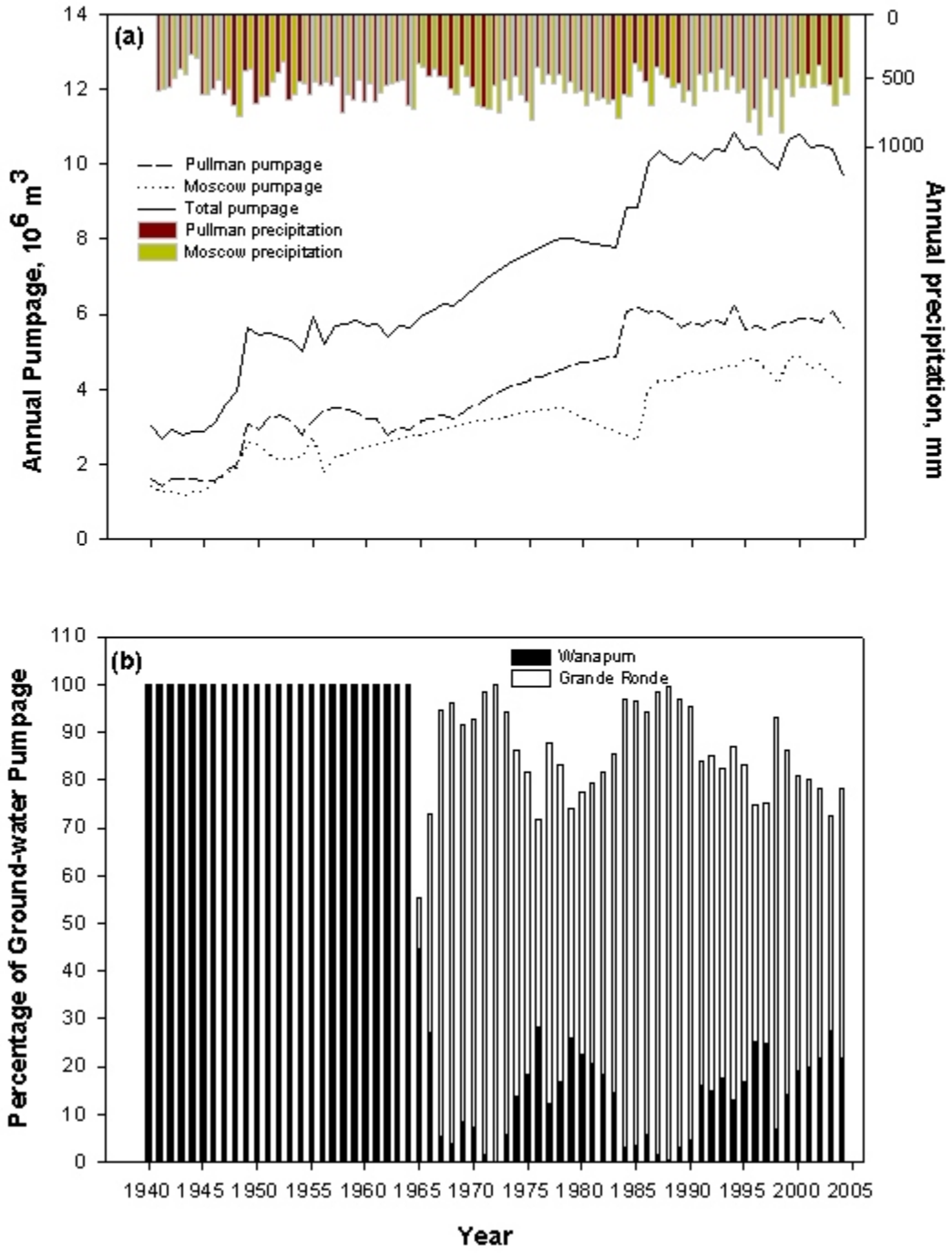

Figure 6. Long-term ground-water pumpage from the Wanapum and Grande Ronde aquifers. (a) Total pumpage for Pullman and Moscow with annual precipitation included for comparison. (b) Fraction of pumpage from the Wanapum aquifer for Moscow.

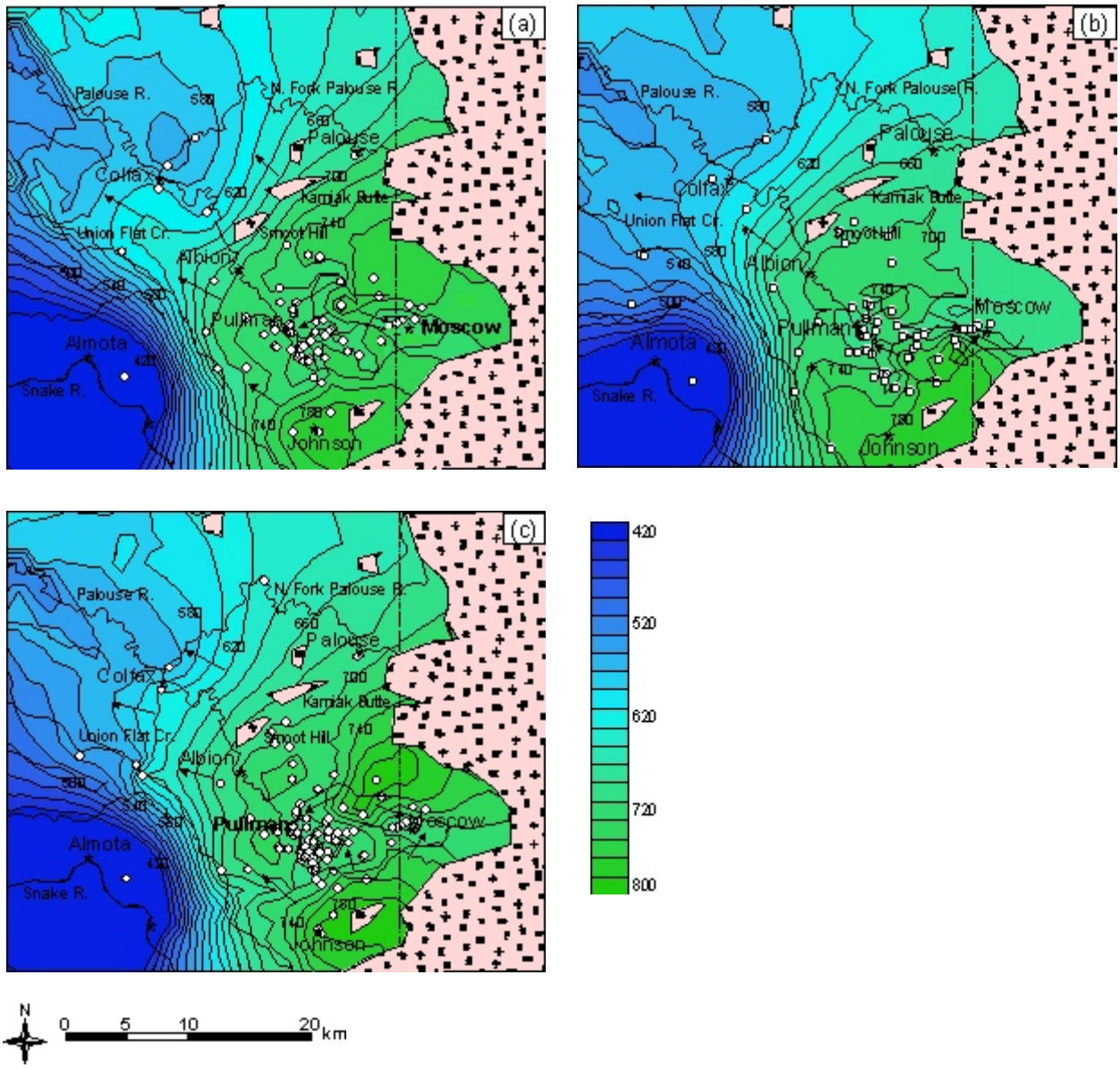

Figure 7. Contour maps of potentiometric surface (m, a.s.l.) for the Grande Ronde aquifer based on water-level data in (a) 1960s, (b) 1980s, (c) 1990s. The arrows indicate lateral ground-water flow directions.

levels of about 700 m (2,297 ft) throughout the 1960s, and about 690 m (2,264 ft) during the 1980s and 1990s. Detailed data from the wells at the two pumping centers showed that the ground-water level was slightly higher in Moscow at 703 m (2,306 ft) in the 1960s, and declined gradually to 700 m (2,297 ft) at Pullman, forming a hydraulic gradient of 2.33×10^{-4} and implying ground-water movement from Moscow to Pullman. In the 1980s, the flow direction reversed, with the ground-water level slightly higher in Pullman at 694 m (2,277 ft) vs. 689 m (2,260 ft) in Moscow. In the 1990s, ground-water levels at both pumping centers reached 692 m (2,270 ft).

These transient changes in ground-water levels and flow regimes were potentially caused by multiple factors. First, pumpage from the Grande Ronde has been consistently lower in Moscow than in Pullman. Greater withdrawal in Pullman, in principle, should have led to a lower ground-water level. Second, although annual precipitation has not shown statistically significant change for both cities from simple regression, it does exhibit a mild increasing trend in Moscow and decreasing trend in Pullman as shown in Figure 2. The basalt-crystalline contact along the Moscow Mountain has long been speculated as the area of recharge to the Grande Ronde aquifer, though further investigation is needed. As such, change in climatic conditions, in particular, precipitation patterns, may affect the ground-water level of Grande Ronde. Third, Grande Ronde has historically been a confined aquifer as ground-water levels observed in most wells screened in this aquifer were above the Vantage interbed, the upper confining layer. However, because of the continuous decline of ground-water level in Grande Ronde, the aquifer appeared to have become semi-confined in certain areas of Pullman as shown in Figure 12 (further discussed later). If this were the case, decrease in ground-water level would be relatively less than in a confined aquifer. All these factors interactively and collectively affect the ground-water flow regime in the Pullman-Moscow area.

In summary, evident cones of depressions at Moscow and Pullman have resulted from heavy

pumping over time, which distinguishes the northwestern from the southeastern area of the Palouse Basin. That ground-water flow is generally toward the northwest, which is consistent with early findings by Foxworthy and Washburn (1963) who submitted that the existence of gentle flexures in the basaltic Wanapum and Grande Ronde appeared to retard the westward ground-water movement toward the Snake River.

Axes of major northwest trending folds in the Palouse Basin are shown in Figure 3. The potential impact of basin geological structures on ground-water movement has been reported (Teasdale 2002; Bush and Garwood 2003; Bush 2005). It was proposed that a barrier likely was present near the Union Flat Creek (Barker 1979), and the northwest trending folds might have led to ground-water flow approximately following the major axis of these folds (Brown 1976). From the Wanapum and Grande Ronde potentiometric surface maps, existing structural features (anticlines, monoclines, and synclines) in both aquifers create local areas where rapid changes in ground-water levels occur in the direction of the trend of the folds. For instance, the ground-water level of Grande Ronde drops over nearly 150 m (490 ft) over 24 km (15 mi) from Pullman to Colfax, creating a hydraulic gradient up to 6.25×10^{-3}.

4.1.4. Long-term Hydrographs

Measured ground-water levels dating back to the 1920s are shown in Figure 8. For comparison, hydrographs recorded from the Palouse Formation wells are also included. Each aquifer appears to exhibit a distinct pattern of water-level fluctuation as affected by pumping, climate and recharge. Although the water levels in the uppermost loess wells fluctuated in response to seasonal cycles of precipitation, in the long term, they remain stable. The Wanapum and Grande Ronde aquifers, however, have undergone considerable declines. Additionally, the long-term trends of the hydrographs clearly indicate weak vertical hydraulic connection between the two basalt aquifers.

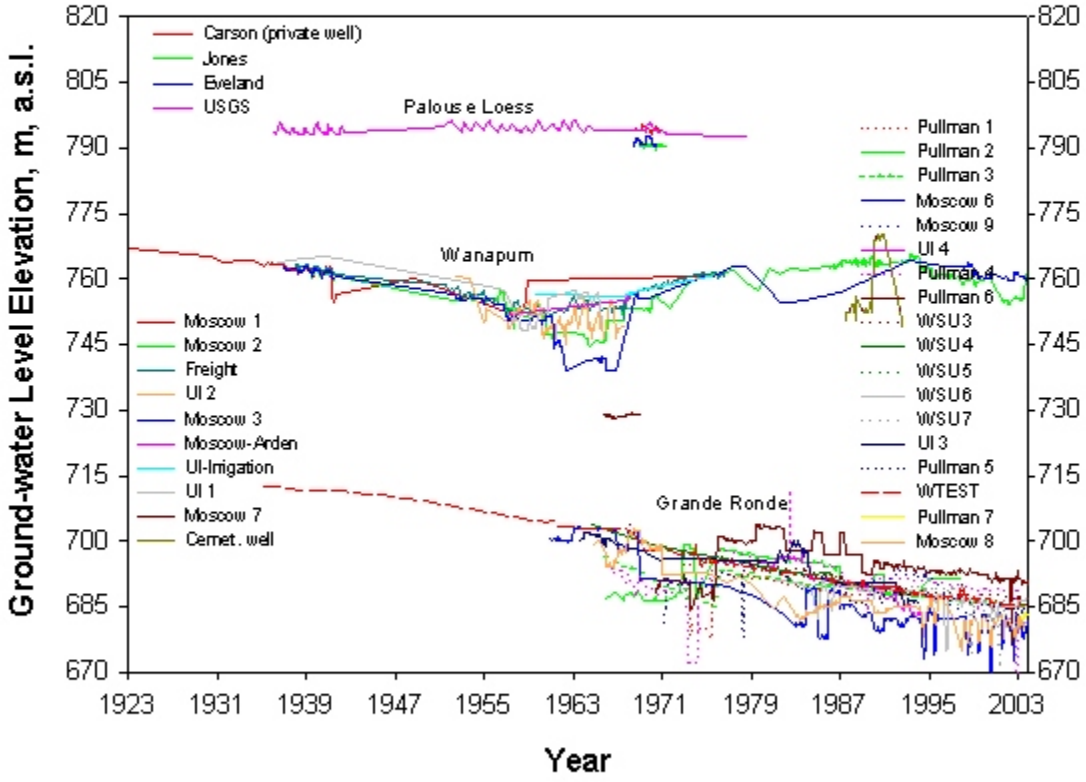

Figure 8. Composite ground-water hydrographs of major wells in the Palouse Basin.

Complete ground-water level data used to create this figure is presented in Appendix D.

The water level in the Wanapum was near 770 m (2,524 ft) in early 1920s, and dropped to 735 m(2,411 ft) by early 1960s. The significant reduction in pumpage from the Wanapum when the Grande Ronde wells in Moscow were developed in the year of 1965 resulted in the recovery of ground-water levels in the Wanapum thereafter. By 2004, the water level reached 762 m (2,500 ft), close to the pre-development stage (Figure 8).

The long-term hydrographs of the Grande Ronde aquifer indicate a substantial decline of 30 m (98 ft) from the initial value of 715 m (2,346 ft), which may approximate the pre-development level (Figure 8).The most pronounced decline began in 1965, the year when ground-water withdrawal in Moscow was largely shifted from Wanapum to the Grande Ronde (Figure 6), averaging 12 m (39.4 ft) across the Pullman-Moscow area between 1965–1990.

An agreement between the major water users in the basin was reached in 1992 (PBAC 1999) to limit yearly pumping from the Pullman-Moscow ground-water system, based on a five-year moving average to a 1 percent increase from the average a decade ago, i.e. 1982–1986. In fact, from 1992 to 2004, total withdrawal from the entire ground-water system decreased by 0.5% per year on average, while pumping from the Grande Ronde decreased by 1.3% per year for the Moscow area and 0.1% per year for Pullman area through conservation measures, such as using effluent from waste water treatment plants for irrigation and shifting certain pumpage to the shallower Wanapum in Moscow.

Hydrographs for Pullman and Moscow Grande Ronde wells over 1975–2004 were plotted to obtain a close view of recent changes in ground-water levels (Figure 9). Water-level data for 1965–1974, the first decade after the significant shift of ground-water pumpage to the Grande Ronde, exhibited considerable data anomalies and inconsistencies, due to technical problems in monitoring, including malfunctioning and failure of measurement devices (e.g., Moscow 6 and

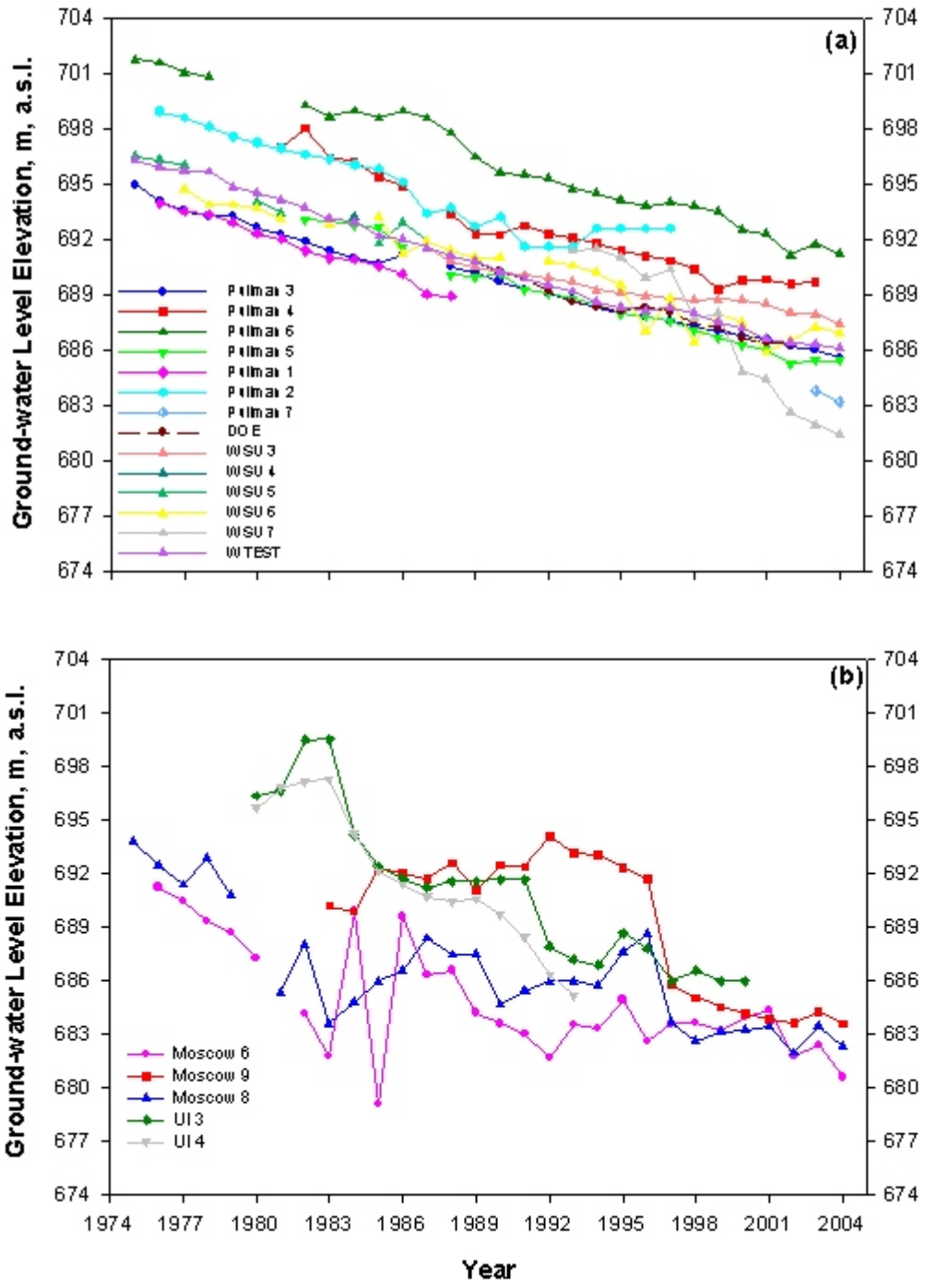

Figure 9. Long-term hydrographs for major wells in the Grande Ronde aquifer in (a) Pullman and (b) Moscow during 1975–2004.

Moscow 8, 1968 data, Pullman 4 and 6, 1973 data, Pullman 3, 1974 data). Hence, data for this period were not plotted. The pattern of declining water levels during the last three decades was consistent throughout the period for Pullman and erratic for Moscow. The presence of multi-layered sediments within the basalts, discontinuity of the water bearing zones (Sokol 1966; Jones and Ross 1972), and the proximity to boundaries of pre-CRBG rocks were likely the major factors causing the erratic patterns of the hydrographs in the Moscow sub-basin. Additionally, replacement of measurement devices in all Moscow wells during 1997–1998 (PBAC 2000) has led to systematic changes in recorded water levels. Differences in hydrograph shapes were suggested in earlier studies by Sokol (1966) to be related to discontinuity of some aquifer zones caused by buried structural features in the basalt and associated sediments. Owsley (2003) also reported the possible existence of different aquifer zones based on the different behavior among the Moscow city and UI wells in response to short-term pumping tests. For example, when Moscow 8 was pumped, Moscow 6 and UI 3 responded, but Moscow 9 and UI 4 did not. All of these wells were located within a radius of 1,500–2,000 m (5,000–7,000 ft), and all withdrew water from the Grande Ronde aquifer.

4.1.5. Hydrogeological Cross-Sections

A total of seven hydrogeological cross-sections were constructed to better understand the subsurface structures and ground-water flow patterns within the Palouse Basin. Three most relevant hydrogeological cross-sections are presented and the remaining four are included in Appendix F.

The cross-section A–A′ from Pullman to Moscow illustrates the nature of the lateral changes between basalts and sediments as well as the interconnectivity of the water-bearing units (Figure 10). To the west in the Pullman area, thin sedimentary interbeds are interspersed throughout the

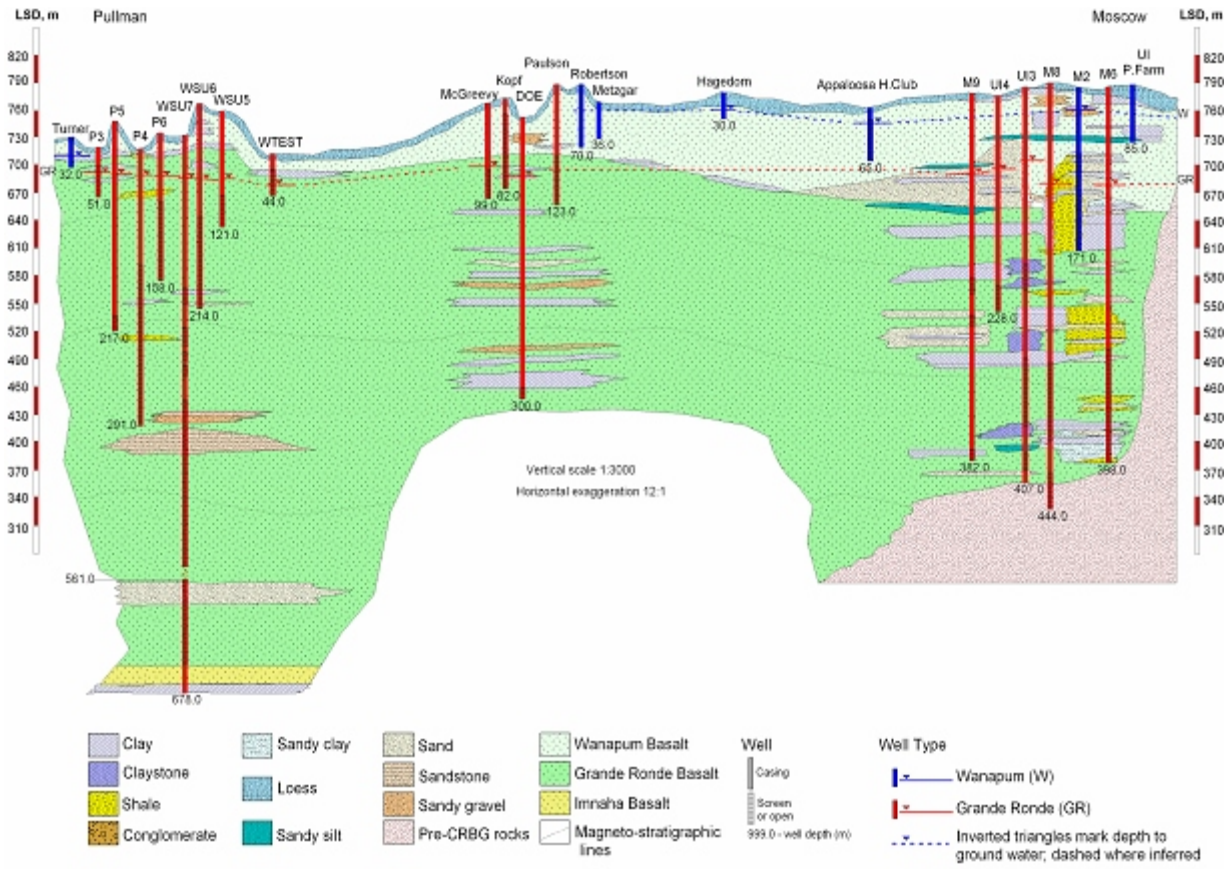

Figure 10. Hydrogeological cross-section (A-A′) from Pullman to Moscow. Transect A-A′ is shown on Figure 3.Ground-water level data was extracted from the Palouse Basin hydrogeology GIS database.

Grande Ronde, whereas in Moscow, thicker sediment interbeds dominate the sub-basin.

The Wanapum aquifer consists of over 120 m (400 ft) of basalt and sediments in Moscow, whereas in Pullman it comprises primarily basalt and is less than 45 m(150 ft) at most localities. In general, the top of Grande Ronde Formation dips eastward in towards Moscow, which may be due to a compaction of the clayey interbeds (Lum et al 1990). Some of the basalt flows in the Moscow area did not fully extend to meet the crystalline basement rock (Sokol 1966), which may have also contributed to the eastward dip. Water levels of the Wanapum and Grande Ronde shown in the cross-section are primarily the most recent data. Most Wanapum wells are located in the Moscow area as the Wanapum Formation thins towards and is much less productive in the Pullman area. The potentiometric surface in Moscow remains above the Vantage interbeds and it drops below this confining zone in Pullman. Hence, the Grande Ronde aquifer may have become semi-confined in parts of the Pullman sub-basin.

The cross-section B–B′ from Pullman to Colfax is shown in Figure 11. The Grande Ronde units dip northwest towards Colfax with a hydraulic head change of up to 150 m (492 ft). A dry well about four km (2.5 mi) to the southeast of Colfax that penetrates Wanapum and Grande Ronde to 152 m (500 ft) below surface suggests likely reflected the substantial folding down of both basalt formations.

The cross-section C–C′ from Pullman to the Snake River (Figure 12) displays more structural features than found on other cross-sections. The significant difference of nearly 460 m (1,500 ft) in the hydraulic heads of the Wanapum and Grande Ronde aquifers near the canyon walls of the Snake River appears to be related to the dip of the basalt flows to the northwest away from the Snake River.

The deep well, located approximately two km (1.5 mi) north of Lower Granite Dam on the

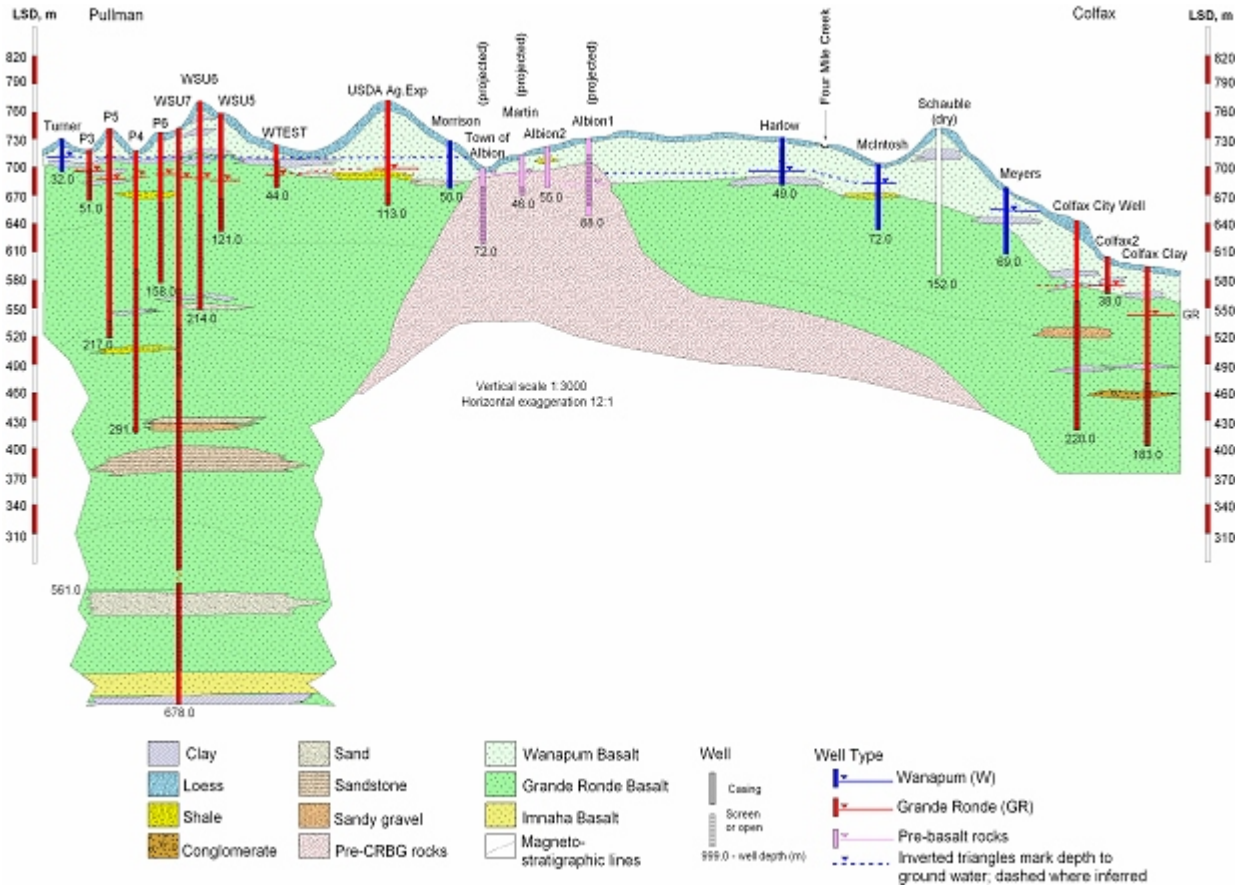

Figure 11. Hydrogeological cross-section (B-B′) from Pullman to Colfax. Transect B-B′ is shown on Figure 3. Ground-water level data was extracted from the Palouse Basin hydrogeology GIS database.

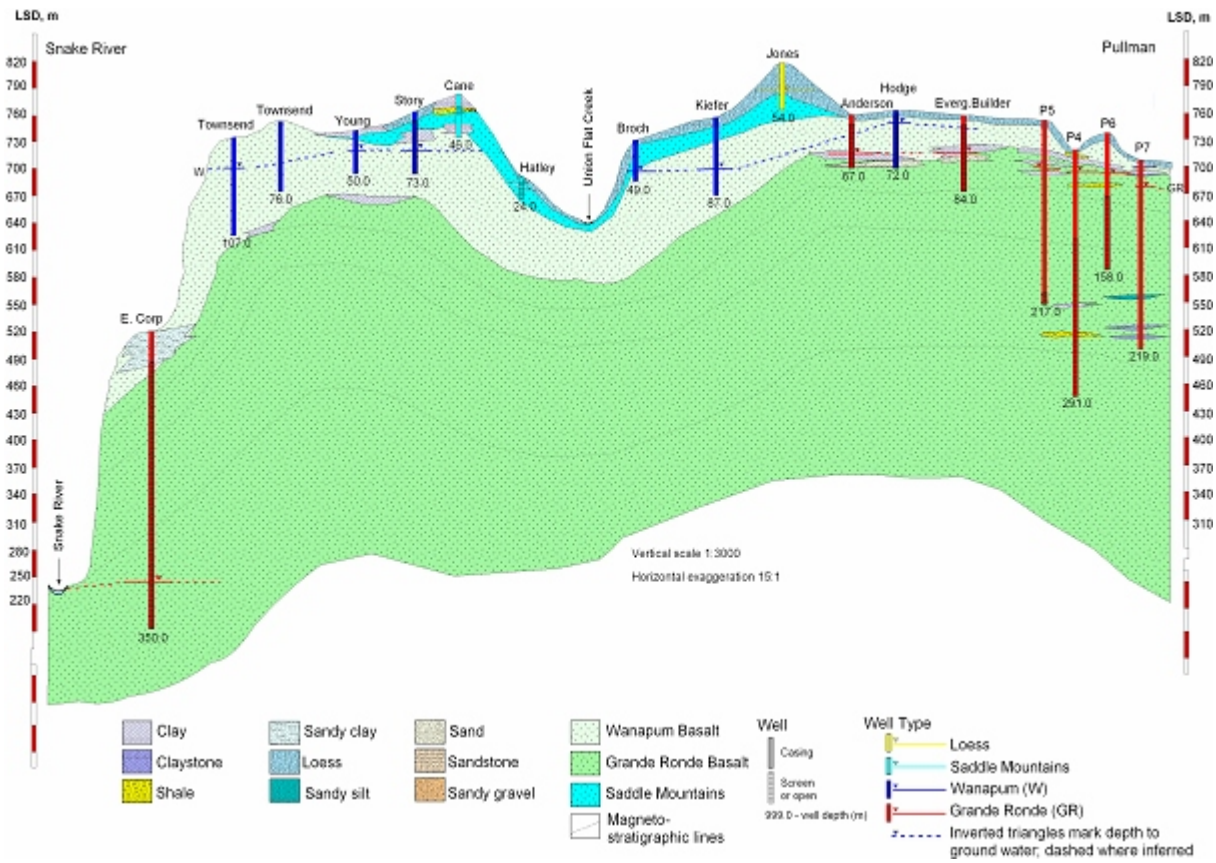

Figure 12. Hydrogeological cross-section (C-C′) from Pullman to the Snake. Transect C-C′ is shown on Figure 3. Ground-water level data was extracted from the Palouse Basin hydrogeology GIS database.

Snake River, does not appear representative of the general potentiometric surface of the Grande Ronde in the Palouse Basin. For instance, it was assumed that because the pool elevation behind the dam was about 225 m (738 ft) (U.S. Army Corps of Engineers 2006) and the water level in Grande Ronde was 235 m (770 ft) in 1975 (the year the well was drilled), that there was discharge to the Snake River (Smoot and Ralston 1987). However, geochemistry data indicates a lack of Grande Ronde discharge to the Snake River (Larson 2000; Douglas 2004). Our hydrogeological cross-section and well data also implied that, although local discharge may be present, no evidence suggests regional discharge to the Snake River through the canyon walls. Hence, assuming the canyon walls of the Snake River as a seepage discharge boundary, as in Lum et al. (1990), may be inadequate.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

A comprehensive hydrogeology GIS database was developed for the Palouse Basin through this study. The GIS database contained map coverages pertinent to surface hydrology (topography, stream network, soil, land use) and hydrogeology (wells, subsurface topographic relief, and potentiometric surfaces). Additionally, long-term climate records, ground-water pumpage, and ground-water hydrographs were compiled and analyzed, and a total of seven hydrogeological cross-sections were developed. The newly available spatial and temporal data in GIS format proved valuable in helping us attain new knowledge of the complex ground-water flow system in the Palouse Basin.

The data used to develop the Palouse Basin hydrogeology GIS database were obtained from original historical records archived in various formats and stored in different localities. In this study, more than 800 wells have been digitized and included in the GIS database. In addition, wells were linked to their attribute tables, allowing efficient display and analysis of relevant well properties. These attributes can be easily maintained and updated by other researchers, enabling effective collaboration.

Long-term ground-water hydrographs demonstrate that each aquifer has a distinct pattern of water-level fluctuations, related to pumping, climate, recharge, and in some cases, measurement errors. Fluctuations in Grande Ronde wells appeared more consistent over time in Pullman and rather erratic in Moscow, which was likely due to the presence of a multi-layered sediment system, discontinuity of water bearing zones, proximity to low-permeability boundaries of the pre-CRBG rocks, and the confined nature of the aquifer, in the Moscow area.

The potentiometric surface maps reveal that ground-water movement in the two basaltic

aquifers is to the west or northwest, and that structural features tended to create local areas with rapid changes in water levels in the direction of basalt flow and associated sedimentary units. Shifting of ground-water withdrawal from the Wanapum aquifer to the Grande Ronde aquifer in the mid-1960s had led to the recovery of the ground-water level in the former. The potentiometric surface of the Grande Ronde aquifer shows two cones of depression as a result of pumping.

Hydrogeologic cross-sections indicate largely different characteristics between the two cities of Pullman and Moscow. There is less sedimentary interbedding in the Pullman sub-basin where the loess is essentially in direct contact with the basalt, and the Wanapum aquifer is thin and unproductive. In contrast, there exist more sedimentary interbeds on the Moscow side, and the Wanapum aquifer is highly productive. The hydraulic gradient between Pullman and Moscow has been nearly level, primarily due to the continuous pumping at the two locations.

In summary, subsurface topography delineated and potentiometric surface maps developed, together with the hydrogeological cross-sections created in this study were helpful in advancing our understanding of the hydrogeologic characteristics of a fractured basalt aquifer system in inland Pacific Northwest. Previously developed ground-water models for this region have assumed simplified, “layer-cake” type of basalt system, and uniform aquifer hydraulic properties. Results and findings from this research suggest that the Palouse Basin ground-water system is largely governed by highly complex geological structures and spatially varying recharge and discharge mechanisms, aquifer geometric configurations and hydraulic properties. These complexities should be taken into consideration in order to develop a more reliable, process-based model that can be used for ground-water resource management in the Palouse Basin.

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